MAINLINE

MAINtenance, renewal and Improvement of rail transport iNfrastructure to reduce Economic and environmental impacts

Collaborative project (Small or medium-scale focused research project)

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Deliverable 4.2:
Solutions to Gaps in Compatibility between Monitoring and Examination Systems and Degradation Models

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PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Abstract of the MAINLINE Project

Growth in demand for rail transportation across Europe is predicted to continue. Much of this growth will have to be accommodated on existing lines that contain old infrastructure. This demand will increase both the rate of deterioration of these elderly assets and the need for shorter line closures for maintenance or renewal interventions. The impact of these interventions must be minimized and will also need to take into account the need for lower economic and environmental impacts. New interventions will need to be developed along with additional tools to inform decision makers about the economic and environmental consequences of different intervention options being considered.

MAINLINE proposes to address all these issues through a series of linked work packages that will target at least €300m per year savings across Europe with a reduced environmental footprint in terms of embodied carbon and other environmental benefits. It will:

- Apply new technologies to extend the life of elderly infrastructure
- Improve degradation and structural models to develop more realistic life cycle cost and safety models
- Investigate new construction methods for the replacement of obsolete infrastructure
- Investigate monitoring techniques to complement or replace existing examination techniques
- Develop management tools to assess whole life environmental and economic impact.

The consortium includes leading railways, contractors, consultants and researchers from across Europe, including from both Eastern Europe and the emerging economies. Partners also bring experience on approaches used in other industry sectors which have relevance to the rail sector. Project benefits will come from keeping existing infrastructure in service through the application of technologies and interventions based on life cycle considerations. Although MAINLINE will focus on certain asset types, the management tools developed will be applicable across a broader asset base.

Partners in the MAINLINE Project

UIC, FR; Network Rail Infrastructure Limited, UK; COWI, DK; SKM, UK; University of Surrey, UK; TWI, UK; University of Minho, PT; Luleå Tekniska Universitet, SE; Deutsche Bahn, DE; MÁV Magyar Államvasutak Zrt, HU; Universitat Politècnica de Catalunya, ES; Graz University of Technology, AT; TCDD, TR; Damill AB, SE; COMSA EMTE, ES; Trafikverket, SE; SETRA, FR; ARTTIC, FR; Skanska a.s., CZ.

WP4 in the MAINLINE project

The main objectives for WP4 are:

- to clarify what inputs degradation assessment models require from advanced monitoring techniques and examination systems, investigate their use and identify how these can operate in the most cost-effective and reliable way to complement or replace existing examination techniques for elderly infrastructure. Such monitoring and examination systems, together with the degradation models, will form a part of an effective and efficient integrated whole life asset management system developed in WP5.
- to provide case study/validation evidence so as to promote the uptake of the proposed approaches by Infrastructure Managers.

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Glossary

Abbreviation/ acronym	Description
AE	Acoustic Emission
ANT	Actual Neutral Temperature
CIRIA	Construction Industry Research and Information Association
DM	Degradation Mechanism
DRF	Dose Response Function
DTM	Digital Terrain Model
DSS	Decision Support System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
INSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
LRU	Long-Range Ultrasonics
M&E	Monitoring and Examination
MDZ	Mechanized Tamping Train (in German)
MEMS	Micro Electro-Mechanical Systems
MFL	Magnetic Flux Leakage
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
PEC	Pulsed Eddy Current
RCF	Rolling Contact Fatigue
RSHI	Rock Slope Hazard Index
SAR	Synthetic Aperture Radar
SB	Sustainable Bridges
SCADA	Supervisory Control and Data Acquisition
SMD	Soil Moisture Deficit
SSHI	Soil Slope Hazard Index
SWOT	Strengths Weaknesses Opportunities Threats
TCMI	Tunnel Condition Marking Index
TDR	Time Domain Reflectometry
TQI	Track Quality Index
UT	Ultrasonic Testing
WP	Work Package

1. Executive Summary

One of the key objectives of MAINLINE, Work Package 4 in particular, is to review currently used Monitoring and Examination (M&E) techniques with a view to identifying and providing solutions to address gaps in compatibility between inspection systems and degradation models, and provide validation of improved approaches via case studies.

Deliverable D4.1 reported on the assessment of current monitoring and examination practices in relation to the degradation models for five railway assets: (i) cuttings, (ii) metallic bridges, (iii) tunnels with concrete and masonry linings, (iv) plain line and switches and crossings, and (v) retaining walls.

For optimum performance, however, a monitoring or examination system needs to be consistent with the data required for assessment by the use of degradation reliability models. Therefore, the focus of this report, Deliverable D4.2, is to identify the gaps and compatibility issues on the current interface between output from monitoring and examination techniques and inputs for reliability models considered in deliverable D2.1. In addition, solutions to address these compatibility gaps are proposed and guidance is provided as to what additional information could be captured to achieve consistency and increase efficiency and cost effectiveness.

This report builds on work carried out to date within the MAINLINE Project, particularly related to the deliverables D2.2 and D4.1, as well as research from other relevant European projects, such as “Sustainable Bridges” (Sustainable Bridges 2007), “INNOTRACK” (Ekberg and Paulsson 2010) and “SMARTRAIL” (SMARTRAIL 2013).

2. Acknowledgements

This present report has been prepared within Work Package (WP) 4 of the MAINLINE project by the following team of contractors with TWI Ltd as the task leader:

- TWI Limited (TWI), United Kingdom
- Network Rail (NR), United Kingdom
- Sinclair Knight Merz (SKM), United Kingdom
- Luleå Tekniska Universitet (LTU), Sweden
- MAV Magyar Allamvasutak Zartkoruen Mukodo RT (MAV), Hungary
- Damill AB (DAMILL), Sweden
- Union Internationale des Chemins de fer (UIC), France

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The authors of this report have used their best endeavours to ensure that the information presented here is of the highest quality. However, no liability can be accepted by the authors for any loss that may be caused by its use.

3. Introduction

The predicted increase in traffic on existing elderly rail infrastructure across Europe (European Commission 2006) will result in increased rates of deterioration for the civil engineering and track assets concerned. These assets need to be maintained, and when necessary, replaced in as short time as possible to minimise the disruption of the flow of freight and passengers. Monitoring and Examination (M&E) techniques play a vital role in the process of rail infrastructure maintenance and, more widely, form a vital part of any integrated asset life cycle management system. However, these maintenance and renewal interventions need also to take account of the need for reduced economic and environmental impacts. Even though the residual life of each historic asset varies and is difficult to predict, degradation models are being developed to assist this.

In recent times, technological developments have led to better M&E techniques. However, the uptake of such techniques within an integrated life cycle management programme has been slow due to reasons that include:

- M&E techniques do not often provide the sort of inputs required by degradation models that form a part of assessment within life cycle management decision support approach/tools.
- M&E techniques are yet to be validated in practical context
- The costs of wide scale implementation of monitoring systems in combination with operators’ uncertainty on whether such systems represent good value for money.

WP4 aims to provide solutions by assessing current M&E practices as they relate to degradation models, identify and address gaps in compatibility issues with regard to data from M&E systems and data required from such models, and validate new approaches using Case Studies. WP4 interacts with WP2 obtaining insights on what inputs are required by the relevant degradation models and provides WP2 with suitable methods of acquiring such data.

This report, MAINLINE Deliverable D4.2, builds on work carried out in relevant EU Projects, such as “Sustainable Bridges” (Sustainable Bridges 2007), “INNOTRACK” (Ekberg and Paulsson 2010), “SMARTRAIL” (SMARTRAIL 2013) and ACEM-Rail (ACEM-Rail.1.1 2011). It also takes account of the UIC project on 'Monitoring Track Condition to improve Asset Management' (UIC 2010), as well as other sources of state of the art knowledge, including but not limited to reports generated by the UK’s Rail Standards & Safety Board (RSSB) - for example, reports T844 (RSSB 2009) and T853 (RSSB 2010) that examine remote condition monitoring IT system architecture across the rail industry to determine if they are being utilised optimally.

A benchmarking exercise carried out earlier within MAINLINE identified five asset types as the key focus areas based on a collective assessment of the probability for knowledge increase within a 3 year period and the availability of useful validation data. Each asset type is addressed within Deliverable 4.2 of MAINLINE in individual chapters as listed below:

- Chapter 4, Cuttings
- Chapter 5, Metallic bridges
- Chapter 6, Tunnels with concrete and masonry linings
- Chapter 7, Plain line
- Chapter 8, Retaining walls.

This report identifies gaps and compatibility issues on the current interface between output from monitoring and examination techniques and inputs for reliability models. In addition, potential solutions to address these compatibility gaps are proposed and evaluated using a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis.

An overview of the general organisation of the project is presented below together with the list of all the partners in work package WP4:

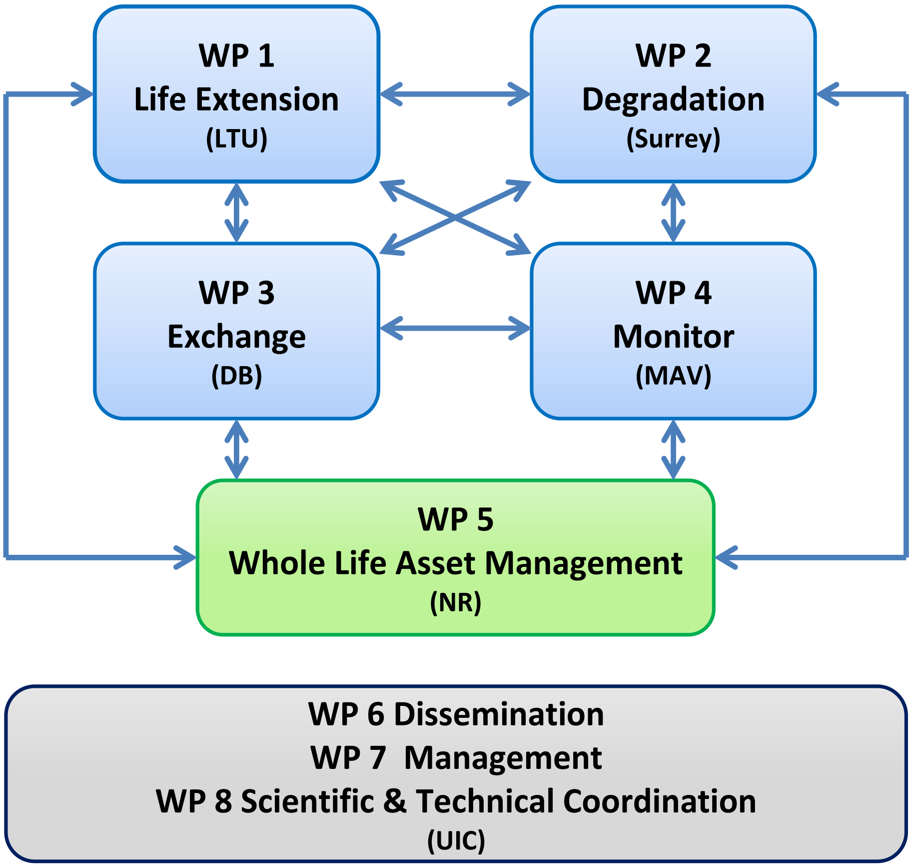


Figure 3.1 General organisation of the project

Table 3-1 List of partners participating in WP4 of MAINLINE

Part n°	WP4 Partners	Country
1	Union Internationale des Chemins de fer (UIC)	FR
2	Network Rail (NR)	UK
4	Sinclair Knight Merz (SKM)	UK
6	TWI Limited (TWI)	UK
8	Luleå Tekniska Universitet (LTU)	SE
10	MAV Magyar Allamvasutak Zartkoruen Mukodo RT (MAV)	HU
14	Damill AB (DAMILL)	SE

4. Cuttings

4.1 Introduction

This Chapter identifies gaps and compatibility issues between the outputs of monitoring and examination techniques and degradation modelling inputs. From this analysis potential solutions have been identified and examined. This report builds upon work done to date within other MAINLINE Work Packages and therefore a summary of the key findings related to the monitoring and examination techniques and deterioration and intervention modelling of railway cuttings is provided in the sections below. The MAINLINE project considers both rock and soil cuttings, thus both types are included in the following chapter.

4.2 Current Monitoring and Examination Practices

This section summarises (see Table 4-1) the monitoring and examination practices explored in D4.1 (MAINLINE.4.1 2013), as well as research from the ALERT-ME (Automated time lapse electrical resistivity tomography for monitoring embankments) project (Ground Engineering 2010) and SMARTRAIL (Smart Maintenance Analysis and Remediation of Rail Infrastructure) project (Gavin 2013).

These techniques play a valuable role in detecting the changes in an earthwork that indicate deterioration is occurring. The data collected using these techniques can thus be analysed and used to develop deterioration models that can be used to predict the condition or the risk of failure of cuttings in the future.

Table 4-1 Summary of monitoring and examination techniques for cuttings

	Technique	Explanation	Soil/Rock cuttings	Degradation mechanisms monitored	Output Data	Advantages	Disadvantages
Examinations	Visual inspection	An operator uses a hand-held device to answer predefined questions about the observed condition of the slope. In some countries operators are not engineers who understand the structure of the asset, but competent examiners who understand condition. Network Rail uses the Soil Slope Hazard Index (SSHI) and Rock Slope Hazard Index (RSHI) as rating mechanisms to understand the concatenation of the observed conditions and the impact on operability of the asset	Both soil and rock cuttings	Anything visual / available by non-intrusive methods Water presence Washout Long term creep Scour Failure of supporting structures Erosion Landslides and rockfalls Vegetation	Mainly quantitative data – a hand-held device uses GPS technology to record the location of any observed defects.	System is quick and easy to use and does not involve large set up costs (e.g. procurement and installation of expensive instrumentation) The standardised format provides a mechanism to increase consistency of reports. Allows trending in degradation to be plotted instantly from previous examinations. The use of a hand held device allows electronic examination records to be transmitted instantly and stored in a database Information related to multiple degradation mechanisms is collected, giving a good indication of overall cutting condition.	The process requires trained engineers to walk the length of the cuttings (costly/time consuming). Lower qualified examiners also carry out visual examinations but may not be able to identify all signs of structural impairment. Inspection data can be subjective, and may vary depending on the skill and experience of the examining engineer. Inspection data is subject to observable defects only, and dependent on current environmental conditions The inspections are slow compared with vehicle-based observations of other asset types. The majority of data collected is static, e.g. geometry and geology. There are fewer measurements of variable data, such as the condition of drainage.

	Technique	Explanation	Soil/Rock cuttings	Degradation mechanisms monitored	Output Data	Advantages	Disadvantages
Monitoring	Inclinometers	Used to measure lateral ground movements.	Both soil and rock cuttings	Long term creep Failure of supporting structures Landslides and rockfalls	The horizontal displacement at different depths (in millimetres).	Cost Easy to use Fast reading	The battery drop in power affecting no. or quality of readings obtained The probe not functioning properly as a result of equipment fault or poor installation or calibration Sensitive to damage during maintenance activities Highly localised readings
	Light Detection and Ranging (LiDAR)	Determines three dimensional data points through laser surveying techniques.	Both soil and rock cuttings	Water presence Scour Failure of supporting structures Landslides and rockfalls Vegetation	Measures the distance from a target. The distance measurements can be used to build a Digital Terrain Model (DTM) and calculate slope angles.	High quality Digital Terrain Models (DTM) for the whole of the rail network Flood prediction Vegetation coverage Geometric calculations	Cost (however this is reducing so will become economically viable in the future) Requires extensive data post processing and analysis It is inaccurate in some weather conditions, such as heavy rain and mist. Subject to observable defects only – changes in vegetation or structures prevent detection of underlying changes

	Technique	Explanation	Soil/Rock cuttings	Degradation mechanisms monitored	Output Data	Advantages	Disadvantages
Monitoring	Time Domain Reflectometry (TDR)	Detects movement/vibration within the cutting and can be used to monitor displacement/strain.	Both soil and rock cuttings	Water presence Landslides and rockfalls Scour	Determines the position and magnitude of displacement in the slope	Long measurements range over several tens of kilometres Effectively monitors deformations in the slope. Detects blocked drains	Cost Time required to take measurements Unable to quantify the amount of movement Localised measurements Cannot detect surface ravelling Detects only evidence of failure rather than predicting future likelihood.
	Interferometric Synthetic Aperture Radar (InSAR) methods	Method of comparing two separate Synthetic Aperture Radar (SAR) scans to determine the phase differences between the waves in the scan. This can be used to measure changes in position. Monitoring can be either ground based, satellite based or airborne based.	Both soil and rock cuttings	Landslides and rockfalls	Measures small movements in the slope. Any change in the scan readings results in a warning of impending rock fall or landslide.	Remote sensing capability at a distance of up to 1km The system has accuracies of 0.1mm at 850m or more distance Readings from ground based InSAR monitoring are not prone to the reflection of the vegetation. Real-time simultaneous mapping of deformations Fast installation and operation, independently of weather conditions	The accuracy of this technique is dependent on the system's capabilities, the radar's location and ground parameters Corner reflector installation may be required Requires highly qualified engineers to review the outputs. Cost impact high. Results from satellite based InSAR monitoring are subject to vegetation effects. Vegetation changes could affect results.

	Technique	Explanation	Soil/Rock cuttings	Degradation mechanisms monitored	Output Data	Advantages	Disadvantages
Monitoring	Resistivity measurements	Measures the cuttings electrical resistance which gives an indirect measurement of water content, as soil resistivity generally decreases with increasing water content. New ALERT-ME technology is being tested to monitor soil moisture deficit (SMD) remotely and provide 3D images to map spatial and temporal changes in moisture content.	Both soil and rock cuttings	Water presence Washout	A graph showing the variation in soil resistivity over an area. ALERT-ME technology produces volumetric images of the subsurface in real time.	Vertical and lateral ground water movements to be modelled. Differential images to monitor changes in the moisture content; threshold moisture levels give early warning on instability. Allows asset owners to remotely assess the physical integrity of important earthworks. The system can be powered by renewable sources such as solar panels Quick installation.	Stray electrical currents on the Network must be avoided at all times due to signalling concerns. If remote technology is unavailable resistivity measurements require regular site visits to ensure that cables and electrodes are kept in location.
	Global Positioning System (GPS)	Method of using a land based unit to receive time stamped signals from satellites orbiting the earth. It can be used to monitor the movement aspect of slope degradation.	Both soil and rock cuttings	Long term creep Failure of supporting structures Landslides and rockfalls	A map or image of the earth's surface. Hand-held GPS can record field data ties to a specific position.	Can be used to record field data tied to specific co-ordinates Installation is simple and takes approximately an hour GPS precision monitoring technology can determine the position to mm accuracy (e.g. Leica GMX901 system)	Reliable positional accuracy requires signals to be received from a number of satellites which is not always possible due to geometries or obstructions. Technology is new and expensive Surface mounted thus open to vandal attack/damage during maintenance activities

	Technique	Explanation	Soil/Rock cuttings	Degradation mechanisms monitored	Output Data	Advantages	Disadvantages
Monitoring	Video and Image analysis	Video cameras can be used as an affordable way of monitoring cuttings for large scale movements and rock falls	Both soil and rock cuttings	Washout Scour Failure of supporting structures Landslides and rockfalls Vegetation	Images/film of the slope	Cost Image analysis could enable automated recognition of a change, leading to an alarm being raised.	It cannot monitor small scale movement. Requires operator to review and make assumptions remote from site about condition of asset. Results may be subjective as a result.
	Acoustic Monitoring	A developing technology in seismic analysis to monitor large earth movements	Both soil and rock cuttings	Washout Failure of supporting structures Erosion Landslides and rockfalls	Acoustic Emission (AE) slope displacement rates (relationship between AE and displacement rate derived through laboratory calibration)	High sensitive equipment can detect very low displacement rates, which are typical of slope deformations Alerts obtained from continuous measurements are real-time therefore providing the possibility of a timely response to reduce consequences of slope failures and hence reduced risk	Requires the development of signal analysis to separate out different signals from the background noise. Equipment requires careful calibration in order to give accurate readings
	Micro Electro Mechanical Systems (MEMS) (Rowsell and Owen, 2009)	New inclinometers which allow stacking of in situ inclinometers in bore holes	Both soil and rock cuttings	Water presence Long term creep Failure of supporting structures Landslides and rockfalls	Lateral movement, soil temperature and moisture content.	Development in wireless and fibre optic technology will allow this technology to be monitored remotely. Sensors are relatively low cost Useful method for real time slope monitoring under rainfall	Requires extensive equipment installation (time and cost implication)

	Technique	Explanation	Soil/Rock cuttings	Degradation mechanisms monitored	Output Data	Advantages	Disadvantages
SMARTRAIL monitoring instrumentation	UMS T4e Tensiometers	Measures soil pore pressure from -80kPa to 100kPa	Soil cuttings	Presence of water Landslides	Pore water pressure (in kPa)	Equipment accurate to 5kPa. Wide variety of lengths Fast response	Requires external refilling; must be calibrated to give a relationship between pore water pressure and slope condition in order to be used in degradation model. Previous use of this instrumentation in Sweden was found to be unreliable. Although the equipment is very accurate, reliability was found to be poor because of high variability in the soil. The method was found to create false alarms and cause services interruptions.
	Campbell Scientific Soil moisture probes	Measures the volumetric water content from 0% to saturation. Probe is buried or inserted into the soil from the surface.	Soil cuttings	Presence of water Landslides	Volumetric water content (in % saturation)	Fast response time Very accurate equipment	Must be calibrated to give a relationship between saturation and slope condition in order to be used in degradation model Previous use of this instrumentation in Sweden was found to be unreliable. Although the equipment is very accurate, reliability was found to be poor because of high variability in the soil. The method was found to create false alarms and cause services interruptions.
	Trimble Mensei Laser Scanner	Takes 3D laser scans to monitor movement of cuttings. Volume change can be monitored over time by using a time sequence.	Both soil and rock cuttings	Washout Scour Failure of supporting structures Landslides and rockfalls Vegetation	3D images of the slope	Continuous monitoring could enable automated recognition of a change, leading to an alert/notification/warning being raised. Accurate to 1.4mm in 50m.	Equipment and installation cost

4.3 Degradation and Intervention Modelling Techniques

Condition scoring systems are being used for degradation modelling to observe and predict how the defined condition of an asset changes over time. The modelling can adopt either a deterministic or probabilistic approach, the selected approach depending on the level of uncertainty involved in the process and the input parameters available, including volume of reliable data upon which the model is constructed. A deterministic model is one which will always lead to the same outcome given the same set of inputs. A probabilistic model is one whose outcomes can vary even when provided with the same set of inputs (MAINLINE.2.2 2013).

Table 4-2 summarises three different soil slope degradation and intervention modelling approaches that have recently been developed or are currently under development:

- MAINLINE WP2 cuttings model 2013 (the present FP7 Project)
    - This is a soil cuttings deterioration model based on historic Network Rail SSHI inspection data translated into a generalised format known in the context of this project as the SKMA.
- CeCost cuttings models 2012 (Network Rail/SKM)
    - These are soil and rock cuttings deterioration models based on historic Network Rail SSHI inspection data.
- SMARTRAIL WP2 slope stability model 2013 (concurrent FP7 Project)
    - This is a soil slope stability reliability model based on NDT data from instrumented test slopes.

Table 4-2 Summary of Degradation and Intervention Techniques in cuttings

Technique	Soil or rock cuttings?	Probabilistic or deterministic?	Input Data	Output data	Deterioration mechanisms that can be monitored	Advantages	Disadvantages
MAINLINE (SKMA model)	Soil cuttings	Deterministic	Qualitative inspection data. Requires repetitive past examination data to be collected.	The expected future condition score determined by the probability matrix.	Deep Rotational Shallow Translational Earthflow Washout Burrowing	The model is deterministic but uses the ‘probable value’ method to account for uncertainties in the deterioration on a cutting. For a single asset an expected value is more useful than a set of probabilities, however, the probabilities will be valuable if this technique is extended to model a portfolio of assets. Separate deterioration matrices can be determined for each region or climate, improving the reliability of the model. This technique can also be used to model rock cuttings and other asset types.	Qualitative inspection data is subjective, reducing the reliability of the model. The deterioration estimates are only applicable for that region. The model requires large quantities of past inspection data in order to validate the deterioration model. The model is retrospective, based entirely on historical data. However, analysing the data for other regions or climates may enable the modelling of future conditions.

Technique	Soil or rock cuttings?	Probabilistic or deterministic?	Input Data	Output data	Deterioration mechanisms that can be monitored	Advantages	Disadvantages
Network Rail CeCost Model) (SKM 2012a; SKM 2012b; Network Rail 2012a)	Both soil and rock cuttings	Probabilistic	<u>Soil Cuttings</u> SSHI inspection data which is used to determine: • Actual Score • Potential Score • Slope Height Factor • Burrowing condition • Drainage condition • Deterioration Matrix • Intervention Matrix <u>Rock Cuttings</u> Historical RSHI inspection data which is used to determine: • 12 overall rock slope condition bands • 12 drainage condition bands- Deterioration matrix values were derived using historic condition examination data	Outputs are in the form of a risk (condition) profile and cost/volume profiles over time for the asset populations.	Deep Rotational Shallow Translational Earthflow Washout Burrowing	It can be used at an individual asset level or a whole population of assets It is able to calculate the probabilities of each of the possible outcomes occurring, producing accurate results when considering a large number of assets. The model builds upon extensive research undertaken by Network Rail and incorporated additional experience and engineering judgement from SKM	It has no optimising or automated optioneering capability. It under-estimates the condition improvement that many intervention types deliver. The model algorithm requires drainage deterioration data, which was not available. Instead the input for drainage deterioration was assembled by judgement. No assessment of deliverability. Some factors are not included in the model, such as climate change, drainage works and mining. The reliability of a probabilistic model is limited by the quality, quantity and time span of existing data records which may not be available for large parts of Europe.

Technique	Soil or rock cuttings?	Probabilistic or deterministic?	Input Data	Output data	Deterioration mechanisms that can be monitored	Advantages	Disadvantages
SMARTRAIL (Gavin 2013) (UCD Reliability Model – GASSA)	Soil cuttings	Deterministic	Quantitative monitored data including: • Soil pore pressure • Soil moisture content • Rainfall intensity Slope angle	Advance of the wetting front and rate of infiltration. Determines the critical slip surface and the various soil properties along this fixed surface, such as shear strength.	Shallow translational slips	Considers soil properties and slip coordinates as variables, so allows for them to change over time. The model has been tested on a range of 14 soil properties and was found to have a higher reliability index when compared to 3 no. alternative methods in all but one case (SKM 2012a)	High costs involved in installing monitoring equipment over long lengths of cuttings.

4.4 Good examples of data compatibility

MAINLINE WP2 soil cuttings deterioration model

The MAINLINE project has made use of the inspection data that has been collected for Network Rail's SSHI algorithm. This examination data has been reformatted, allowing the information to be used in a more generalised SKMA (see Section 4.3) deterioration model. Rather than map the SSHI scores directly to the SKMA scores, the SSHI *features* were mapped to the SKMA *features* and then appropriate scores in the SKMA system were assigned to each feature. The observations made during each SSHI examination are recorded via a series of alphanumeric codes which identify certain features present in the cutting. These alphanumeric codes were analysed and grouped into sets corresponding to the six variables defined in the SKMA. It was then possible to map the SSHI features to the SKMA features, and then an overall SRV value could be assigned. For full details of the SSHI to SKMA data conversion process refer to MAINLINE Deliverable 2.3.

This suggests that if inspection records are made available for other countries it would be possible to convert the information into this standardised format and further increase confidence in the output model. The use of 10 years of historical UK data has been essential in the validation of the deterioration matrix.

CeCost soil and rock cutting deterioration models

The CeCost model (SKM 2012b; Network Rail 2012) directly uses SSHI and RSHI condition scores as the main inputs. The deterioration matrix values were derived using historic condition inspection data for assets that have been examined more than once. This data was used to generate frequency distributions illustrating how the various scores change over time. The CeCost deterioration model is designed to be applied to UK assets, and so the use of a UK specific data set is appropriate.

SMARTRAIL WP2 soil slope stability model

The SMARTRAIL project has specifically selected monitoring techniques that provide compatible input data for the UCD reliability model 'GASSA' (SMARTRAIL 2013). The project also includes collecting large quantities of monitoring data from a test embankment. A rainfall induced failure was triggered on the embankment, allowing the reduction in suction to be monitored until failure. This data was then used to validate and improve the UCD GASSA model.

4.5 Identified gaps, compatibility issues and potential solutions between Monitoring and Examination output and Deterioration Modelling input

4.5.1 Lack of data records across Europe

There appears to be little available earthwork examination records held by railway infrastructure owners in most of Europe, with Network Rail the only operator to carry out systematic recorded examinations of the entire asset catalogue. This may import inaccuracies in the methodology of developing a deterioration model that can be applied across Europe, as the input parameter weighting and intervention uplift effects used in the model need to be validated with past data and refined for different regions.

The rate of deterioration is greatly affected by the exposure environment and geological conditions, such as precipitation, wildlife, seepage, and soil durability. There are large variations in these factors across Europe; therefore, solely using historical inspection data for the UK will be insufficient to validate the deterioration models for the whole of Europe.

There may also be a lack of consistency in monitoring and examination techniques across Europe, levels of acceptable condition and defects or simply different available technology, resulting in a variety of M&E outputs. This is a significant issue as a deterioration model will only be beneficial if it is able to incorporate data from different areas. The rate of deterioration varies on an asset by asset basis due to the large number of variables involved in the assessment of earthwork condition. For this reason it is paramount to obtain large datasets, in similar formats, for each region, in order to validate the deterioration matrix.

4.5.1.1 Potential solutions to address this gap

A possible solution to these issues is the introduction of a standardised Europe wide earthwork assessment sheet and corresponding algorithm. This will bring greater consistency in earthwork monitoring and enable a single deterioration model to be used across Europe. The SSHI and RSHI algorithms have been developed based on UK experience alone so may not be suited to the assessment of earthworks in all other European regions. For this reason the MAINLINE Project has developed a prototype for generalised inspection sheet; this algorithm might be applicable to different regions and railway infrastructure managers within the European Union. This method has been outlined in Deliverable 2.2 (MAINLINE.2.2 2013).

A notable limitation of this technique is that the collection of data using this inspection sheet will be both costly and time consuming, due to the large quantity of past data required to validate the deterioration matrix. It will require a culture shift in the infrastructure companies to value the data available to them on the condition of their assets to allow them to proactively manage future condition and capability without resorting to unplanned/emergency maintenance.

There are further problems that may arise from a standardised condition assessment. Regional specific problems are not tackled, such as sensitive soils in Sweden, which may have significant effects on deterioration patterns.

This standardised approach will need to be reviewed and refined by other European Infrastructure Managers and geotechnical expects in order to enhance its quality and reliability. This engagement with industry can be achieved through technical events, workshops, one to one meeting and questionnaires. This is vital as input when creating this standardised method since to date it has been limited to that of UK partners with largely UK experience. If other European experts are willing to collaborate with this scheme, this amalgamation of knowledge could be a great opportunity. By consulting experts from around Europe a more reliable algorithm could be developed.

4.5.1.2 SWOT Analysis to identify optimum solutions

Figure 4.1 SWOT analysis of the development and implementation of a generalised algorithm

4.5.2 Integration of models containing examined and monitored data

Simultaneous use of Monitoring and Examination techniques could greatly improve the reliability of deterioration models. There are a number of sophisticated monitoring techniques available for earthworks; however, many of these are not currently used in deterioration modelling. The International Union of Railways (UIC) has identified this as a critical issue for European Infrastructure managers because the visual inspection of a slope will not reveal whether a deep-seated failure mechanism, such as a weak soil layer, is present and likely to cause a failure. Furthermore, the subjective nature of visual inspection introduces variability in the data which can limit the reliability of a deterioration model based on that data. As a result, Work Package 1 of the SMARTRAIL project has been set with the aim of bringing about a step change in the traditional methods of visual inspection and ad-hoc monitoring by the introduction of integrated monitoring systems (SMARTRAIL 2013).

Monitored data can be captured much more regularly than examination data and produces quantitative results as opposed to the qualitative results from examination sheets. These differences can prove to be problematic when inputting data into deterioration models.

A further problem encountered when attempting to incorporate monitored data into deterioration models is the lack of monitoring techniques for some failure mechanisms. Investigations so far have only identified monitored data for shallow translational slip failures, using the SMARTRAIL technology. Further research should be conducted to develop methods to monitor deep rotational, earthflow, washout and burrowing failures. Monitoring requires intelligent installation of equipment to detect actual movements or changes of interest.

4.5.2.1 Potential solutions to address this gap

Further research should be undertaken to ascertain ways of incorporating monitored data into deterioration models. SMARTRAIL research has concluded that the development of algorithms to link continuously observed sensor data with the rating of a cutting would be of significant benefit. The condition rating derived in this process would be significantly more robust than those currently available for non-instrumented cuttings, due to the reduction in both known and unknown uncertainties. This is of particular benefit when used to trigger emergency works rather than reactive works once a failure has already occurred. The use of monitored data will also reduce subjectivity that can be problematic in inspection techniques.

A notable limitation of monitoring techniques is the quantity of detectors required over long lengths of cuttings. This would be of great cost to the asset owner. Projects, such as ALERT-ME, are investigating cost effective early warning systems for monitoring the stability of vulnerable earth structures. Through research projects like these, monitoring techniques are likely to become more economically viable in the future.

A potential solution to integrate monitored data in a cost effective manner is to install the monitoring equipment only when a cutting reaches a poor condition. The timing of this intervention would be determined by the deterioration model. The monitoring equipment could then be used to generate alarms for impending or actual failure, which would aid risk mitigation. This method would improve reliability in condition modelling for unstable earthworks. It will enable intervention works to be postponed to a later stage, due to a greater confidence in the condition of the cutting.

4.5.2.2 SWOT Analysis to identify optimum solutions

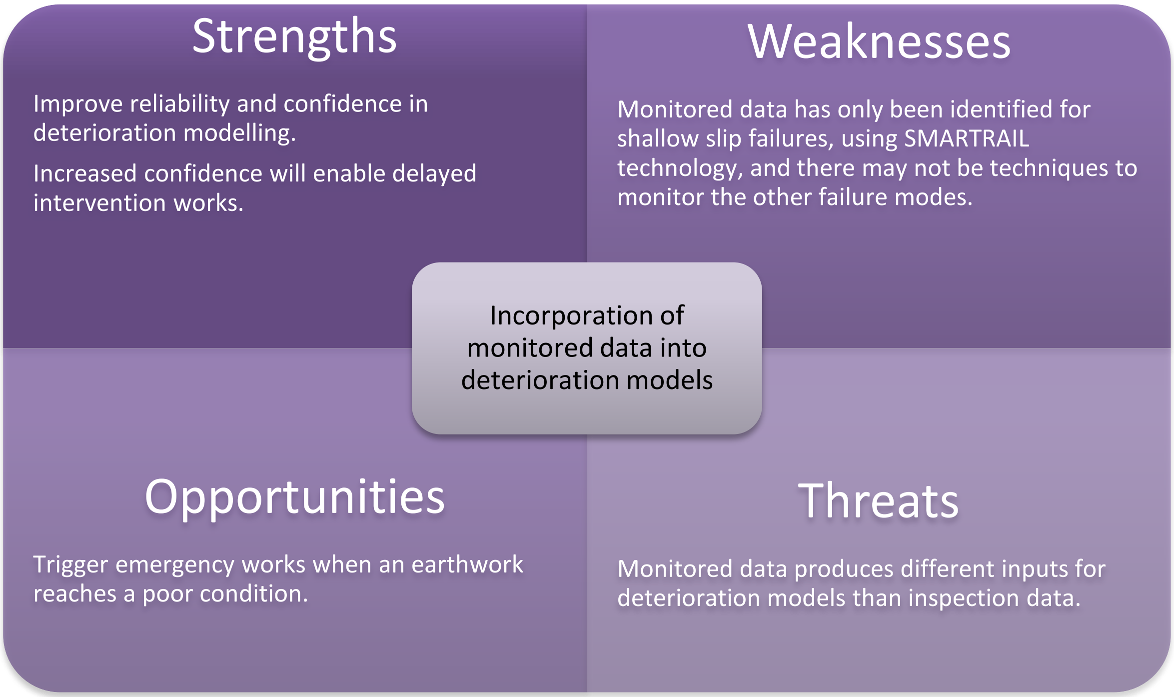


Figure 4.2 SWOT analysis of the incorporation of monitored data into deterioration models

4.5.3 Earthwork stability may alter with climate change

A major concern when assessing earth structures is how climate change will affect their degradation. There are high degrees of uncertainty surrounding possible climate change future scenarios with changes being expected to vary greatly between regions and different seasons.

The UN's Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report states: *"Annual precipitation is very likely to increase in most of northern Europe and decrease in most of the Mediterranean area. In central Europe, precipitation is likely to increase in winter but decrease in summer. Extremes of daily precipitation are very likely to increase in northern Europe. The annual number of precipitation days is very likely to decrease in the Mediterranean area. The risk of summer drought is likely to increase in central Europe and in the Mediterranean area"* (Toll *et al.*, 2012). The IPCC has recently released (September 2013) the first volume of its 5th Assessment Report on "The Physical Science Basis of Climate Change", which provides a strengthened body of evidence of man-made climate change since its last major review six years ago. In regard to projections on precipitation, the summary of this report states: "*Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions*" (IPCC 2013).

In addition to the research into possible climate change scenarios, intensive research is being undertaken in the prediction of the changes to slope properties due to these anticipated climatic changes. The stability of soil cuttings is provided by suction. Increased sustained rainfall will cause a reduction in soil suction as empty void space is filled, reducing capillary action. This decrease in soil suction will result in a reduction in shear strength, increasing slope movement. An increase in frequency of extreme weather events could result in worsened freeze thaw deterioration, where freeze heaving and thaw softening effects can cause a decline in strength and stiffness. The cycle of swelling during wet periods and shrinkage during dry spells can also cause deformations (MAINLINE.2.1 2012).

These findings are emphasised by a study conducted by Network Rail as part of the development of their CP5 Earthworks Asset Policy in 2012 (Network Rail, 2012a). The study compared earthwork failure records with national average rainfall data, as well as records of local rainfall events. The findings were as follows:

- There is broad correlation with the wetter years showing higher numbers of failures.
- Many failures are due to local rainfall events that are not reflected in average national figures.
- Analysis of the 2003-2011 data showed that 42% of primary and secondary earthwork failures relate to rainfall events and approximately 30% are related to blocked/poor drainage or water concentration features.

The significant changes in climatic patterns across Europe will greatly impact deterioration modelling, as historic rates of deterioration will not be indicative of future deterioration. This could considerably reduce the reliability of many models, such as CeCost and MAINLINE, which are solely based on past data. The deterioration models must be able to incorporate changing climatic conditions, such as precipitation and temperature, which have a substantial effect on slope stability.

4.5.3.1 Potential solutions to address this gap

<u>1) Inputting climatic data into deterioration models</u>

One method for overcoming this problem is through the integration of climate change predictions into deterioration modelling, so that accelerated deterioration is accounted for. The models will need to account for climatic trends that have not been observed in the past and predict how these changes will affect stability. The climatic data could be incorporated into a deterministic model, based on soil mechanics, using precipitation or soil moisture deficit (SMD) input parameters. High quality field observations involving climate/soil interaction will be required to validate the models.

The Biological and Engineering Impacts of Climate Change on Slopes (BIONICS) project aims to develop this high quality data set through calibrating numerical models of soil responses to climate change. A full scale embankment was subjected to a climate control system designed to impose different climate change scenarios. Advanced monitoring technology was used to track the effects of the climatic states on the stability of the embankment. Climate change impact on slope stability investigated by BIONICS will be relevant to cuttings and embankments

Other projects are currently being undertaken which may provide useful input data for the deterioration models. These include:

- SMARTRAIL project, as detailed in chapter 3.3.
- Climate Impact Forecasting For Slopes (CLIFFS), a consortium to improve forecasting of slope instability.

- Climate change Risk Assessment: New Impact and Uncertainty Methods (CRANIUM), a project developing new methodologies for analysing uncertainty and making robust risk based decisions for infrastructure design and management in the face of climate change.

2) Adopting deterioration matrices developed for different regions

The previous technique could prove difficult to implement, as it requires the development of new deterioration models. A more cost-effective way of incorporating changing climatic conditions is through using the deterioration matrices developed for different regions or climates. For example, many climate models project that climatic conditions in the UK will change, for example summers will become warmer and drier, at times mimicking conditions from warmer regions such as Southern France, consequently new models could incorporate findings and lessons from those regions. This method not only requires past earthwork assessments from other regions, but also the corresponding climatic data for that period, which could prove difficult to acquire. The accuracy of this technique is limited as future climates will not match up directly with previous trends in other regions.

4.5.3.2 SWOT Analysis to identify optimum solutions

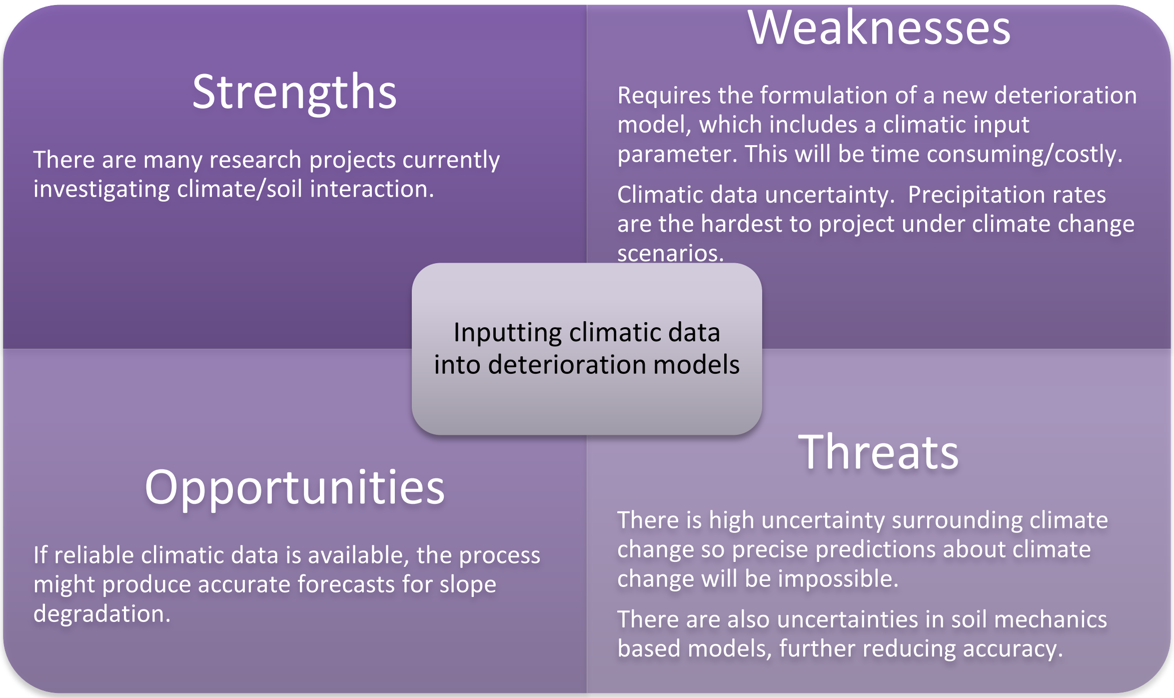


Figure 4.3 SWOT analysis of inputting climatic data into deterioration models

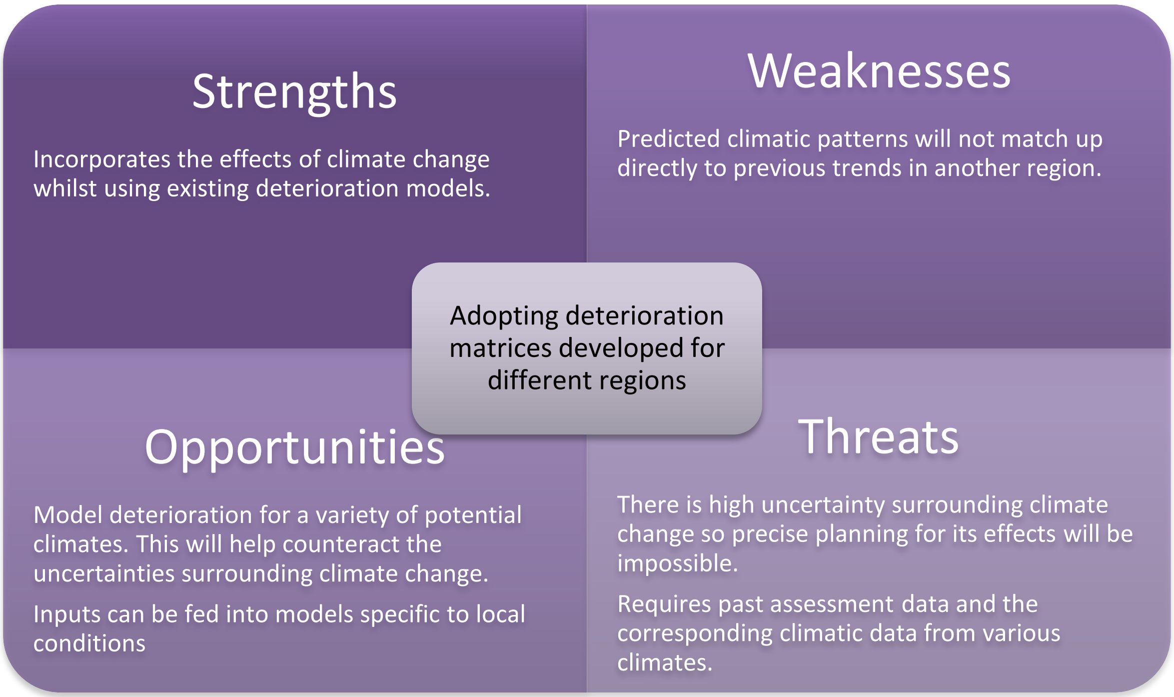


Figure 4.4 SWOT analysis of adopting deterioration matrices developed for different regions

4.6 Summary

Table 4-3 SWOT Analysis to identify optimum solutions in cuttings

Solutions	Strengths	Weaknesses	Opportunities	Threats
Development and implementation of a generalised algorithm	May allow the MAINLINE deterioration model to eventually be used across Europe. A larger data set will improve the reliability of the deterioration matrix. Uses historical data to predict future deterioration.	Completing inspection sheets for a large quantity of data will be costly and time consuming.	A generic algorithm will ensure consistency in earthwork monitoring. Pooling knowledge across Europe.	Success will be reliant on input from several Infrastructure Managers and geotechnical experts across Europe. This is a challenging task since soil conditions differ considerably. Does not account for regional specific soil type, problems and priorities.
Incorporation of monitored data into deterioration models	Improve reliability and confidence in deterioration modelling. Increased confidence will enable delayed intervention works.	Monitored data has only been identified for shallow slip failures, using the SMARTRAIL technology, and there may not be techniques to monitor the other failure modes.	Trigger emergency works when an earthwork reaches a poor condition.	Monitored data produces different inputs for deterioration models than inspection data which may cause compatibility issues.
Inputting climatic data into deterioration models	There are many projects currently investigating climate/soil interaction.	Requires the formulation of new deterioration models, which include an input parameter that can be correlated with climatic trends. This will be time consuming and costly.	The effect of different climate change trends on slope deterioration could be modelled. External research in predicted climate change scenarios could be incorporated as and when it becomes available in order to develop more reliable forward looking deterioration models	There is high uncertainty surrounding climate change so precise predictions about climate change will be impossible. There are also uncertainties in soil mechanics based models, further reducing accuracy.
Adopting deterioration matrices developed for different regions	Incorporates the effects of climate change whilst using existing deterioration models.	Predicted climatic patterns will not match up directly to previous trends in another region.	Model deterioration for a variety of potential climates. This will help counteract the uncertainties surrounding climate change.	There is high uncertainty surrounding climate change so precise planning for its effects will be impossible. Requires past assessment data and the corresponding climatic data from various climates.

5. Metallic Bridges

5.1 Introduction

This Chapter identifies gaps and compatibility issues between the outputs of monitoring and examination techniques and degradation modelling inputs for metallic bridges. MAINLINE deliverable D2.2 (MAINLINE.2.2 2013) describes two major degradation processes for metallic structures: degradation due to fatigue and degradation due to corrosion. Chapter 4 of MAINLINE deliverable D4.1 (MAINLINE.4.1 2013) describes and evaluates the currently available examination and monitoring techniques for metallic bridges. These methods are considered in this report in regard to their potential to provide valuable information for the fatigue and corrosion processes.

5.2 Current Monitoring and Examination Practices

This section provides an overview of the currently available monitoring and examination practices described in deliverable D4.1 (MAINLINE.4.1 2013), focusing on techniques that are capable of inspecting the degradation phenomena of fatigue and corrosion in metallic bridges.

The inspection of metallic bridges has been the focus of several projects to date. Railway infrastructure owners tend to inspect their bridge stock regularly, with most of the European railway owners having three or four different inspection levels. According to questionnaires carried out for the purposes of the FP6 Project Sustainable Bridges (2007), 13 of 17 railway owners perform annual inspections (Bell 2004). The frequency of the inspection depends on the level of inspection carried out and the asset owner. More specifically, the frequency of thorough inspection may differ between 2 and 10-12 years amongst European countries. In regard to other inspections (different levels), these could be carried out from once every 6 months to once every 8 years.

Within the Sustainable Bridges (SB) project, a guideline for inspection and condition assessment for railway bridges was developed, SB-ICA (2008). Based on the state of the art, the project concluded that there was no need for new inspection rules but enhancing the available inspection approaches would be beneficial. The project was a step forward towards the direction of enhancing inspection and unification of understanding NDT methods in order to upgrade inspection regulations from local/national level to a trans-European network. Some of the limitations that were identified surrounded the fact that, in most of the European countries, bridge inspections are carried out independently of the structural assessment and that, on European level, databases on typical defects in railway bridges or bridge testing methods are not available (Helmerich 2007). In the guideline, SB-ICA (2008), there is also an Appendix with a detailed tool-box of non-destructive testing, while UIC recommendations for bridge maintenance procedures are given in UIC 778-1(2011), UIC 778-2(1986) and UIC 778-4R (2009).

Furthermore, valuable lessons were learnt from the Sustainable Bridges project in regard to monitoring of railway bridges, with a report, SB-Mon (2008) providing valuable guidelines to monitor tasks carried out on railway bridges. This report provides a systematic methodology to specify, design, implement and operate monitoring systems. In addition, a toolbox with recommendations for the application of methods, data processing algorithms and sensors was developed. The goal of this monitoring toolbox is to provide information about methods, algorithms and sensors that may be applied when monitoring a bridge. Concepts and recommendations for planning and implementation of monitoring of steel railway bridges are also available in a report by Sedlacek *et al*. (2007), for the Sustainable Bridges project.

Condition assessment of bridges comprises two main phases: (i) “in situ” inspection of the structure and (ii) evaluation of condition, SB-LRA (2008). During the first phase, all relevant information is collected for the subsequent calculation of an index related to the condition of the structure. Thus, the first step in the condition assessment sequence is the inspection process, which includes both standard inspection and advanced inspection. Standard inspection techniques are based on obtaining a result of the inspection when it is decided to perform such inspection, whereas advanced inspection makes use of more advanced techniques besides the visual inspection and the simple tests used during a major inspection. Since a deterioration process can start just after a standard inspection has been carried out, the use of advanced sensors is increasingly being introduced to decrease the number of inspections. With the use of such sensors, which allow the continuous inspection for the whole service life of the structure, the continuous condition assessment of a bridge is possible (Casas and Cruz, 2003). However, such a type of assessment may also generate excessive and often unnecessary data. Table 5-1 summarizes monitoring and examinations techniques and degradation mechanisms that were identified in deliverable D4.1 (MAINLINE.4.1 2013).

Table 5-1 Monitoring and Examination (M&E) techniques and Degradation Mechanisms (DM) affecting metallic bridges as summarized in D4.1 (2013) [1]

MAINLINE Project
WP4: Monitoring and Examination Techniques
D4.1: Report on assessment of current monitoring and examination practices in relation to the degradation

DM / M&E	Water presence	Presence of discontinuities	Fatigue/Fracture	Weld defects	Deformation of elements	Corrosion	Buckling
Visual Inspection	✓	✓	✓	✓	✓	✓	✓
Optical Fibre Monitoring			✓			✓	
Ultrasonic Testing	✓	✓	✓	✓		✓	
Radiographic Testing	✓	✓	✓				
Liquid Penetrant Tests		✓	✓	✓			
Strain gauges/Fatigue sensors			✓	✓	✓		
Acoustic monitoring	✓	✓	✓				
Magnetic Particle Inspection		✓	✓				
Laser Scanning		✓	✓	✓	✓		✓

Table 5-2 below provides a summary of the corrosion monitoring and examination techniques for metallic bridges.

[1] DM here refers to Degradation Mechanisms or Symptoms of/Factors affecting Degradation

Table 5-2 Summary of corrosion monitoring and examination techniques for metallic bridges

	Technique	Explanation	Degradation mechanisms monitored	Output Data	Advantages	Disadvantages
Examinations	Visual inspection	The general inspection involves a visual inspection of all parts of the structure and, where relevant the behaviour and stability of the structure. There can also be close examinations, within touching distance, of all accessible parts of the bridge. The inspections are visually based but can also be supported by measurement and simple testing to gather additional data. See more information in MAINLINE D4.1.	Propagation of surface corrosion (the area affected by corrosion can be measured quantitatively, the depth of section loss mainly qualitatively), Loss of coating (qualitatively), Fatigue crack propagation by periodical observation of crack length.	Photographs, notes. Whilst presently inspection work is performed purely manually, increasing moves have been noted towards the use of supporting technologies. These may employ video camera systems with frame grabber and picture stores, which are often accompanied by PC-based picture libraries, allowing examinations to take place off-site.	Routine visual inspections are carried out by bridge inspectors or examiners, who may also be involved in the day to day maintenance of these bridges. Staff perform the function of a trained pair of eyes able to spot obvious signs of damage and distress, and often have a thorough understanding of the requirements for routine maintenance and straightforward repairs. Other advantages are: low cost, immediate data for viewing and analysis.	Inspection of the structure inside the material is not possible or very difficult. The output of the examination is affected by subjectivity. Accuracy of the obtained output might be insufficient for the required input in the degradation models. Visual inspection, alone, can lead to inconsistent assessments. Uncontrolled offset affects the field of view and the crack's width and length.

	Technique	Explanation	Degradation mechanisms monitored	Output Data	Advantages	Disadvantages
Monitoring	Optical Fibre Monitoring	Optical fibre monitoring can be used for the monitoring of a wide range of bridges in terms of material and structural form, including metallic bridges. The most widely used type is the Fibre Bragg Grating sensor which, by measuring a change in wavelength in the light source, provides a change in strain at a particular location. See (Glisic, Posenato and Inaudi 2007) and (Inaudi 2009).	Degradation due to corrosion. The process of the loss of thickness of a steel element can be monitored. Research is currently on-going on the direct measurement of corrosion in metallic bridges using optical fibres, but is not yet sufficiently advanced for commercial application.	Optical fibre monitoring systems can provide a very large amount of raw data, and hence the minimum required data and any required data interpretation should be specified prior to the procurement of the monitoring system. Typical monitoring data plots are temporal and spatial change in strain, such as the change in strain during trains crossing the bridge, or the variation in strain through the height of a girder at a particular instant in time.	The durability of optical fibre monitoring systems is high, they are suitable for medium-to-long term monitoring. The system is immune to many kinds of external noise due to the electrical isolation of the sensors. Capable of continuously gathering information. Capable to monitor hidden critical structural elements. Possible to develop time-lapse information.	Not yet fully developed for commercial application. Installation typically requires at least a day often with a commissioning period (e.g. controlled load test) to confirm adequate operation. Continuous monitoring over long periods of time generates unmanageable and often unnecessary amount of data. Although durability is good, sensor redundancy should still be considered due to the very long typical service life of a bridge.
	Ultrasonic Testing (UT)	This method relies on high frequency sound waves being introduced into the material and the fact that ultrasonic pulses are not transmitted through large air voids.	Degradation due to corrosion. The process of the loss of thickness of a steel element can be monitored. Development of discontinuities in the structure caused by corrosion and fatigue cracks can be monitored.	Flaw detection in welds, plates, castings, mechanically joined splices and connections, crack sites, as well as detection and location of discontinuities, mainly cracks, thickness measurement of steel, detection and location of porosity, voids, non-metallic inclusions and corrosion can be carried out using this technique. Thickness measurements with access from one side only, with 2% accuracy and for thickness 1 – 200 mm. Detectable defect size: min. 1.3 mm deep and approximately 2.5 mm long.	Highly portable, lightweight units, tests can be performed quickly; Low expertise needed to take measurements; Ability to test from one surface only; Comparative accuracy in determining defect's size and depth.	Surface must be clean, smooth and free of rust or excessive paint; Probe alignment and coupling are critical; High expertise is needed for interpretation of signal data; Small or thin parts are difficult to examine; Requires point by point search, hence the method is expensive when used on large structures.

5.3 Degradation and Intervention Modelling Techniques

This Section summarises the degradation and intervention modelling techniques used in metallic bridges, as these have been discussed in deliverable D2.2 (MAINLINE.2.2, 2013). The focus of this report was on the degradation due to fatigue and corrosion as well as the effect of coatings on the deterioration process.

5.3.1 Modelling corrosion deterioration and coating intervention

This report summarises the modelling of corrosion damage due to atmospheric conditions into three levels of modelling that have been identified for the long-term modelling of corrosion. Deterioration processes of sacrificial organic and metallic coatings that are amongst the most commonly used corrosion protection systems on steel structures are also studied. A summary of the degradation modelling techniques for the corrosion of metallic bridges is given in Table 5-3, while intervention techniques against corrosion, focusing on the process of coating, are summarised in Table 5-4.

Table 5-3 Summary of degradation modelling for the corrosion of metallic bridges

Technique	**Probabilistic or deterministic?**	**Input Data**	**Output data**	**Deterioration mechanisms that can be monitored**	**Advantages**	**Disadvantages**
Level 1 Empirical models (Gavin 2013)	Deterministic	Exposure conditions, metal type, etc. are taken into account through fixed model constants. These are experimentally determined coefficients obtained through regression analysis on test results in different environmental exposure conditions.	Average loss of thickness after *t* years of corrosion, *C(t)*	Corrosion	Requires only a few input parameters. Simple model, easy to apply. Exposure conditions are simply classified.	Model coefficients are associated with very high uncertainty. Available statistical properties may not be reliable and hence not suited for probabilistic analysis. Questionable model transferability. Inability to consider separately the impact and future evolution of each of the climatic and atmospheric variables. The model gives inaccurate estimates of corrosion damage when used in conditions dissimilar to the ones used for its calibration
Level 2 Empirical models which directly relate the rate of corrosion to specific exposure variables	Deterministic and probabilistic	Exposure variables (e.g. temperature, relative humidity, atmospheric pollution, etc.) These models use average annual values for the input climatic and atmospheric pollution variables. Main parameters in the models:	Corrosion loss is quantified in terms of metal thickness or mass loss in function of time, C(t).	Corrosion	Suitable for probabilistic analysis when sufficient data for the exposure conditions is available.	These models strongly rely on the data availability of atmospheric pollutants and climatic parameters in a particular area.

Technique	Probabilistic or deterministic?	Input Data	Output data	Deterioration mechanisms that can be monitored	Advantages	Disadvantages
Dose Response Functions		- annual average concentration of chloride or chloride deposition rate - annual average concentration of sulphur dioxide - the annual average temperature - the annual number of rainy days or average relative humidity - empirical coefficients for various type of metals				
Level 3 Simulation-based mechanistic models. They may involve advanced simulation techniques (e.g. Computational Fluid Dynamics - CFD) to predict airflow patterns to determine rate of pollutant mass transfer on the exposed surfaces.	Deterministic	Exposure variables	No defined outputs	Corrosion	The models are sophisticated. Provides the most accurate results when sufficient input parameters are available.	Predicted results depend on modelling assumptions. Insufficient input data for practical applications, especially for probabilistic analysis.

Table 5-4 Summary of Intervention Techniques (with the use of coatings) against metallic bridge corrosion

Technique	Probabilistic or deterministic?	Input Data	Output data	Deterioration mechanisms that can be monitored	Advantages	Disadvantages
Level 1 models	Deterministic	Exposure conditions that are determined by several climatic and atmospheric variables. Data on coating performance gathered by regular inspection at certain time-intervals (e.g. every year or every a few years inspection)	Either a single value or a range of values is available for the expected service life of a coating system for a particular environmental exposure (e.g. service life is roughly 10 years for industrial environmental exposure). The expected service life is often provided by the coating manufacturer.	Coating deterioration	Very simple	No quantitative information is available on the influence individual factors on coating performance.
Level 2 and Advanced Level 2 models	Deterministic and probabilistic	Exposure conditions that are determined by several climatic and atmospheric variables. Data on coating performance gathered by regular inspection at certain time-intervals (e.g. coating type, thickness, quality).	The basic statistical properties of the coating's service life are available (i.e. mean and standard deviation). When the distribution type is also known then these models are denoted as Advanced Level 2	Coating deterioration	More precise output	Although these models can take into account the performance variability, no functional relationship between the coating performance and the several influencing parameters is established.
Level 3 and Advanced Level 3 models	Deterministic and probabilistic	Exposure conditions that are determined by several climatic and atmospheric variables (e.g. temperature, humidity.) Coating type, thickness, quality. In Advanced Level 3 models the statistical	Dose Response Functions (DRF) defines the basic relationship between coating performance and a set of influencing variables. Advanced Level 3 models include DRF using probabilistic analysis where statistical properties of the	Coating deterioration	More precise output	It is difficult to obtain input parameters for the models especially for probabilistic analysis.

Technique	Probabilistic or deterministic?	Input Data	Output data	Deterioration mechanisms that can be monitored	Advantages	Disadvantages
		properties of the influencing (input) factors are also known. Spatial characteristics of the deterioration (i.e. spread of damage on a coated surface)	coating performance can be obtained. The rate of deterioration is determined by the levels of the input values (e.g. the annual relative humidity or the annual deposition rate of chloride on the coated surface is both important deterioration rate-controlling variables)			
Level 4 models	Deterministic and probabilistic	Same as for Level 3 models	These models describe mathematically the fundamental mechanisms involved in the actual deterioration process.	Coating deterioration	Very useful when the interpretation of experimental data is required	Their application in practice is generally limited due to the type of input data required (in many cases such data can be measured only in carefully prepared lab specimens).

5.3.2 Modelling deterioration due to fatigue

The first documented experiences of fatigue in engineering structures derive from the industrialisation in the 19th century. A mining engineer, Julius Albert (1837), reported on failure in mine-hoist chains used to carry baskets up and down into the silver and lead mines in the Harz Mountains in Clausthal in central Germany. He found that the chains after many loadings could fail for a load of only half the original static load – from "fatigue" of the material. With the start of railways, fatigue failure was also experienced in the railway axles. The phenomenon was studied by August Wöhler, starting in 1847, (Wöhler 1858; Timoshenko 1953; Kurrer 2008). Wöhler's colleagues gave his name to the basic curve connecting the stress ranges (S) and the number of cycles (N) a material can stand – the so called Wöhler curve or SN-curve.

Arvid Palmgren, who worked with the design of roller bearings at the Swedish Roller Bearing Factory, SKF, in Göteborg, investigated the influence of dynamic fatigue loads and formulated a principle to design for it (Palmgren 1924; Elfgren 2013). However, Palmgren's findings were not widely recognized at that time and it was not until fatigue of airplanes started to be a problem that the principle was reformulated and published again by M A Miner (1945). This led to the Palmgren-Miner failure hypothesis which states that the sum of relative damage D for a structural element should be $D \leq 1$, where $D = \Sigma\, n_i/N_i$. Here n_i is the number of load cycles at a specific stress level i and N_i is the number of load cycle that gives failure if the element is solely subjected to that specific stress level. Better analyses and design tools could be carried out using Fracture Mechanics, a closer study of cracking and cracks in materials, see e.g. Griffith, (1921), Paris et al (1961) and Rossmanith (1997), Fisher (1977), Stephens *et al.* (2000) and Dahlberg & Ekberg (2002).

Deliverable D2.2 (MAINLINE.2.2 2013) presents a review of fatigue as a deterioration phenomenon in metallic bridges, with particular attention to the critical elements of the structure, the fatigue aggressors, consequences and detection methods. The general concepts associated with the fatigue assessment are outlined and modelling frameworks and approaches that consider the properties and parameters affecting performance are identified and described. Several guidelines, frameworks and probabilistic approaches have been developed to estimate the consequences of bridges failures as well as predict the vital parameters of the remaining life of the structure.

Probabilistic approaches can allow uncertainties to be taken into account and provide a framework to estimate the remaining life of the structure. Such approaches, such as the one proposed by Imam *et al.* (2006) for the fatigue assessment of riveted railway bridges and the algorithm proposed by Liu and Frangopol (2004) for optimal life-cycle maintenance planning, take into account randomised variables to estimate the fatigue resistance of the bridge. The remaining fatigue life (through the probability of the fatigue failure) of the fatigue-critical connections can be estimated for different target failure probabilities. Such approaches allow the inclusion of uncertainties associated with strengths, bridge responses and loadings. The problem with the spread of the probability density function for fatigue assessment needs also to be considered; it has been reported that the in-built capacity of a railway bridge can be found by calibrated refined assessment with linear elastic fracture mechanics and the use of reliability based models.

The remaining service life of steel bridges is limited by fatigue or corrosion damage (or a combination of these two) and in order to ensure the safety of these bridges it is often necessary to inspect the structure using traditional as well as more advanced techniques (NDT methods incorporating sensors). Key inputs (parameters) associated with such types of models are highlighted; the uncertainties of these parameters, in particular in terms of fatigue loading, resistance and modelling, are often taken into account using probabilistic analyses.

D2.2 (2013) also makes reference to typical intervention strategies applied to address fatigue related issues in metallic bridges such as (1) surface treatments, (2) repair of through-thickness cracks and (3) modification of the connection or the global structure. Some of these methods are exemplified in SB-STR (2008) and Täljsten *et al.* (2009). The report also provides a link between the degradation phenomenon and intervention triggers and modelling techniques.

An intervention such as retrofitting or retiring a bridge may require the scatter in the bearing capacity and the load to be considered to get an estimate of the reserve capacity. This is an important factor particularly when old bridges are been assessed. A combination of proof loading, numerical analysis and acoustic emission may provide important inputs to the assessment; these are also being considered in other on-going research (Walraven 2013).

5.4 Good examples of data compatibility

5.4.1 Compatibility related to corrosion assessment

In Level 1 modelling using empirical models, the effect of all influencing factors (i.e. exposure conditions, metal type, etc.) are taken into account through well-defined specific model constants, which are obtained from regression analysis on test results. Estimated mean values and other statistical properties are given in a table form for different metal types and exposure conditions. The model enables the calculation of the average loss of thickness of a metal element after *t* years of corrosion as an output. This output value can easily be validated either by visual examination or other type of instrumented monitoring (such as optical fibre monitoring or ultrasonic testing) that can detect changes in thickness.

More sophisticated models for corrosion degradation (such as Level 2 and 3 corrosion models) require exposure variables (e.g. annual average concentration of chloride or chloride deposition rate, concentration of sulphur dioxide, temperature, number of rainy days or average relative humidity, etc.) and empirical coefficients for various types of metals. If this data is available or measured for a given structure in a certain area, the degradation models can be applied without the need for monitoring or examination activity, albeit the reliability of predictions for the rate of degradation, this can be further improved by in-situ tests.

Dose response functions (Level 2 corrosion models) appear to be the most suitable for modelling the corrosion process. Dose Response Function (DRF) models – which explicitly relate several exposure variables to observed thickness losses due to corrosion – can be used either deterministically or be part of a probabilistic framework.

5.4.2 Compatibility related to coating assessment

Deliverable D2.2 (MAINLINE.2.2 2013) notes that Level 2 or Advanced Level 2 models seem to be the most likely candidate models for estimating the performance of organic coatings. Data on coating performance can be gathered by regular inspection at certain time-intervals (e.g. coating type, thickness, quality).

5.4.3 Compatibility related to fatigue assessment

Structural Health Monitoring is treated in e.g. Fixter & Willamson (2006) and Golterman (2002) and assessment methods for steel structures are given in e.g. Kühn et al (2008).

Fatigue of steel bridges has been studied in Sweden by e.g. Åkesson (1994), Al-Emrani (2002), Enochsson *et al.* (2008) and Larsson (2009). Their most important results are incorporated in SB-LRA (2008).

In recent work, Pipinato et al (2011, 2012) have studied high-cycle fatigue of riveted connections for old railway metal bridges and Akhlaghi (2009) and Aygül (2012) have studied welded connections. Furthermore, Brühwiler (2012) has assessed a 150 year old riveted railway bridge in Switzerland, while Andersson *et al* (2013) have studied how the life length can be extended by local approaches, Leander (2010, 2013) has studied the fatigue capacity of the Söderström Bridge in Stockholm and McGormerly *et al*. (2013) have studied fatigue evaluation and retrofit of the Pearl River Bridge in the United States. The fatigue deterioration potential of railway traffic has been studied by Grigoriou and Brühwiler (2013) and fatigue reliability assessment of retrofitted steel bridges integrating monitored data by Liu et al. (2010).

Furthermore, fatigue sensors have been developed and installed to assist with the estimation of the remaining life of welded steel structures. Such an example is the CrackFirst sensor system, which was developed for use on welded steel structures where fatigue performance is a primary concern. The fatigue sensor included in this system, when installed on a welded steel structure, can enable engineers to estimate its remaining life (Dore and Tubby, 2011). Further information on this technique can be found in deliverable D4.1 (MAINLINE.4.1 2013).

5.5 Identified gaps and compatibility issues between Monitoring and Examination output and degradation models input

5.5.1 Compatibility gaps related to corrosion degradation

Prediction of the time-dependent deterioration due to corrosion damage is an important aspect in any bridge management system. The development of corrosion models requires the systematic gathering of data for the factors associated with the exposure conditions and the corresponding corrosion losses in the exposed specimens. However this systematic data gathering is not feasible for a number of factors especially when a probabilistic model requires a data set with statistical properties.

A large number of studies are available in literature reporting results from corrosion tests performed under field exposure conditions; however, a very high variability is observed in the results. This highlights the difficulty in comparing results from different studies performed under similar (but different) exposure conditions with specimens of varying composition. Although these results are very useful in assessing the corrosiveness of different environments, their limited time periods (i.e. < 10 years) over which the experiments were performed do not allow long-term estimations of the corrosion losses. Such data, however, can be useful in assessing the corrosion models.

A further problem encountered when attempting to incorporate monitored data into deterioration models is the lack of monitoring techniques for some failure mechanisms. D4.1 report describes only a few techniques for the examination and monitoring of metal corrosion. These involve visual examination, ultrasonic testing and optical fibre monitoring. However, it is unlikely that these techniques are able to provide data regarding all necessary factors to describe exposure conditions. Other techniques such as those based on the measurement of the electrical resistivity of the material may provide valuable information on the corrosion process, however experiment on the use of these techniques for corrosion monitoring is yet very limited.

5.5.2 Compatibility gaps related to coating

Obtaining realistic value ranges for the variables associated with the development and input of Level 3 (or above) models is a difficult task. Another limitation, which currently hinders applying Level 3 and Level 4 models in practice, is the inability to predict a priori the failure mode of a particular coating, since this is a function of a large number of variables and their interactions.

The development of Level 3 models (i.e. DRF) could be an attractive solution when the assessment of specific exposure variables on coating performance is required. However, the generalization of a Level 3 model would not be recommended for coatings dissimilar (e.g. different compositions and thicknesses) to the coating used for its derivation. The development of such a model requires the systematic monitoring of several parameters (e.g. climatic and atmospheric parameters) as well as coating performance and is unlikely that such data is currently available.

The development of time-profiles on coating performance requires consideration of both the deterioration at a local (material) level as well as the evolution of the time dependent spread of damage. Their application in practice is generally limited due to the type of input data required.

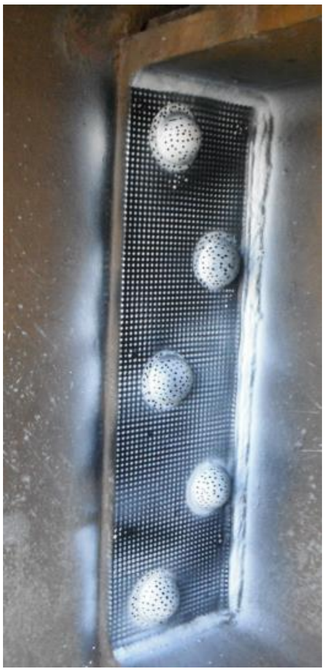
A number of failure mechanisms are associated with the different coating types; this depends, however, on the coating type and the exposure conditions. The pre-existing defects also have an adverse effect on the coating service life.

It should be noted that the original quality of surface preparation and environmental control will also affect deterioration rates and modes; however, these parameters are not considered in the models.

5.5.3 Compatibility gaps related to fatigue assessment

In regard to the degradation phenomenon of fatigue, an example of gap compatibility is given in the test to failure of an old truss bridge in Sweden, Blanksvärd *et al*. (2014). The steel truss railway bridge at Åby River was built in 1957 with a span of 32 m (105 feet). A traditional assessment of the remaining fatigue capacity of the bridge was carried out in 1994 according to Swedish codes. It was found that some of the joints connecting the longitudinal beams to the transverse beams had an accumulated Palmgren-Miner sum higher than 20, which indicated that a fatigue failure was already overdue. However, no fatigue cracks were noticed when the bridge was inspected.

In 2012 the bridge was replaced by a new steel beam bridge and the old bridge was placed beside the river. In September 2013, it was tested to failure to study its remaining load-carrying capacity. The test was carried out by Luleå University of Technology by commission from Trafikverket for the purposes of the MAINLINE project. Two hydraulic jacks, anchored by cables to the bedrock, pulled the bridge downwards. The bridge remained elastic up to about three times the original design load and the load could then be almost doubled with substantial yielding deformations before a buckling failure appeared in the top girders for a load of ca. 11 MN (1000 short tons) for a midpoint deflection of ca. 0.25 m (10 inches). The strains were followed in critical details to monitor any fatigue failure. Ordinary gauges were used but also a new type of optical measurements was applied; in the latter, a grid is painted on the detail, which is photographed continuously during the tests (Figure 5.**1**). However, no brittle or fatigue failure appeared in any of the joints and the bridge proved to behave in a ductile way with a substantial hidden capacity.



The data from the test will be further analysed in order to evaluate damage modelling and compare monitoring and examination results regarding fatigue as well as corrosion. An assessment of the load-carrying capacity of the bridge with a reliability based method has also been carried out by Casas and Soriano in D1.2 (2013). A critical review of methods and enabling technologies for automated inspection and restoration of steel bridges was given in McCrea *et al*. (2002).

Figure 5.1 Optical measurements of strains in a critical riveted connection between a transverse and a longitudinal beam in the Åby Bridge in northern Sweden, Blanksvärd et al (2014).

5.6 Potential solutions to address gaps in a compatible/cost effective way

5.6.1 Solutions to compatibility gaps related to corrosion assessment

According to experiments atmospheric pollution (i.e. SO_2 concentration) and airborne salinity have the greatest impact on the long-term rate of corrosion. Simplified modelling could be achieved if data is collected by monitoring these key parameters as well as other exposure parameters. A probabilistic approach could be developed to take account for the large uncertainties associated with the determination of input parameters.

Furthermore, the simultaneous use of visual inspection and monitoring techniques, such as optical fibre monitoring, could improve the reliability of deterioration models. Instrumented monitoring of the thickness of the element can enable the validation of the degradation model parameters.

5.6.2 Solutions to compatibility gaps related to coating assessment

Level 2 models could be developed using the available inspection data on the performance of organic coatings. Whether the development of such a model would fall within the Level 2 or Advanced Level 2 group of models depends on the amount and quality of the inspection data. For instance, ideally the availability of inspection records from several bridges exposed to similar exposure conditions and protected by the same type of coating would allow the development of an Advanced Level 2 model.

A very limited number of models are available for the modelling of coating performance. However, a number of experimental techniques are available (e.g. electrochemical impedance spectroscopy), which could be used to quantify the evolution of coating performance under varying exposure conditions.

The high uncertainty associated with the performance of coating systems subject to varying exposure conditions could be taken into account using probabilistic-based modelling approaches.

5.6.3 Solutions to compatibility gaps related to fatigue assessment

According to Leander (2013), the fatigue life prediction of a metallic bridge involves:

i. the estimation of the load effect,
ii. the estimation of the resistance, and
iii. the selection of a prediction model.

Estimation of the load effect

In the quasi-static approach suggested in most standards, the influence of dynamics may not be considered in a way that reflects the true dynamic behaviour of a bridge. The formulas used may, for example, not be applicable to short stiff beams such as stringer beams and crossbeams. Performing a dynamic moving load analysis gives for many studied cases a more favourable fatigue life, see e.g. Leander (2013) and Leander and Karoumi (2013). Longer monitoring campaigns may also lead to better estimations on the load effect on the strain development in different parts of a bridge; see e.g. Leander *et al.* (2013a).

Estimation of the resistance

The fatigue endurance model has a fundamental influence on the fatigue life. Assessment of typical joints with linear fracture mechanics (LEFM) may render somewhat more favourable resistance than standard models, see e.g. Leander (2013), Leander *et al.* (2013b).

For example, the high calculated accumulated damage in stringer beams are often caused by low fatigue strength in combination with high number of stress cycles. The crucial detail is, however, mainly exposed to compression. The governing codes impose a restriction in using a mean stress correction, referring to the possibility of high tensile residual stresses. A fracture mechanics approach with consideration of residual stresses may offer a more realistic indication of damage, Leander (2010).

Selection of a prediction model

In a deterministic fatigue assessment, partial coefficients are assigned both to the load and the resistance. The safety factors are raised to the power of m which is the coefficient in the Paris equation. The imposed safety has extreme consequences regarding the fatigue service life.

A reliability based model enables consideration of uncertainties in the stochastic variables comprising both the fatigue strength and the load effect as well as corrosion, see e.g. Cremona (2011). Therefore, all parts and uncertainties can be combined within the same prediction, see e.g. Leander (2013), Leander *et al.* (2013c).

Finally, a potential solution to address compatibility gaps in an efficient way is the use of optical sensors (Sas *et al.* 2012) instead of traditional strain gauges; this approach may enable a more reliable assessment of strain ranges in critical sections of a bridge compared to current results.

5.7 Summary

The methods described earlier could be used to obtain a more optimal performance, which can incorporate:

- Better methods for estimation of the load effect including the use of optical sensors
- Better methods for estimation of the resistance
- Better prediction models using reliability based methods.

Table 5-5 summarises the conclusions of this Chapter, identifying compatibility gaps between the outputs of existing inspection techniques and degradation modelling inputs for metallic bridges and providing guidance for optimum performance via potential solutions to address these gaps.

Table 5-5 Summary of compatibility gaps and suggested solutions in metallic bridges

Linkages with other Tasks / **Asset Type**	**D2.1 Degradation Mechanism**	**D.2.2 Model Type and Input**	**D4.1 Monitoring & Examination Technique and Output**	**D4.1 - D4.2 Compatibility Gap**	**D4.2 Potential Solutions**
Metallic bridges: (1) Beams (2) Riveted joints (3) Welded joints	Corrosion	Empirical or Based on simulations Material and Exposure properties & conditions	Visual inspection Optical fibre Ultrasonic testing	No monitoring available for exposure parameters	Monitoring procedures for exposure
	Coating deterioration	Empirical or based on Simulations Material and Exposure properties & conditions	Visual inspection	No monitoring available for exposure parameters and the coating performance	Better monitoring procedures Probability-based modelling
	Fatigue	Load Effect	Visual Inspection Optical Fibre Monitoring Ultrasonic testing Radiographic testing Liquid penetrating tests Fatigue monitoring Acoustic monitoring Magnetic particle Inspection Laser scanning	To measure at points with maximum damage	Optical sensors
		Resistance Accumulated damage (Palmgren-Miner sum)	Test of details Fracture mechanics Full scale tests		
		Prediction of life length	As above	Existing models lack relevant data and give results with large spreads	Reliability based models More full-scale tests of old structures to calibrate models
	Combined corrosion and fatigue	Combination s of above	Combinations of above	Models for combined effects	New or refined models

6. Tunnels

6.1 Introduction

Tunnels are important infrastructure assets which provide access to otherwise inaccessible locations, such as mountainous areas or underground, assisting the economic development of a country. A tunnel is an underground passageway, completely enclosed except for openings for egress, commonly at each end. There are several types of tunnels including unreinforced and reinforced concrete (pre-cast segmental, cast in-situ, sprayed concrete), masonry (brick, stone block), rock tunnels and metal lined tunnels, as well as unlined tunnels. The condition appraisal of tunnels encompasses all the activities undertaken to determine the adequacy of the tunnel structure to perform its required functions. These activities can include inspections to determine current tunnel condition and gather data, site investigations to obtain more specific information, and structural assessments to evaluate the tunnel's structural behaviour.

For optimum performance, a monitoring and examination system needs to be consistent with the data required for assessment by the use of degradation reliability models. The focus of this Chapter is to identify the gaps and compatibility issues on the current interface between output from monitoring and examination techniques and inputs for reliability models in the case of masonry and concrete lined tunnels.

In addition, solutions to address these compatibility gaps are proposed and guidance provided as to what additional information could be captured to achieve consistency and increase efficiency and cost effectiveness. This Chapter builds on work carried out to date within the MAINLINE Project, particularly related to the deliverables D2.2 (MAINLINE.2.2 2013) and D4.1 (MAINLINE.4.1 2013), as well as research from other European projects.

Response to a questionnaire carried out within MAINLINE (D2.1 report) reveals that all 3 Infrastructure Managers, who participated in the questionnaire, have masonry and concrete lined tunnels, whilst only two of them have unlined tunnels. Although the response is limited, it suggests that focus is directed towards lined tunnels. There is some variability in the response but one Infrastructure Manager indicates that imminent failure develops more rapidly for concrete linings than for masonry linings. Another infrastructure manager indicates that degradation of masonry lining is more costly and has the greatest lack of knowledge when compared to concrete lining. Based on the above statements and due to the fact that masonry and concrete linings experience similarities in deterioration mechanisms, focus at this stage of the project should be on both of these types of lining.

Whilst masonry and unlined tunnels have been in use on railway networks with limited maintenance for well over 100 years, concrete tunnel linings have been in use for approximately 50 years.

6.2 Current Monitoring and Examination Practices

6.2.1 Introduction

Since the first railway tunnel was constructed (Liverpool to Manchester, UK) in 1826-1829, significant changes have taken place both in terms of new engineering materials and new condition assessment techniques. Nowadays, due to the large number of tunnels in use and their apparent durability, unless the loading conditions or other key features change, appraisal by inspection is commonly regarded as sufficient to assess their serviceability and identify any special requirements for preventative or reactive maintenance and repairs.

It is necessary to continually update knowledge on asset condition and performance, typically by periodic visual inspection supported by simple assessment techniques. Also, it may be necessary to carry out more in-depth investigations of particular features or phenomena, and to monitor aspects of tunnel behaviour and performance over time using more advanced techniques and instrumentation, as described in deliverable D4.1 (MAINLINE.4.1 2013).

The regime of tunnel inspection should ensure that any deterioration in the condition is detected in good time to allow remedial action. The intervals between inspections are typically specified by tunnel-owning organisations to satisfy compliance with their statutory obligations and internal policies (McKibbins, Elmer and Roberts 2009).

Requirements for M&E systems vary, but include, for example:

- Verifying the continued fitness for purpose (condition and performance) of the tunnel
- Investigating specific changes in the tunnel and its environments over time
- Monitoring the response of the structure to change (e.g. during works on the tunnel or from construction works taking place nearby)

The tunnels maintenance mainly includes measurements in regard to the geotechnical balance and the humidity control, and minor repairs – mortar loss/spalling/mechanical damage has to be repaired occasionally for old tunnels. The geotechnical balance is determined by the convergence rates (the evolution of the distance between different points of the same cross section). Those distances are measured manually or by inspection trains. On the other hand, the humidity control is important because of the electric voltage between catenary and rail and must be controlled by ditches, pipes and plumbs.

6.2.2 Data necessary to the tunnel maintenance

A manager must have documents including information on the geology, on the nature of the linings and on their geometry, an updated report of the state and a history of completed interventions. In particular the data/information listed below should be available:

- Historical, geographical, geological data
- Geometry recordings
- Detailed recordings of damages

Data management systems are being developed (e.g. SCADA Systems, see Stouffer *et al.*, 2007) to homogenize and harmonize the information relating to the situation, state and examination data by combining them into one tool. These functionalities also allow capturing historical data of successive state recordings, statistics and, thus, could provide a valuable assistance during the tunnel assessment in view of defect diagnosis. The key to efficient maintenance of these management systems is maintaining an appropriate documentation (i.e. drawings, specifications, parts lists, backup copies of software and system configuration files) of the system.

6.2.3 Inspection, investigation and monitoring

There are three generic categories of condition and performance assessments carried out for railway tunnels:

i. Visual Inspection
ii. Tunnel Investigation
iii. Tunnel Monitoring

<u>Visual Inspection</u>

Visual observation is used as the first and basic method of obtaining key information on a tunnel, as well as determining and monitoring its condition. The shortcomings of visual inspection can be overcome by supplementing it with additional simple and rapid techniques such as photography, dimensional measurement, hammer tapping and other simple on-site actions. Periodic inspection, however, is the most cost-efficient form of monitoring and is generally very effective. Inspection does have limitations and there are a variety of circumstances where it is appropriate or necessary to use instrumentation to carry out specific monitoring tasks. However, with the automation of survey instruments, the incorporation of automatic target recognition and non-reflecting measurement technology, continuous movement monitoring using survey techniques and instruments, such as mobile robots, is now a viable alternative to applied instrumentation in certain circumstances (Victores *et al.,* 2011; Yu *et al,* 2011).

Effective visual inspection requires an understanding of the tunnel structure, its materials, behaviour and potential causes of deterioration together with knowledge of tell-tale signs of problems and where to look for them. Effective inspection requires an understanding of the tunnel structure, its materials, behaviour and potential causes of deterioration along with knowledge of tell-tale signs of problems and where to look for them. Such an inspection can gather detailed, accurate, well-presented and objective information to permit others (not directly involved in the inspection) to understand the problems, draw conclusions and take action where necessary.

The terminology of, and intervals for, inspection of tunnel structures vary between infrastructure managers, but are similar in terms of their objectives and methodology. This is set out in Table 6-1, which provides an example of the inspection requirements of the main UK infrastructure owners.

Tunnel Investigation

Tunnel investigations are typically carried out to gather information on specific aspects related to a tunnel's construction and performance, for instance its structure, type, characteristics and condition of its fabric and information about the tunnel environment (including ground conditions).

Investigation of the structure of the tunnel and its environment is carried out using techniques such as:

- coring and removal of core samples
- use of endoscopes/borescopes
- water sampling and analysis and local measurements of ingress rate
- traditional and more advanced methods of dimensional measurement and surveying
- semi-destructive in situ testing methods (e.g. carbonation depths, corrosion potentials, strain measurements etc.)
- geotechnical investigation and sampling techniques.

Tunnel Monitoring

Tunnel monitoring involves repeated measurement of parameters at suitable time intervals to allow comparison and assessment. This can be anything from periodic visual inspection to real-time instrumented monitoring of rapidly changing parameters. Monitoring is used to detect and/or measure change in one or more specified parameters; it can be achieved by carrying out discrete repeat observations and measurements of phenomena at suitable times, or gathering such data using a continuous automated approach, e.g. by installing appropriate monitoring instrumentation and logging devices.

The implementation of a systematic monitoring based on the visual observation is increasingly complemented by instrumentation. Practice shows that this systematic method of observation and its traceability are essential in the development of a policy for structures monitoring; tunnel monitoring also enables to carry out reliable assessments and, beyond the simple observation of defects, to try to determine their aggregators.

Traditionally, conventional survey techniques have provided satisfactory results in the periodic measurement of long-term movements such as building settlement. However, these techniques are less suitable in potentially more dynamic situations, where short measurement cycles or instant feedback is required, or where frequent re-measurement is required over a long period of time. For such applications, monitoring would typically be carried out by applied instrumentation. Crack monitoring (e.g. using crack width gauges), displacement monitoring (e.g. using electro-levels, laser scanning, automated laser theodolite systems etc.) and in-situ strain monitoring (e.g. using vibrating wire gauges) are some examples of tunnel monitoring applied in concrete and masonry lined tunnels.

Table 6-1 Current tunnel structure inspection requirements of the main UK infrastructure owners: Network Rail (NR), Highways Agency (HA), British Waterways (BW) and London Underground (LU) (McKibbins, Elmer and Roberts 2009)

Type	Known as	Scope and objective	Intervals[1]
Routine surveillance	Superficial inspection (HA) Length inspection (BW) Permanent way inspection (NR)	Cursory visual check for deficiencies that might lead to accidents or increased maintenance. Part of the day-today surveillance of the transport network carried out by infrastructure owner's staff (not necessarily trained inspectors) in the course of their normal duties	When staff visit the tunnel during their duties
Routine visual inspection	General inspection (HA, LU) Annual inspection (BW)	Visual inspection of accessible representative parts of the structure (including adjacent earthworks, waterways etc) from ground level or from other readily available walkways, platforms etc to identify hazards and changes in condition and determine requirements for detailed inspection	Maximum interval: (LU) 1 year (HA) 2 years after last general or principal inspection (BW) 1 year after last principal inspection
Routine detailed inspection	Principal inspection (HA, LU, BW) Tunnel examination (NR)	Close or tactile (ie touching distance) inspection of all accessible parts of the structure, including adjacent earthworks, waterways etc with provision of special access if necessary. Visually based but can be supported by measurement and simple testing (eg hammer tapping) of structure to gather additional data	Normal intervals: (LU) between 1 and 12 years[2] (NR) 1 year[3] (HA) 6 years[4] (BW) maximum interval 5 years
Non-routine inspection	Special inspection (HA) Additional examination (NR) (BW) Defect advice inspection (LU[5])	Undertaken in response to a specific need (eg where significant deterioration or evidence of structural distress is seen before, during and after the passage of abnormal loads and after flooding and accidents such as impacts on the structure, fires or chemical spillage). Visual inspection can be augmented by specialist techniques for investigation of structure (*in situ* testing, sampling and laboratory analysis) as required	As required, to investigate particular feature or gather specific information. May be as a result of a risk assessment

Notes

1 Stated intervals between inspections are subject to changes in asset owner policy and procedures. The reader should check for current requirements where appropriate.

2 Maximum interval varies according to primary lining type: one year for flexible iron, four years for brick/stone masonry and concrete, 12 years for cast iron. E3701 also specifies principal inspection intervals for shafts: stair (tubbing) maximum interval of four years. For service, vent, plant, pump, cable, disused (tubbing) shafts maximum interval of eight years.

3 Maximum frequency for detailed (tactile) inspection of Network Rail tunnel shafts is six years. Also to a check on the condition of chimneys and for changes in land-use during an annual walkover survey of the ground above the tunnel.

4 Intervals can exceptionally be up to 10 years.

5 London Underground also require special inspections, which are regular visual inspections carried out at short intervals for structures awaiting repairs.

6.2.4 Methods of tunnels' investigation

The range of available techniques for different types of investigation and materials evaluation is enormous and a comprehensive review of them all is beyond the scope of this document. Further information can be found in deliverable D4.1 (MAINLINE.4.1 2013) as well as the relevant CIRIA document (McKibbins, Elmer and Roberts 2009). An overview of the range of the applicable techniques is given in Table 6-2.

Table 6-2 General, specialist, testing and monitoring techniques for tunnel investigation

Inspection, mapping and simple on-site tests	Sampling and testing techniques	Specialist non-destructive investigation techniques	Monitoring techniques
• visual inspection • photography and videography • hammer-tapping • spatial measurement • remote visual inspection • joint mapping • simple on-site • assessment techniques • spatial measurement and surveying techniques.	• core drilling and core samples • laboratory investigation techniques • geotechnical investigation techniques • measurement of *in situ* stress.	• infrared thermography • gravimetric survey • magnetic survey • ground resistivity survey • conductivity survey • seismic survey • 3D seismic tomography • ground penetrating radar • transient electromagnetic • broadband electromagnetic • ultrasonic pulse velocity (UPV).	• crack monitoring • strain monitoring • stress monitoring • displacement monitoring • corrosion monitoring.

The reliability of a diagnosis requires the use of traditional investigation techniques in combination with Non-Destructive Testing (NDT) generally offering a continuous image of data, which is very difficult to access with traditional means. However, the risk of generating excess and unnecessary data combined with the need for economically viable solutions, mean that continuous monitoring is not always the most appropriate approach.

6.2.4.1 Traditional methods of inspection

Traditional methods of examination and investigation include geotechnical measurements or measurements of bearing capacities, geological observations, direct geometrical records, and relative mechanical resistances of materials. Most of these measurements, which are listed below, are already implemented systematically in the majority of the networks across Europe.

Visual inspection:

The "eye" of the observer is a vital part of the inspection process. It can only be a specialist able to make assumptions concerning the evolution of a defect or damage. It is necessary to continually update knowledge on asset condition and performance of tunnels, typically by periodic visual inspection supported by simple assessment techniques (MAINLINE.4.1 2013).

Geometrical recordings:

- topographic recording of the track or of the singular points
- convergence or topometric precision measurements

Inspection of the lining and the supporting structure:

- cored drillings with examinations on sites and in laboratory
- windows
- drillings and endoscopies recordable on computerized support
- surface degradation (cracks, flaking etc.)
- visual inspections and drillings with hammer (hollow sounds)

Inspection of the surrounding ground:

- geological studies
- drillings, core borings, borings, endoscopy, windows
- tests of injectability in the back of vault

Investigation of mechanical characteristics and ground evolution:

- geotechnical and geological studies
- stress measurements with the flat jack
- investigation for deformations (ribbed deformation in the crown or in the springer joints, comparison of successive profiles, convergence measurement etc.)
- studies of samples and of waters analysis
- investigation of the water flow (pressure gauge, assessment of the solid volumes carried away by the waters circulation etc.)

6.2.4.2 Most common Non-Destructive Testing (NDT) techniques

The significant progress made recently in terms of data processing enables, with the use of data compilation, a higher reliability in the interpretation of the measurement using traditional methods; this progress has also led to major development of Non-Destructive Testing methods. Since inspection constraints (in terms of cost and time) applying in tunnel networks become increasingly heavy, it is necessary to employ faster, more effective and if possible more complete means of monitoring and examination whilst considering the concept of cost-benefit analysis. The main advantages of NDT techniques are:

- In the case of fixed stations: enabling the data transmission across long distances and the increase of the measurements cycles without the need for specialists' presence.
- In the case of dynamic methods: enabling continuous measurements, bridging the gap of uncertainties in respect to traditional methods.

The aim of NDT is to carry out an objective and, generally, fast evaluation of the structure state, either for the monitoring (increased or not), or to determine with more certainty the essential interventions and, thereby, to limit the costs to obligatory works. The most commonly implemented techniques are:

- Videoscopic recordings (using camera)

Although this technique follows the same principles as visual inspection, remote analysis offers a distinct advantage. Furthermore, with the use of associated computerized means, the interpretation of the results can often become less subjective.

- Scanner recordings (laser scanning) and data processing
  This method provides an objective and complete image of the structure in one scanning. Laser scanning is mainly used to detect deformation of tunnels' components (MAINLINE.4.1 2013). The precision of the recordings depends obviously on the resolution of the devices and on the speed of the carrier but can detect cracks larger than 0.1mm in concrete lined tunnels and larger than 1mm in masonry tunnels.

- Thermographic records by scanner or infra-red camera (thermal imaging)
  This method allows, subject to a rigorous interpretation, the evaluation of the internal moisture content of materials. The method is able to reliably detect defects such as voids due to lack of fill or delamination by identifying relatively hot and cold areas within the structures (Peters and Day 2003).

- Ground penetrating radar (GPR)/Georadar
  This technique can also be applied to provide condition assessment, for example mapping voids, delamination and moisture within and behind masonry linings. Tunnel surveys using GPR can provide an overview of a 1,000m tunnel in just one short possession (Faize and Driouach 2012). They can provide valuable information when the site includes clear interfaces; aimed drillings allow to adjust the recordings before their processing and, thus, to increase the reliability of the interpretation.

- Other methods include:
  - tunnels clearance measurement by rotating range finders (ACEM-RAIL.1.1 2011),
  - ultrasonic methods of inspection,
  - vibratory measurements (seismic/electric methods) (MAINLINE.4.1 2013),
  - coupled measurements of hygrometry, pressure, temperature with tele-transmission of the data by modem,
  - optical laser triangulation technology complemented with vision solutions (ACEM-RAIL.1.1 2011), and
  - boreholes with inclinometers for convergence measurement.

The NDT methods are gradually being more frequently implemented and in a more systematic way, thereby, increasingly complementing more traditional techniques. The uptake of these methods is expected to increase in the future, especially if the technological improvements and the needs of faster assessment of the structure are taken into consideration. In addition, the quality-price ratio of these types of equipment is supported by the fact that they mobilize less labour and especially the ability of providing a more comprehensive view of the structure's state.

However, practice shows that the establishment of a reliable interpretation highly depends on the combination of several different methods. In addition, the effect of environmental conditions on the measurements should also be taken into consideration. For example, in thermography, temperature differences on the structure surface are essential for the detection of inner voids; however, temperature differences in tunnel linings are usually negligible, which sets a significant limitation to this method. Limitations are also evident in the application of other NDT techniques. For example, electromagnetic wave method can only be used for the measurement of lining thickness and voids between a lining and the natural ground, when neither steel supports are located close together in the lining nor the lining consists of reinforced concrete. Similarly, ultrasonic method may not always be reliable enough for inspection of tunnel linings, since ultrasonic waves attenuate much more quickly in concrete than in metallic materials for which the method is more suitable.

6.2.4.3 Summary of commonly applied inspection techniques

A summary of the most commonly applied Monitoring and Examination techniques in relation to the main degradation mechanisms or symptoms of/factors affecting degradation is provided in Table 6-3. For further information please refer to MAINLINE deliverable D4.1 (MAINLINE.4.1 2013)

Table 6-3 Monitoring and Examination (M&E) techniques and Degradation Mechanisms (DM) affecting tunnels[2]

MAINLINE Project WP4: Monitoring and Examination Techniques D4.1: Report on assessment of current monitoring and examination practices in relation to the degradation								
DM / M&E	Water presence	Heat damage	Fatigue/Fracture (cracks)	Background washout	Deformation of elements	Voids	Spalling	Corrosion
Visual Inspection	✓		✓	✓	✓	✓	✓	✓
Thermal Imaging		✓				✓		
Ultrasonic Testing	✓		✓			✓	✓	✓
Digital Image Correlation			✓		✓		✓	
Resonance Inspection			✓	✓	✓	✓	✓	✓
Time-of-Flight method			✓			✓	✓	
Eddy Current		✓	✓		✓	✓		
Impact Echo			✓		✓	✓		✓
Laser Scanning			✓		✓		✓	

[2] DM here refers to Degradation Mechanisms or Symptoms of/Factors affecting Degradation

6.3 Degradation and Intervention Modelling Techniques

The various methods of tunnel construction (e.g. cut and cover, boring etc.) are beyond the scope of this report and are not discussed herein; a comprehensive review, however, can be found in the relevant CIRIA document (McKibbins, Elmer and Roberts 2009). Several phenomena are associated with the degradation of a tunnel's performance over time, including geotechnical related degradation, deterioration of the lining material, accidental damage and vandalism or terrorism (Inokuma and Inano 1996, Long et al. 2011, Wang 2010, Sandrone and Labiouse 2011). The structural failure of a tunnel can be associated with socio-economic consequences such as loss of life, service disruption, need to re-route and loss of revenue from sensitive goods (e.g. food products). Damage and disruption of services which pass through the tunnel may also occur (e.g. water mains, cables, etc.). Furthermore, neighbouring structures may be affected (e.g. damage in structures located within the zone of influence of the tunnel). As a result, the structural assessment of deteriorating tunnels plays an important role in maintaining continuous safety levels (in and out of the tunnel) and prioritizing any necessary remedial works.

The deterioration mechanisms and their impact on performance, of concrete and masonry tunnels have been discussed in MAINLINE deliverable D2.2 (MAINLINE.2.2 2013). Tunnel deterioration may occur due to geotechnical/geological related phenomena or due to material deterioration (e.g. corrosion of reinforced concrete linings) of the tunnel itself. The main causes affecting tunnel deterioration reported by road (no available data exclusively for rail tunnels) tunnel inspectors internationally are summarised in Table 6-4.

Table 6-4 Main causes affecting road tunnel deterioration in different countries (Sandrone and Labiouse 2011; MAINLINE.2.2 2013).

		Country						
		Switzerland	France	Italy	UK	USA	Japan	South Africa
Construction and geotechnical conditions	Age	×	×			×	×	
	Material quality	×	×				×	
	Construction faults			×				×
	Geological conditions	×	×	×	×	×	×	
	Hydrogeological conditions	×	×	×	×	×		×
Environment	Temperature	×		×	×	×	×	
	Humidity	×		×	×	×	×	×
	Frost, ice formation, freeze and thaw cycles	×	×	×	×	×	×	×
	Biological attack (mushrooms, micro-organisms)	×	×					×
Operation	Traffic	×		×	×	×		×
	Pollution (corrosive atmosphere, ventilation system)	×	×	×		×		×
	De-icing salts	×		×	×	×		
	Fires					×		
	Accidents							

MAINLINE deliverable D2.2 (MAINLINE.2.2 2013) provides a review of the most commonly observed deterioration mechanisms of masonry and concrete tunnels. The available models which can be used to quantify the different types of deterioration on tunnel performance are reviewed with emphasis given to concrete lined tunnels. Even though there is substantial theory behind the deterioration modelling of concrete lined tunnels, deliverable D2.2 and interaction with industry practitioners have confirmed the lack of sufficient modelling techniques for the deterioration of masonry lined tunnels. The conclusions of D2.2 report can be summarised as follows:

- The types of tunnel deterioration can be grouped as geotechnical related deterioration and material related deterioration. A third group is related to degradation due to accidental damage (including fire).

- Geotechnical related deterioration is related to changes in the ground conditions adjacent to the tunnel, with groundwater and ground and rock movements being the most dominant causes of deterioration. Modelling of geotechnical related deterioration can be very complex and requires the use of soil mechanics principles; assessment methods generally involve the use of soil-structure numerical models.

- The main causes of material deterioration in concrete lined tunnels are:
    - Cracking/spalling due to poor casting or installation
    - Reinforcement corrosion
    - Sulphate attack and acid attack
    - Freeze and thawing
    - Alkali-aggregate reactions
    - Tunnel fires

- As per the masonry lined tunnels, the main material deterioration causes are:
    - Freeze-thaw cycling
    - Physical salt weathering
    - Sulphate attack
    - Corrosive attack
    - Biological attack
    - Moisture saturation
    - Ground movements
    - Cyclic loading and fatigue effects

- Cracking and spalling due to poor casting or installation, reinforcement corrosion and frost damage (due to freezing and thawing cycles) are the most commonly observed material-related deterioration mechanisms in concrete lined tunnels. These deterioration mechanisms are responsible for the loss of mechanical properties of mortars and concrete due to cracking development and material disintegration.

- The development of deterioration-time profiles in relation to sulphate attack requires knowledge of the soil composition and concrete characteristics (e.g. through the analysis of sampled soil and concrete cores).

- Similarly, the development of deterioration-time profiles with respect to freeze-thaw action requires understanding of temperature variations in relation to the quality of concrete mixes used.

- A number of models are available for estimating the residual mechanical properties of sulphate and frost-damaged concrete; however, they do not provide information on how degradation develops over time.

- Most of the deterioration mechanisms affecting masonry-lined tunnels are associated with the presence of water in the structure. The main effect of deterioration in masonry is attributed to: (i) loss of section (brick, stone or mortar), (ii) loss of bond (brick-mortar) and (iii) loss of compressive material strength.

- In the absence of deterioration models for masonry lined tunnels, the use of field inspection data needs to be explored in regard to changes of condition with time.

In the case of masonry lining, the lack of deterioration models is evident and, thus, the need for sufficient and reliable field inspection data is even higher.

On the other hand, in the case of concrete lined tunnels, numerical models are available to capture the effect of the three main causes of degradation, namely reinforcement corrosion, sulphate attack and freeze-thaw attack. Several studies have investigated the influence of corrosion on the material and bond properties, with numerical models emerging through these as reported in MAINLINE deliverable D2.2 (MAINLINE.2.2 2013).

For example, the reduction of yield strength with increasing corrosion damage can be quantified using the equation below:

$$f_y^D = \left[1.0 - \alpha_{y1}\left(A_{pit}/A_{stnom}\right)100\right]f_{y0}$$

where, f_{y0} and f_y^D are the original and reduced yield strengths respectively, A_{stnom} is the initial cross-sectional area, α_{y1} = 0.005 and A_{pit} is the area of the pit, which can be estimated through equations using i_{cor} (rate of corrosion). It has been observed experimentally that increasing corrosion damage has a negative effect on the ductility of the affected reinforcements as well as the bond performance of the affected re-bars. For further information in regard to the numerical models please refer to MAINLINE deliverable D2.2. It should be noted that the available deterioration models do not provide information concerning the evolution of material properties with time but rather quantify the effect of certain damage level caused by specific deterioration mechanism action.

A list of the available degradation model types for concrete lining along with the main input parameters required for these models is presented in Table 6-5, which also provides the link with the output from Monitoring and Examination techniques applied in each case.

Table 6-5 The interface between degradation model inputs and inspection output in concrete-lined tunnels

	Degradation Mechanism	Model Type	Model Input	M&E Technique	M&E Output
Concrete lined tunnels	Steel corrosion	Numerical models from experimental observations (f_y^D)	A_{pit}, pit area i_{cor}, corrosion rate	Half-cell mapping, electrical resistivity (4 electrodes), sensors, corrosion coupons	E_{corr} (corrosion potential) i_{cor} (corrosion rate)
	Sulphate attack	Mechanistic model for degradation rate (R)	X_{spall}, spalled layer thickness	VI + Hammer test, Impact Echo, UT, Core testing	Photographic, wave speed, crack depth, sulphate content
	Freeze/thaw attack	Stress-strain models (not time dependent)	Plastic strain caused by frost Temperature	VI, UT, resistance test, laboratory tests	Visual output, wave transit time, Stress-strain lab results
	Alkali-aggregate reactions (ARR)	x	x	VI, laboratory tests	Visual (cracking), flexural and compressive strength, porosity

6.4 Good examples of data compatibility

Each of the major European infrastructure tunnel managers has its own systems and procedures for condition assessment and reporting, so that requirements for data collection are dictated by the needs of the manager. In the UK, a typical condition classification system would have simple condition grades, for example, from A to E, where A represented an asset in an ideal condition and E represented a serious safety concern (Network Rail 2009a).

Response to a questionnaire carried out within MAINLINE deliverable D2.1 (MAINLINE.2.1 2012) reveals that the degradation in tunnels is inspected periodically and not continuously monitored. Several documents are used in Europe to assess the tunnels' degradation; in Germany, for example, Deutche Bahn uses Ril 853.8001 document, while Network Rail, in the UK, makes use of the Tunnel Condition Marking Index (TCMI) Back Analysis document (Network Rail 2009a). Finally, in the United States, the US Tunnel Management System is the qualitative approach applied (FHWA 2005), which is further described in Section 6.4.2.

6.4.1 Tunnel Condition Marking Index (TCMI)

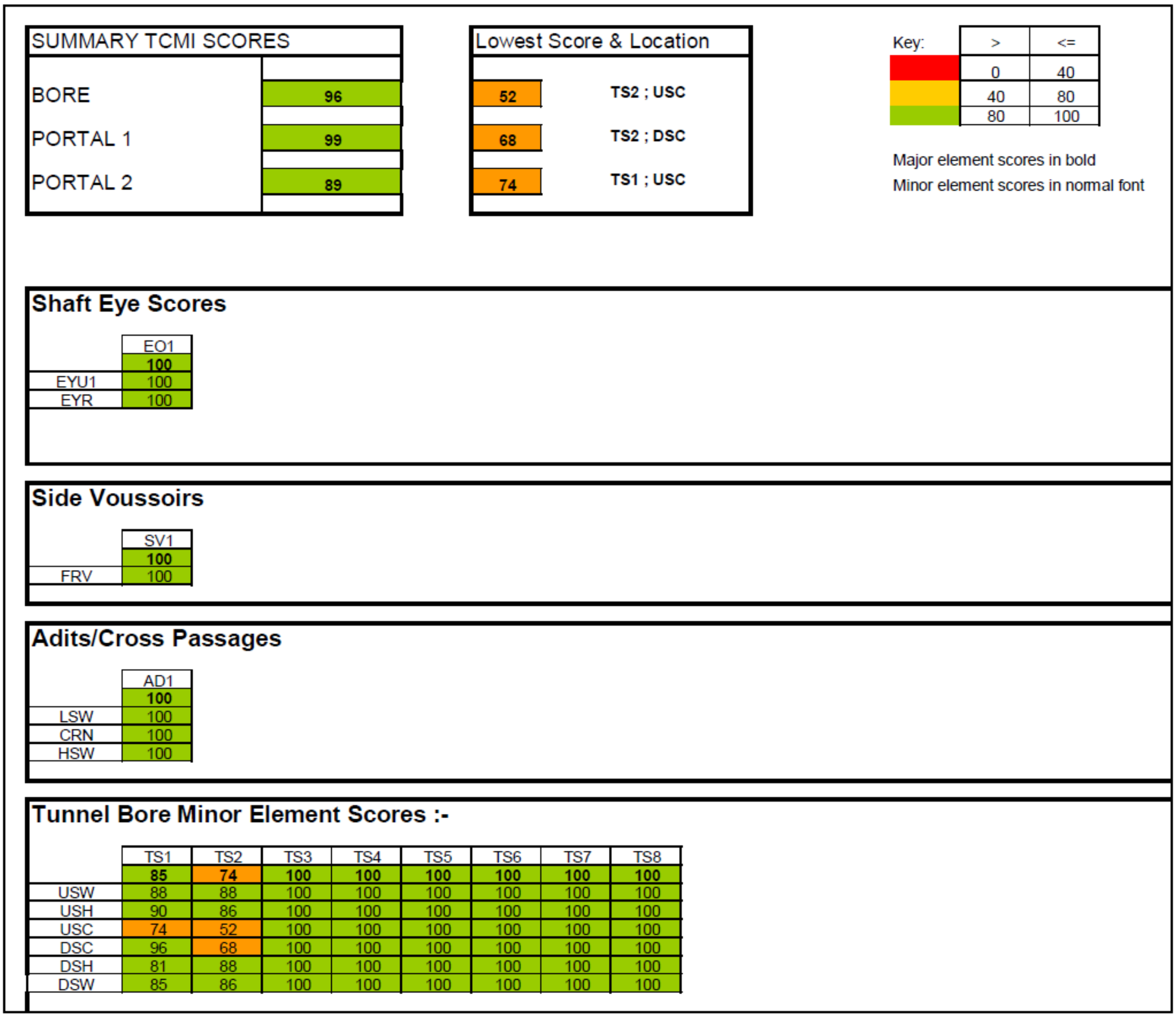
Since 2009, Network Rail has moved towards a quantitative scoring system, Tunnel Condition Marking Index (TCMI), to report tunnel condition at both major and minor element level. The condition mark grades the structure on a scale of 0 to 100 where 100 indicates a tunnel in 'perfect' condition and is based on non-judgemental recording of defects by the examiner. TCMI scores are generated at the minor element, major element or tunnel bore levels. Tunnel bores are divided into 20 metre section lengths for reporting purposes; the tunnel bore TCMI score is an average of these section scores for each tunnel (Network Rail 2009a). The condition of each element is recorded as an alphanumeric severity/extent code on the defect record sheets during inspection; these codes capture information on the type, area or length and number of defects observed (Network Rail 2009b).

According to data presented in recent report (ORR/Network Rail 2013), the number of minor elements with TCMI<40 appears to be minimal (approximately 1.7%) when compared to other railway assets such as bridges. This may be attributed to the fact that tunnel maintenance adopts the philosophy that tunnels are irreplaceable assets, thus, maintenance strategies focus on minor works resulting in generally good condition profiles.

TCMI is a probabilistic technique of utilizing inspection data in the form of a risk (condition) profile; this tool and the tunnel whole life cost model developed by Network Rail enables the development of cost/volume profiles over time for the asset populations. The system is capable of calculating the probabilities of each of the possible outcomes occurring and, thus, produces accurate results when considering a large number of assets; however, the system has no optimising capability. The TCMI scoring system uses principles such as a defect hierarchy to determine the extent to which elements contribute to the overall TCMI score.

Since the TCMI scoring system has been in place since 2009, relatively little data exists for tunnels and as such, no degradation relationships have been derived yet. Also, some factors, such as climate change, are not incorporated into the marking system. Finally, the reliability of the model, as in any probabilistic approach, is limited by the quality and quantity of data records which may not be available for most of Europe. However, overall TCMI offers a promising solution to the compatibility gaps between degradation models' inputs and inspection output.

An example output report representing TCMI scores (marked with red, amber and green according to the condition) is shown in Figure 6.**1** (Network Rail 2009a).



SUMMARY TCMI SCORES	
BORE	96
PORTAL 1	99
PORTAL 2	89

Lowest Score & Location	
52	TS2 ; USC
68	TS2 ; DSC
74	TS1 ; USC

Key:	>	<=
(red)	0	40
(amber)	40	80
(green)	80	100

Major element scores in bold
Minor element scores in normal font

Shaft Eye Scores

	EO1
	100
EYU1	100
EYR	100

Side Voussoirs

	SV1
	100
FRV	100

Adits/Cross Passages

	AD1
	100
LSW	100
CRN	100
HSW	100

Tunnel Bore Minor Element Scores :-

	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8
	85	**74**	**100**	**100**	**100**	**100**	**100**	**100**
USW	88	88	100	100	100	100	100	100
USH	90	86	100	100	100	100	100	100
USC	74	52	100	100	100	100	100	100
DSC	96	68	100	100	100	100	100	100
DSH	81	88	100	100	100	100	100	100
DSW	85	86	100	100	100	100	100	100

Figure 6.1 An example of TCMI output report (Network Rail 2009a)

6.4.2 US Tunnel Management System

Another example of qualitative solution, which provides a good example of monitoring and inspection of tunnels in regard to the degradation mechanisms, is the US Tunnel Management System which is described in the Inspection Manual used by the US Federal Highway Administration and US Federal Transit Administration (FHWA 2005).

Tunnel elements are rated using a numerical rating of 0 to 9 which is assigned to each structural element, 0 being the worst condition and 9 being the best condition. This rating system is a modified form of the one described in the 'Bridge Inspector's Training Manual' published by the Federal Highway Administration. A general description of the rating system is shown below in Table 6-6. The rating is dependent upon the amount, type, size, and location of defects found on the structural element as well as the extent to which the element retains its original structural capacity.

Table 6-6 General Condition Codes used in United States for tunnels (FHWA 2005)

Rating	Description
9	Newly completed construction.
8	Excellent condition - No defects found.
7	Good condition - No repairs necessary. Isolated defects found.
6	Shading between "5" and "7."
5	Fair condition - Minor repairs required but element is functioning as originally designed. Minor, moderate, and isolated severe defects are present but with no significant section loss.
4	Shading between "3" and "5."
3	Poor condition - Major repairs are required and element is not functioning as originally designed. Severe defects are present.
2	Serious condition - Major repairs required immediately to keep structure open to highway or rail transit traffic.
1	Critical condition - Immediate closure required. Study should be performed to determine the feasibility of repairing the structure.
0	Critical condition - Structure is closed and beyond repair.

6.5 Identified gaps and compatibility issues between Monitoring and Examination output and degradation models input

Significant technological advances have taken place in the field of automated inspection and wireless monitoring to complement visual inspection, which is most commonly applied in the case of tunnels and other railway assets. For optimum performance though, a monitoring and examination system needs to be consistent with the data required for assessment by the use of degradation models. Identifying the gaps and compatibility issues at the interface between output from monitoring and examination techniques and inputs for reliability models is the focus of this section.

6.5.1 Lack of data for validation purposes

In order to develop deterioration models that incorporate output generated from monitoring and examination techniques whilst being applicable across Europe, input parameters used in the model need to be validated for different regions. However, currently, railway infrastructure owners in most of Europe do not hold sufficient tunnel inspection records.

Since environmental and geological conditions vary considerably across Europe, systems such as TCMI need to be validated using historical inspection data for different EU Member States. Solely using historical inspection data for the UK is insufficient to validate the deterioration models for the whole of Europe. In addition, the form of this output is not always consistent, which further complicates the task of model validation and standardisation at a European level.

6.5.2 The limitations of periodic inspection

Periodic inspection is the cheapest form of monitoring and is generally very effective. However, it has certain limitations and there are a variety of circumstances where it is appropriate or necessary to use instrumentation to carry out specific monitoring tasks. Usually this involves the installation of an automated measurement system:

- where access to staff is limited or presents a safety hazard (inhospitable environments with Health and Safety constraints),
- where the frequency and timing of measurement makes manual measurement unfeasible, uneconomic or impossible,
- where long-term measurement is required, either due to the objectives of the monitoring exercise, or due to the nature of the parameter being monitored.

Such systems are typically based on the installation of instrumentation (i.e. sensors and transducers such as tiltmeters or strain gauges) onto the elements to be monitored, or alternatively, for monitoring movement by setting up a system based on surveying equipment and techniques. Applied instrumentation is most useful where the parameters to be monitored are clearly definable and suitable measurements can be made at specific locations. For example, measuring changes in crack width over time, mid-span deflections of a beam under changing loading conditions, or the strain developed at a specific critical point of an element under stress. Sensors and transducers tend to have specific characteristics, and some familiarity with their capabilities and limitations is required to use them effectively.

Furthermore, the invisible interior or rear surface of the lined concrete can only be inspected from the inner hollow position. This requires destructive inspection to be made by boring core, which means long time and cost are needed to receive data from one position.

Although data captured through monitoring provides a continuous data flow, which can be utilised as inputs for degradation models, these data are not always available in sufficient quantities, and limitations in regard to the monitoring instrumentation, such as the ones described above, need to be taken into consideration.

6.5.3 Lack of models for masonry lined tunnels

Section 6.3 provides a summary of the main deterioration causes in masonry-lined tunnels; it is interesting to note that most of these deterioration mechanisms are associated with the presence of water in the structure. Even though inspection techniques that can collect information on the water content in the structure are available, very few physically based models exist for material deterioration in masonry lined tunnels.

Some recent attempts, however, were made to adapt models developed for freeze-thaw damaged concrete, assuming that the underpinning behaviour of masonry is similar (porous material), see (Bozinovski *et al*. 2011).

In the absence of models for deteriorating masonry (i.e. brick-mortar system), the alternative is to develop empirical condition-based degradation profiles using field inspection data.

6.5.4 High cost of continuous monitoring

Visual observation, hammering test and evaluation based on experience rely on the need for a great amount of manpower. In order to enable automated monitoring, future maintenance needs to adopt advanced techniques that depend on how accurately and effectively inspection can be carried out while picking up the same movement and condition degradation markers.

However, the installation and use of sensors to continuously measure key input parameters to provide inputs for the available deterioration models, such as the corrosion rate (i_{cor}) in the case of steel corrosion, corresponds to increased cost.

Continuous monitoring can provide information that enables increased accuracy and confidence on the inspection data. However, the time and cost required to obtain the required volumes mean that the process may not be economically viable.

6.5.5 The effect of environmental conditions

Despite the fact that only minor climatic fluctuations are reported inside tunnels, the effect of environmental conditions in the performance of inspection techniques is evident. The accuracy of certain inspection techniques is significantly affected by environmental conditions, thereby having a negative impact on the usability of inspection output as input to degradation models.

For example, the performance of some techniques used for inspection of concrete lined tunnels, such as half-cell mapping or electrical resistivity, is dependent upon the existing environmental conditions.

Another example of the effect of environmental conditions on the measurements refers to the limitation to tunnel lining inspection using thermography; this is due to the fact that temperature differences on the structure surface, which are obscure in tunnels, are essential for the detection of inner voids when using this method.

6.6 Potential solutions to address gaps and guidance for optimum performance

In order to address the gaps mentioned in the previous Section, several potential solutions are suggested which are explored through a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis. These solutions vary from approaches that address the lack of reliable comprehensive inspection data to decision support systems that could integrate all relevant data into one tool.

The validation of optimum solutions through case studies will be the focus of Task 4.3 of the Project, the results of which will be reported in deliverable D4.3.

6.6.1 Standardisation of the inspection assessment through a commonly accepted framework

In order to overcome the lack of consistent and reliable inspection data across Europe (see Section 6.5.1), a generalised framework/model could be developed and utilised to be applicable to different regions and railway networks within Europe.

A framework, such as TCMI, could be used for the purposes of the standardisation of the condition assessment. Inputs from European Infrastructure Managers are essential towards this approach. However, the challenge of this task lies on the cost and time requirements associated with the data collection required to validate the deterioration model.

The Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis of this solution is shown in Figure 6.2.

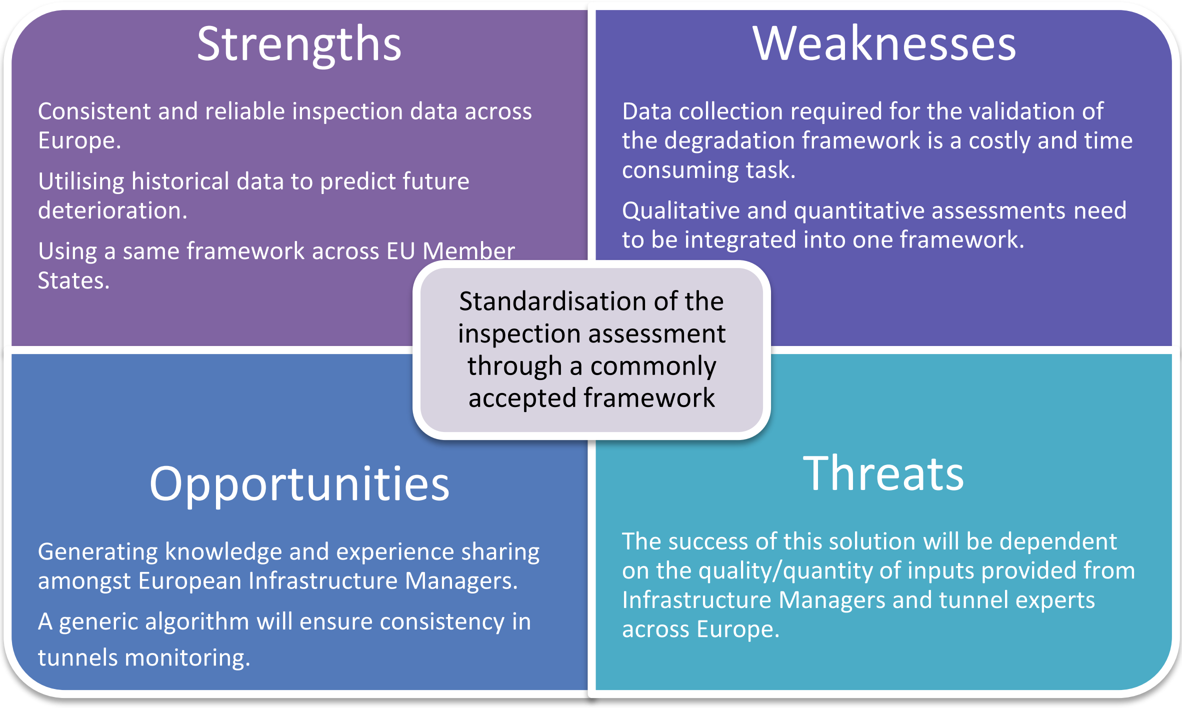


Figure 6.2 SWOT analysis of the standardisation of the inspection assessment across Europe

6.6.2 Use of field inspection data to develop empirical models

In the absence of models for deteriorating masonry (see Section 6.5.3), an alternative solution is to develop empirical condition-based degradation profiles using field inspection data. Although Infrastructure Managers across Europe have a substantial knowledge and experience of the behaviour of masonry structures, the lack of quantitative models (either deterministic or probabilistic) to capture the deterioration of masonry material in tunnels with time needs to be addressed.

This could be achieved by developing empirical models based on existing data available by Infrastructure Managers and further inspection data captured using a number of monitoring and examination techniques. However, it needs to be taken into account that climate change means that empirical methods based on past evidence may not be very reliable, as also mentioned in Section 6.6.4. An analysis of this solution is shown in Figure 6.3

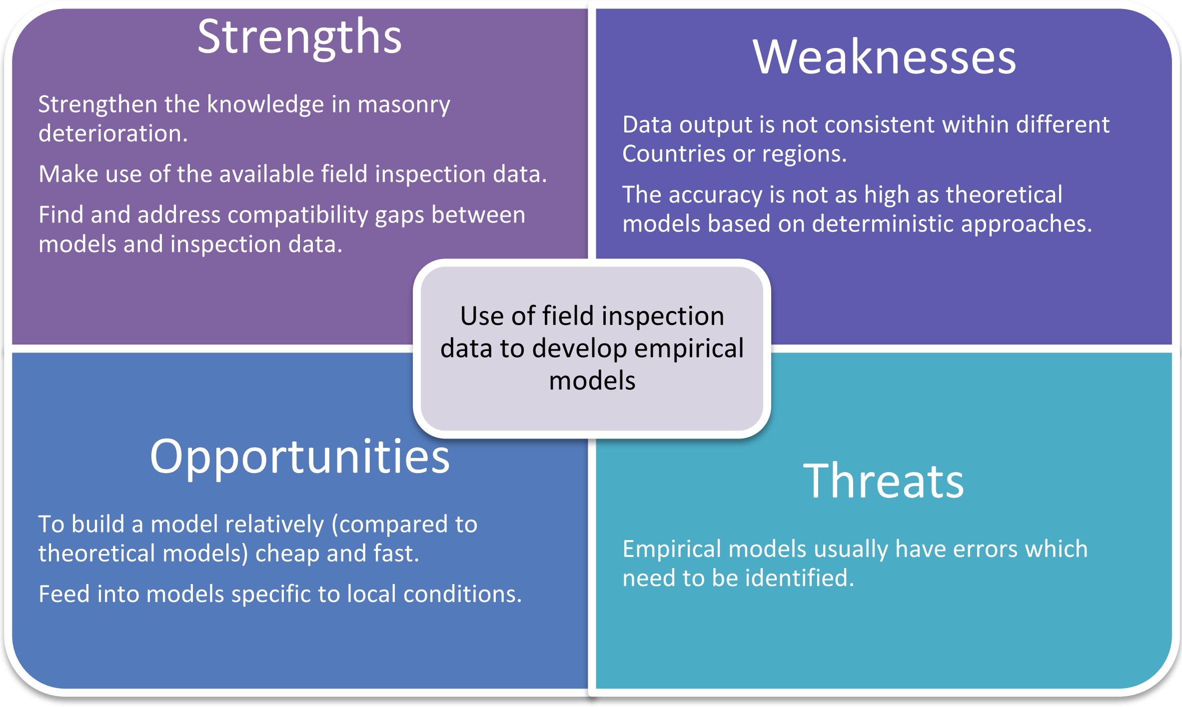


Figure 6.3 SWOT analysis of using field inspection data to develop empirical models

6.6.3 Monitoring specific parameters

Due to limitations of periodic inspection (see Section 6.5.2), on one hand, and the high cost of continuous monitoring on the other (see Section 6.5.4), which commonly involves costs associated with sensors installation and wireless technology, it is important to monitor specific required parameters and generate the necessary output (Figure 6.4).

It is often desirable to supplement historical information with continuing assessments to monitor condition and discern any changes. Many aspects of tunnel behaviour and performance are the result of complex interactions between parameters that undergo change over time: that means rates of change can vary. It is very important to gain a thorough understanding of how parameters of interest are affected by other variables (e.g. temperature effects) so that these may be accounted for when interpreting monitoring results avoiding inaccurate conclusions.

For any monitoring results to be useful, the significance of observed changes in monitored parameters and their relevance to the structure should be properly understood. Some changes may cause no impact, whereas others may be highly significant, and an accurate and comprehensive interpretation should be able to discern between these two.

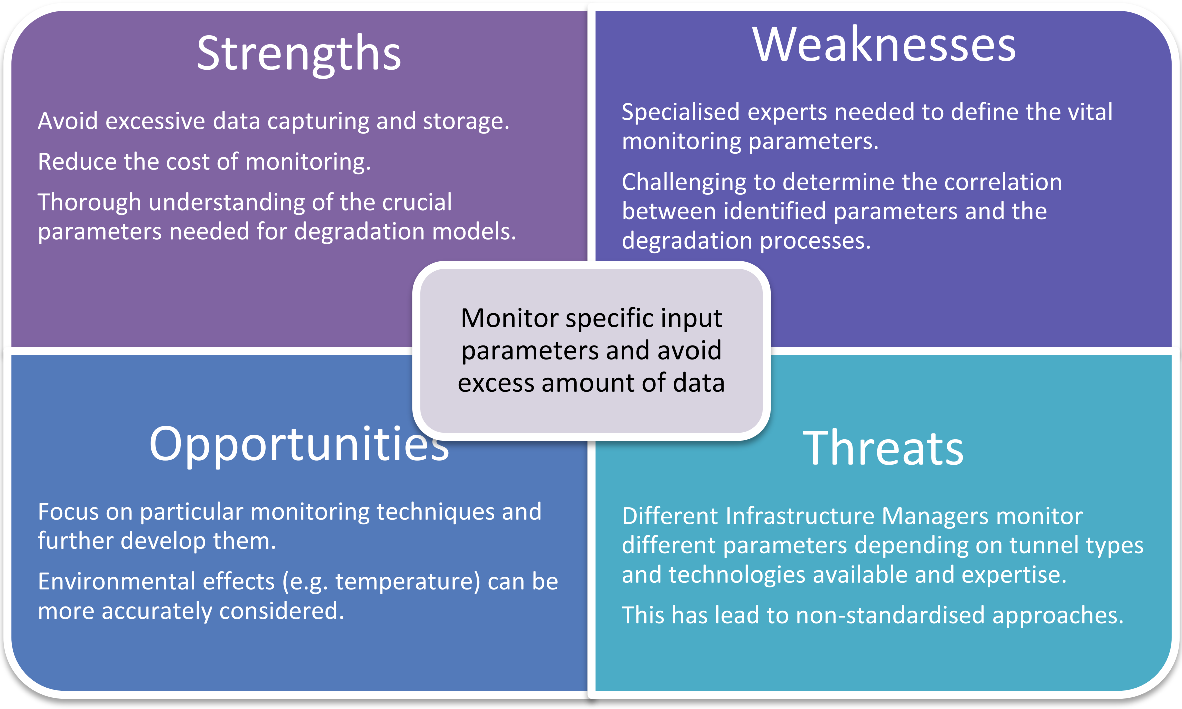


Figure 6.4 SWOT analysis of the monitoring specific input parameters and avoid excess amount of data

6.6.4 Adding environmental data into the deterioration models

Environmental conditions are a major concern when it comes to accurate and reliable inspection of railway assets (see Section 6.5.5). The significant changes in climatic patterns across Europe substantially influence degradation modelling as historic rates are not representative of future degradation of assets. However, in the case of tunnels, changes in climatic conditions are considerably smaller than in other railway assets. Despite the fact that only minor climatic fluctuations are reported, the effect of environmental conditions in the performance of inspection techniques is evident.

Most of the deterioration mechanisms affecting tunnels lining are highly dependent on the water content. The environmental conditions vary significantly between regions and seasons. In order to capture the effect of the environment into the degradation models, historical climatic data can be incorporated into the models to enable the more effective prediction of the condition of tunnels. An analysis of this potential solution is provided in Figure 6.5.

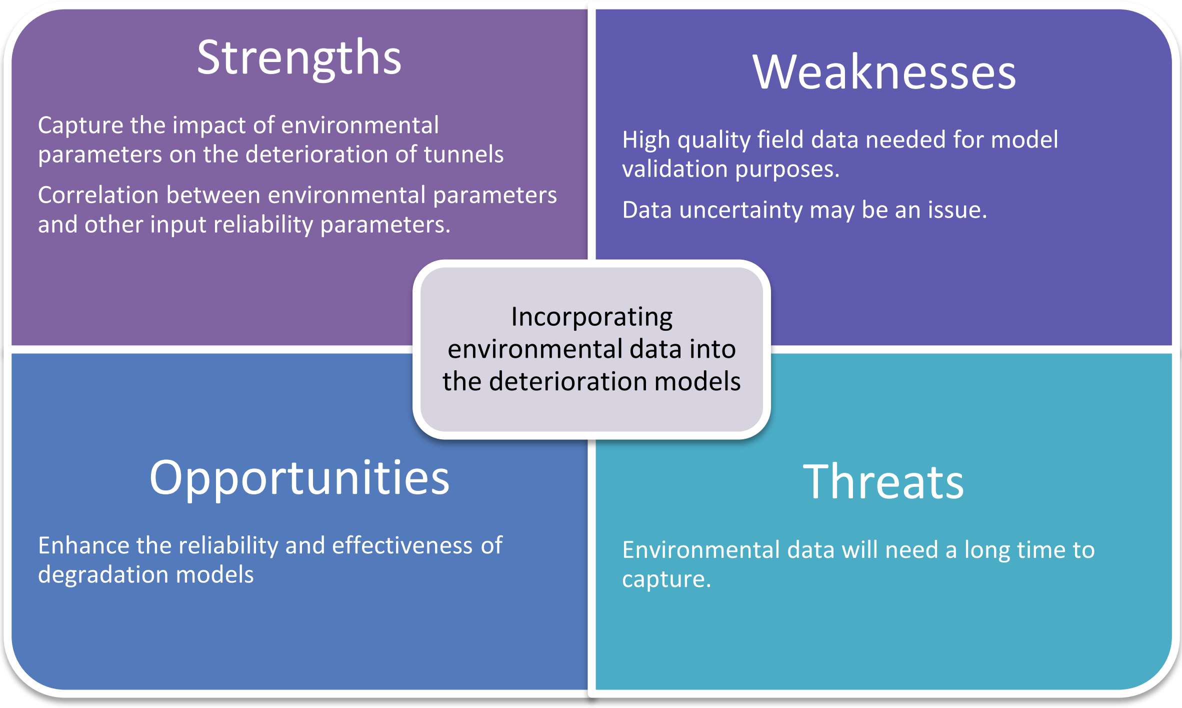


Figure 6.5 SWOT analysis of adding environmental data into the degradation models

6.6.5 Guidance via decision support and data management tools

The data interface gap between inspection output and input required by the degradation models needs to be addressed. Monitoring data generally produce quantitative results as opposed to the qualitative information gained through examination sheets. This can cause a limitation factor when inputting data into the degradation models, since these two types of output need to be integrated into one system.

Approaches to address this interface gap are required, such as the use of the software RADIS, available by the UIC, which can facilitate the elaboration of the diagnosis. RADIS application is a tool that incorporates a detailed computerised record of tunnel damages and enables organizing the information relating to the situation, the state and the investigations of a tunnel by joining them together on a same support (Winum *et al.* 1999)

In order to integrate diagnostic and maintenance in terms of data and maintenance planning process being complete and structured, approaches that allow correlation of different aspects of railway assets are being developed. Network Rail have developed a database for the management and interrogation of tunnel defect (damage) data to allow the production of degradation curves which hopefully support empirically developed assessment techniques. Another example is MERMEC's RAMSYS decision support system (Swift, Aurisicchio *et al.* 2011) which is aimed at providing a comprehensive solution including an integrated platform (suite) for the management of all data related to: maintenance, long and short-term planning, key performance indicators monitoring and decision support system tools. Tunnel measuring can be automated using, for example, MERMEC T-Sigh 5000 which can recognise defects with a resolution of 2mm travelling at 30km/h (Swift, Aurisicchio *et al.* 2011).

Furthermore, Supervisory Control and Data Acquisition (SCADA) systems can assist with the task of data management. These systems typically include human machine interfaces (HMIs), programmable logic controllers (PLCs), remote terminal units (RTUs) and a communication infrastructure that ties all of these components together. Several SCADA systems are available worldwide and their performance is being improved constantly (Stouffer *et al.*, 2007).

The inspection of the tunnel controls should include a visual observation that the control panel indicators represent the operating condition(s) of the equipment each control serves. Applying SCADA systems to railway tunnels may offer significant advantages; the use of such a system enables the control of the entire facility. These systems operate with a minimal amount of hardware maintenance, with the exception of the component level sensors.

The key to efficient maintenance of SCADA systems is having documentation (i.e. drawings, specifications, parts lists, backup copies of software and system configuration files) of the system. An adequate supply of spare parts should be available in the case of system failure. With technology changing quickly over time, a full upgrade/replacement of the system should be considered when the annual maintenance costs of the existing system begin to outweigh the benefits that would be gained by a new system.

Overall, there is a requirement to develop efficient and effective methods to collect and process data to provide adequate responses to maintenance engineering departments (Figure 6.6). For this to be achieved, proper decision support to convert inspection data into valuable information for maintenance optimisation purposes is required.

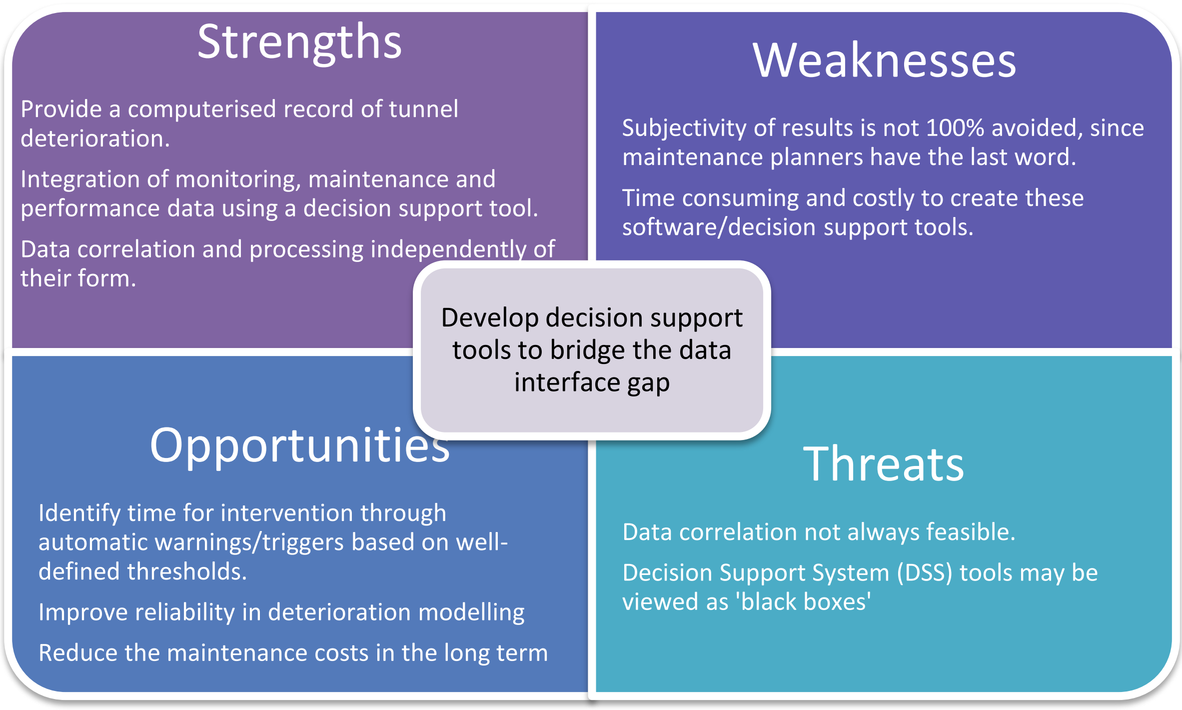


Figure 6.6 SWOT analysis of the standardisation of developing decision support tools to bridge the data interface gap

6.7 Summary

The condition appraisal of tunnels encompasses all the activities undertaken to determine the adequacy of the tunnel structure to perform its required functions. For optimum performance, a monitoring and examination system needs to be consistent with the data required for assessment by the use of degradation models.

In this report, a review of available monitoring and examination techniques as well as the degradation models applicable is carried out; this review has identified the gaps and compatibility issues on the current interface between output from monitoring and examination techniques and inputs required by reliability models.

In addition, solutions to address these compatibility gaps have been proposed and analysed through a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis. The results of these conclusions have been summarised in Table 6-7.

Further investigation and validation through case studies, however, will be required to explore the benefits and uptake of the suggested approaches.

Table 6-7 Summary of compatibility gaps and suggested solutions in tunnels

Identified Gap	Solutions	Strengths	Weaknesses	Opportunities	Threats
Lack of consistent and reliable inspection data across Europe	Standardisation of the inspection assessment through a commonly accepted framework	Consistent and reliable inspection data across Europe. Utilising historical data to predict future deterioration. Using a same framework across EU Member States.	Data collection required for the validation of the degradation framework is a costly and time consuming task. Qualitative and quantitative assessments need to be integrated into one framework.	Generating knowledge and experience sharing amongst European Infrastructure Managers. A generic algorithm will ensure consistency in tunnels monitoring.	The success of the solution depends on the quality/quantity of inputs provided from Infrastructure Managers and tunnel experts across Europe.
Lack of models for masonry linings	Use of field inspection data to develop empirical models	Strengthen the knowledge in masonry deterioration. Make use of the available field inspection data. Find and address compatibility gaps between models and inspection data.	Data output is not consistent within different Countries or regions. The accuracy is not as high as theoretical models based on deterministic approaches.	To build a model relatively (compared to theoretical models) cheap and fast. Feed into models specific to local conditions.	Empirical models usually have errors which need to be identified.

High cost of continuous monitoring and limitations of periodic inspection.	Monitor specific input parameters and avoid excess amount of data	Avoid excessive data capturing and storage. Reduce the cost of monitoring. Thorough understanding of the crucial parameters needed for degradation models.	Specialised experts needed to define the vital monitoring parameters. Challenging to determine the correlation between identified parameters and the degradation processes.	Focus on particular monitoring techniques and further develop them. Environmental effects (e.g. temperature) can be more accurately considered.	Different Infrastructure Managers monitor different parameters depending on technologies available and expertise. This may lead to non-standardised approaches.
Effect of environmental conditions on inspection	Incorporating environmental data into the deterioration models	Capture the impact of environmental parameters on the deterioration of tunnels Correlation between environmental parameters and other input reliability parameters.	High quality field data needed for model validation purposes. Data uncertainty may be an issue.	Enhance the reliability and effectiveness of degradation models	Environmental data will need a long time to capture.
Combining monitoring data (quantitative) with examination information (qualitative)	Develop decision support tools to bridge the data interface gap	Provide a computerised record of tunnel deterioration. Integration of monitoring, maintenance and performance data using a decision support tool. Data correlation and processing independently of their form.	Subjectivity of results is not 100% avoided, since maintenance planners have the last word. Time consuming and costly to create these software/decision support tools.	Identify time for intervention through automatic warnings/triggers based on well-defined thresholds. Improve reliability in deterioration modelling Reduce the maintenance costs in the long term	Data correlation not always feasible. Decision Support System (DSS) tools may be viewed as 'black boxes'

7. Plain line

7.1 Introduction

This Chapter identifies gaps and compatibility issues between the outputs of monitoring and examination techniques and degradation modelling inputs for tracks and proposes potential solutions. Chapter 5 of deliverable 2.2 (MAINLINE.2.2 2013) provides valuable information on degradation and intervention modelling techniques used in the case of plain line. Deliverable 4.1 (MAINLINE.4.1 2013) offers a description and evaluation of currently available examination and monitoring techniques for plain tracks, switches and crossings. In this report, particular focus has been given to identifying compatibility gaps in regard to plain line, as well as recommending potential approaches to provide solutions to these gaps.

Combining plain line degradation models and inspection output data in an efficient and cost-effective way, in order to minimise maintenance costs, is a challenging task. In this Chapter, the gap between measureable data and degradation models are identified, whilst considering maintenance costs. The depreciation cost becomes very dominant if the depreciation rate is high when allocating costs on an annual basis.

In order to comprehend the complexity behind a degradation model, Figure 7.***1*** provides an overview of the system parts relevant to degradation prediction. All relevant inputs to a degradation model are marked as “DM”. Monitoring and Examination techniques check both current system condition and affecting boundary conditions. Track has an inherent capability due to its system design; this capability is the starting point for the life length prediction. The next step is to define the current system condition and the change of its key parameters over time.

By applying a regression curve, using historic data for minimum 5-10 years (to give relevant trends), an extrapolation is possible. This approach is quite simple but it does not consider any change in neither boundary conditions nor maintenance interventions. This is fairly true as parameters such as traffic volume, vehicle types or grinding intervals are probably changed over time.

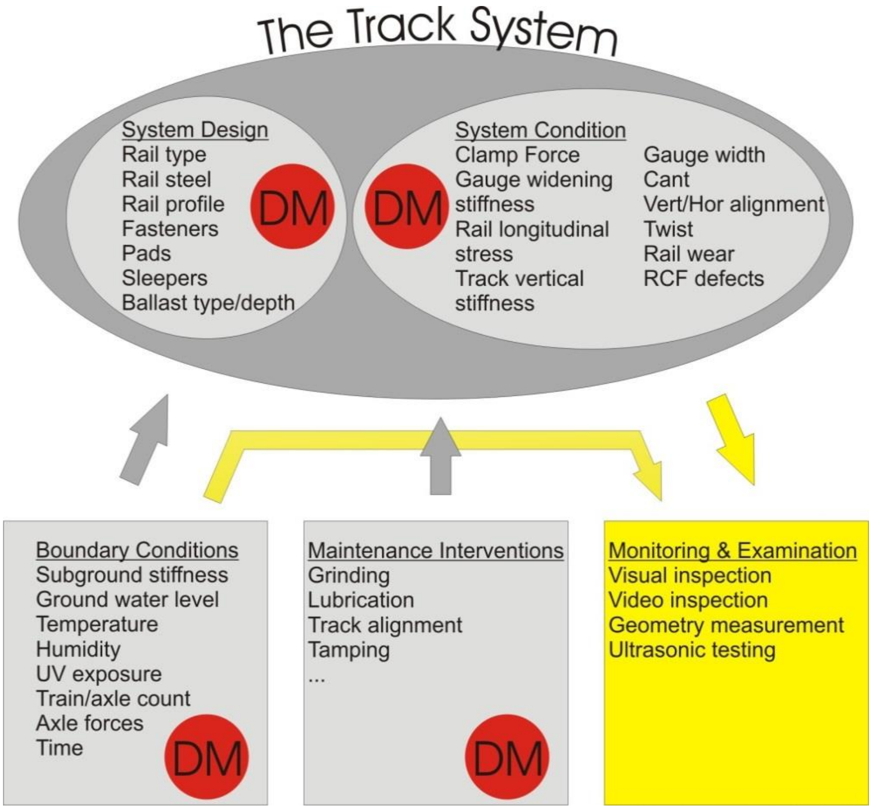


Figure 7.1. The track system integration with parameters relevant to a Degradation Model (DM) and Monitoring and Examination techniques.

Three different levels of prediction can be identified:

Level 1: This requires observation over time of track geometry deterioration and some other parameters, such as the rail head wear and Rolling Contact Fatigue (RCF). Data is available for an existing line over several years (min 5-10 years) and no change in maintenance interventions or traffic takes place. Therefore, it is possible to use a simple regression of empirical data in this case. The objective of this level of prediction is, for example, to plan tamping intervals and to support long term economic calculations by observing historical trends. This is, currently, the standard method followed for maintenance predictions.

Level 2: This level adds complexity to the degradation model in level 1 by including adaptation of the model to varying tonnage, varying vehicle types, varying maintenance routines and varying intervention intervals. Unlike the situation in the level 1 prediction, the use of long-term trends for regression calculation is not feasible. The level 2 model needs to take account of the impact of each affecting parameter individually and make predictions with an incremental approach at component level. The prediction is still supposed to be on an existing line where model corrections can be made if measured data indicates such a necessity. This level can support planning of major maintenance interventions such as grinding and rail replacement and can take into account a change in axle loads or number of trains.

Level 3: At this Level, the prediction model is fully modular and can handle any set of track design, maintenance routines and traffic. The model includes separate component degradation and supports both economic and technical evaluation of the track design even before built, i.e. on a fictive line.

The current discussion of prediction models and measured data can either be classified as a late Level 1 or early Level 2 implementation. Some typical challenges for new M&E techniques are e.g. to measure track geometry under variable vertical and lateral load and to measure boundary conditions such as traffic volume, train generated forces and substructure stiffness. M&E systems must also be developed towards compact and price effective solutions that can be installed on many regular trains. That would support more robust prediction trends and earlier detection of problems without conflict with the track availability.

7.2 Current Monitoring and Examination Practices

7.2.1 Introduction

Monitoring and examination of railway tracks is generally based on hierarchy of inspections, involving different levels of inspection as a process and different levels of personnel. For example, Network Rail (UK) has the following hierarchy adopted (Network Rail 2012b):

- Basic visual track inspection carried out by patrollers
- Supervisor inspection
- Engineer's inspection
- Peer review

While basic visual inspections are carried out to identify immediate or short term interventions required, detailed inspections aim to check the condition of specific types of track infrastructure with measurements being taken. Furthermore, the concept of risk based inspection is increasingly being adopted so that deterioration is addressed before it affects the safe operation of the track.

Several techniques can be used for the monitoring of plain lines and switches and crossings, in particular visual inspection, inspection using measurement tools (e.g. track gauge meter, measuring trains etc.), eddy current method, laser and camera, ultrasonic techniques to name the most common.

In regard to inspection of plain line, an overview of the techniques most commonly used in the UK and elsewhere is presented in Table 7-1

An overview of the most commonly used monitoring and examination practices is presented in deliverable 4.1 (MAINLINE.4.1 2013) and the summarising Table 7-2:

Table 7-1 Overview of techniques used for Monitoring and Inspection of Plain line.

Plain line		
Parameter to inspect and/or monitor	**Method**	**Equipment**
Track gauge	Measuring wheel or laser +camera or manual measurement	Track geometry measuring train or trolley or track ruler
Longitudinal level (sinking)	Measuring wheel or laser +camera or manual measurement	Track geometry measuring train or trolley or manual chord measurer
Alignment	Measuring wheel or laser +camera or manual measurement	Track geometry measuring train or trolley or manual chord measurer
Cross level (superelevation in curves)	Measuring wheel or laser +camera or manual measurement	Track geometry measuring train or trolley or track ruler
Twist	Gyroscope or cross level measurement on a base length	Track geometry measuring train or trolley or track ruler
Rail profile	Laser+camera	Rail diagnostic train or trolley or manual device
Rail inclination	Laser + camera	Rail diagnostic train or trolley or manual device
Rail corrugation	Magnetic Induction	Rail diagnostic train or manual device
Rail flaw in head or web	Ultrasonic	Ulrasonic Measuring train or trolley
Missing fasteners	Camera	Video inspection train
Broken or cracked fishplates	Camera	Video inspection train
Rail surface defects (Headchecks, squats)	Eddy current	Measuring train or trolley/video inspection or grinding machines
	Camera	Video inspection train
Weld defects (total rail area incl foot)	Ultrasonic	Trolley and for the railfoot hand-held US device

Table 7-2 Monitoring and Examination (M&E) techniques and Degradation Mechanisms (DM) affecting plain line, switches and crossings[3]

MAINLINE Project WP4: Monitoring and Examination Techniques D4.1: Report on assessment of current monitoring and examination practices in relation to the degradation								
DM / M&E	**Wear**	**Rolling Contact Fatigue**	**Fatigue cracking**	**Corrugation**	**Vegetation**	**Corrosion**	**Track geometry defects**	**Alignment**
Visual Inspection	✓	✓	✓	✓	✓	✓	✓	✓
Using Measurement Tools/Cars	✓		✓	✓	✓		✓	✓
Eddy Current		✓						
Laser and Camera					✓		✓	
Ultrasonic Method	✓		✓			✓		
Magnetic Flux Leakage		✓		✓				
Alternating Current Field Measurement	✓			✓		✓		
Video Inspection	✓		✓		✓		✓	

[3] DM here refers to Degradation Mechanisms or Symptoms of/Factors affecting Degradation

7.2.2 Limitations of existing techniques

Even though traditional or more advanced inspection techniques are increasingly being developed and enhanced with novel augmentation systems that increase their accuracy and reliability, certain limitations in their applicability still need to be overcome.

Visual inspection

Its disadvantages are the subjectivity and the necessary great time and human resource consumption.

Mechanised track measurement

Automated inspection of turnouts from a measuring train is difficult due to the complex geometry. An important aspect of inspecting switches using mechanised track measurement is the fact that the switch should be measured in both positions when inspected and that the point machinery is also part of inspection. This makes the automated measurement from train time consuming since the train has to go through the switch several times and the point machinery cannot be checked. A manual inspection might, therefore, still be necessary in this case.

The two most commonly used methods of measuring technologies are (i) chord measurement and (ii) inertial measurement (MAINLINE.4.1 2013). Some railway companies, who make use of chord-based measuring cars, disregard the data measured at crossings, because of the cross level while the wheel is moving from the wing rail on to the frog, and due to the fact that the measuring wheel is not pushed against the frog in crossings. Between the two aforementioned methods of mechanised track measurement, the chord measurement offers the advantage of providing a distortional result; an individual longitudinal-level fault, for example, can be plotted between two fictitious peaks.

According to point 4.3.2 (longitudinal level measurement) and point 4.5.2 (alignment measurement) of EN 13848-1 standard, the measuring methods applied on TEN-T lines are (CEN 2008): *“Longitudinal level measurements shall either be made with an inertial system or a versine system (that should preferably be asymmetric) or by a combination of both methods. If the versine method of measurement is used, a re-colouration of the measured signals is necessary in order to eliminate the influence of the transfer function of the versine system.”*

On the other hand, inertial measurement is contact free; however, one disadvantage of this measurement is the fact that the measuring results for longitudinal-level and alignment cannot be provided for very low speeds (between 0 km/h to some km/h). One disadvantage of manually pushed track geometry measuring trolleys is the measuring speed (walking speed) and that they do unloaded measurement because of their low weight, so they don’t measure the dummy sinking and elastic gauge widening which can be formed under loading.

Eddy Current measurement

This is an automated way to find headchecks (HC) that can be detected by visual inspection as well as video inspection. Statement of the depth of HC faults can be further developed; presently it depends on the setting of the calculation angle of damage depth which is dependent to manual (and potentially subjective) setting.

Laser-based clearance gauge measurement

The technology is quite well established but can be severely affected by bad weather conditions or sun-light exposure from some angles. Making the instruments work with higher rotation speed (frequency) at the same travelling speed would mean that the measuring spiral could follow tighter turns and, thus, the step interval become more frequent.

Ultrasonic measurement

The most commonly used method for the statement of internal rail defects. Its disadvantage lies with the fact that ultrasonic instruments mounted on a vehicle don't see the total cross-section of the rail and that the measuring speed is only 50-80 km/h, and that a great quantity of coupling liquid is necessary for the measurement. The technology has a "dead zone" of some millimetres close to the surface that is not inspected for cracks. Eddy current technology can be a support.

Magnetic Flux Leakage

Transversal cracks are not detectable with the Magnetic Flux Leakage (MFL) method either because the fissures run parallel to the magnetic flux lines and hence they do not cause sufficient flux leakage, or they are too far away from the sensing coils to detect (i.e. the rail web and foot). MFL is also adversely affected by increasing inspection speed. With increasing speed the magnetic flux density in the rail head decreases and as a result, the signal becomes too weak for the detection of defects at speeds that exceed 35km/h. More recently, Pulsed Eddy Current (PEC) probes have been added on certain ultrasonic test trains to offer increased sensitivity in the detection of surface defects at high inspection speed. PEC probes perform better than MFL sensors at higher inspection speeds but, as it was mentioned earlier, they are affected more by lift-off (lifting above the rail top) variations.

Automated vision systems

Despite the usefulness of automated vision systems, their applicability is restricted to the detection of surface defects only. Another disadvantage of video inspection systems is that leaves fallen on the tracks can give false alarms. Such images should be removed from the evaluation by adequate pre-processing. Video inspection cannot be used when the track is covered by snow.

Radiographic inspection

Radiography, although a particularly efficient Non-Destructive Evaluation (NDE) method for inspecting rails for internal flaws, inherently involves health and safety drawbacks. And the examination is time consuming.

Long range ultrasonic (guided waves)

Even though Long-Range Ultrasonics (LRU) can be effective over distances up to 180m from the sensor array, the signal is affected by various factors and, thus, the effective distance is limited to a few metres. Research in the field of rail inspection using this technique is currently on-going. Research in the field of rail inspection using this technique is currently on-going worldwide, for example, in the U.S. (The Pennsylvania State University), South Korea (Seoul National University of Technology) and the U.K. (TWI) (Ekberg and Paulsson 2010).

7.3 Degradation and Intervention Modelling Techniques

Available degradation and intervention modelling techniques relevant to track deterioration have been discussed in MAINLINE deliverable D2.2 (MAINLINE.2.2 2013). Track deterioration can be modelled with an exponential function and, once a deterioration model is calibrated, the time of future maintenance actions can be predicted using forecasts based on recent track quality measurements. This is valid for a level1 model, as described in Section 7.1.

Deliverable D2.2 contains a description of track geometry quality and degradation, which is the focus of the report. This document mainly focuses on the plain line without making reference to turnouts. The reason behind this is that the work has been focused on assets that were able to provide sufficient data for the LCAT tool (WP5) (MAINLINE.2.2 2013). Point 4.1.4 (MAINLINE.2.2 2013) contains the follows: “Extensive data on track performance from the Austrian railway network has been collected and analysed by TU Graz. This has been used in this document for forecasting the performance of track but, in the first instance, only plain track will be assessed, with switches and crossings treated in a possible future development”. The main reason is the lack of available data for turnouts, as well as the partial lack of standardisation of geometrical sizes in connection with turnouts. It is worth noting that the geometrical size regulation of EN 13848 series concerns solely plain track (CEN 2008). It is entrusted on the infrastructure managers that besides defining intervention limits, they also work out alarm limits and immediate action limits for the turnouts.

The track quality approach described in deliverable D2.2 is based on the track quality index MDZ (for ‘Mechanized Tamping Train’ in German), a riding quality index for mechanised tamping trains in Austria and Germany. This can be used very effectively for the evaluation of the track quality. However, it is worth noting that other forms of quality number also exist mainly based on standard deviation. Different railways use different Track Quality Indices (TQIs), such as, for example, SAD (Weighted additive) number used by MÁV Co.

MDZ takes longitudinal-level, alignment and super-elevation into consideration, SAD number takes longitudinal-level, alignment and twist. An effort to develop a standardised qualification across Europe is carried out in EN 13848-6 under work entitled “Characterization of track geometry” (CEN 2008).

Intervention (e.g. tamping) can be necessary on the base of the measured track geometrical parameters from two reasons:

- Local faults exceed the limit values (twist, longitudinal level and alignment). Tamping is then made of the local faults.
- Quality number of track section(s) (qualification length e.g. 200 m) (MDZ or TQI) exceeds the intervention limit value of the quality number, and therefore we do the tamping on that section.

Diagrams presented in deliverable D2.2 indicate that tamping should be carried out solely on the base of the quality number but as described above, it can sometimes be necessary to also adjust (tamp) local faults although the quality number does not require tamping yet.

7.4 Good examples of data compatibility

The necessary measurement data for track geometry qualification are available from the measuring vehicles. Most track geometry measuring vehicles can measure the following data:

- gauge
- longitudinal-level
- cross-level, super elevation
- alignment
- twist

Based on these data, a computer program makes the qualifying number TQI (such as MDZ, SAD or any other qualifying number). Qualifying number can be calculated for different track lengths. EN 13848-5 proposes the qualification for the length of 200 m.

7.5 Identified gaps and compatibility issues between Monitoring and Examination output and degradation models input

7.5.1 Lack of modelling techniques for the track super-structure and switches and crossings

The qualification of the state of track geometry is described in detail in deliverable D2.2. It is worth noting that the degradation of the quality state of the track depends on at least four of the items presented in Figure 7.1. These are:

- Current geometrical state of the track
- Type and state of the substructure
- Type and state of the 4 main components of the superstructure: rail, fasteners, sleeper and ballast
- The traffic load (axle count, tonnage, wheel forces).

The qualification of the state by track geometry has already been presented (MAINLINE.2.2 2013). Future degradation models and measuring techniques should include algorithms and data to fully comply with the Level 2 ambition mentioned in the introduction of this Chapter. They should not only cover the track geometry degradation but also the deterioration of:

- rails
- fasteners
- sleepers
- ballast

By such a detailed model it would be possible to indicate the optimal time or interval for:

- Ballast cleaning.
- Replacement of ballast.
- Replacement of rails (from wear, ultrasonic or fatigue point of view).
- Grinding or milling the rails.
- Sleeper repairing.

- Replacement of sleepers.
- Replacement of fasteners.
- Track gauge adjustment.
- Full replacement of superstructure.

7.5.2 Need for standardised database and decision support tools

Another obvious issue is the lack of applicable European standards. A first step would be to establish limiting standards for track stiffness and the condition of rail, fasteners, sleeper and ballast.

With the application of modern technology, railways could digitally record results into a common registering and decision support tool. Such examples of decision support system tools are MERMEC's integrated software platform 'RAMSYS' for the management of all the data related to railway infrastructure maintenance (Swift, Aurisicchio *et al*. 2011), MAV's railway diagnostics system 'PATER' (MAV 2013) and 'IRISSYS' software for maintenance optimisation developed by Erdmann Software GmbH (ERDMANN 2012).

Asset management programmes can enable the assessment of track condition (e.g. calculation of TQI) in an objective manner and support further actions, such as speed restrictions or maintenance works. Such tools can store inspection measurements for several years, and enable operators to carry out comparisons and analyses as deemed necessary.

7.6 Potential solutions to address gaps in a compatible/cost effective way

7.6.1 By capturing additional information using existing techniques

By using the existing monitoring and examination techniques it would be possible to make a step forward in the working out of deterioration models of track components. Existing techniques can be further developed in terms of accuracy, speed of measurement, method of data transfer as well as data processing.

Measurement of the track stiffness and especially the substructure behaviour is still quite unexplored but there are some inventions made. The state of the substructure can be examined by measurement of the actual vertical stiffness and damping. In Sweden, Trafikverket uses a special vehicle "RSMV" (Rolling Stiffness Measurement Vehicle) (Berggren 2009). It generates low frequency vibration while simultaneously measuring the dynamic response of the track. In France, an alternative solution is available under the name "Portancemetre". There is a good reason to evaluate and standardise such methods and then to form a European standard for acceptable limits related to the data measured. The state of the four main elements of the superstructure (rail, fasteners, sleepers and ballast) are important to rank and to include in degradation models. An example on how it can be done is found at MAV Co, via the use of a qualifying number called MAD (Material additive number)**.** It is based on the data (stated, counted and measured) during the inspection on foot and/or video inspection. MÁV Co. has worked out the theory of MAD qualifying number for the 4 main elements of superstructure, and tested the theory some years ago (only by inspection on foot). Currently MAV are planning to introduce this MAD number to complete the SAD number (TQI).

In the United States, a special instrumented axle has been in use for many years under the name GRMS (Gage Restraint Measurement System) (Zarembski *et al.*, 2007). While putting a controlled lateral load to the wheel, the lateral response of gauge width is recorded. This technique is mainly developed to help to detect faulty wood sleepers with spike fastenings which are still common in U.S. In spite of that, it might be of interest to use same technology also on concrete sleepers with clips as the clips stiffness can drop with time and the pads can be degraded or even missing. We do not know about any documented use in Europe. The traffic load can be determined with wayside monitoring stations that measure both vertical and lateral forces. There are also manufacturers of such systems available in Europe. However, existing degradation models are not yet adapted to fully handle this data.

7.6.2 By replacing a specific technique with another etc.

There are diagnostic areas in which break-through development would be necessary. Among others these areas are:

- developments in the measurement of track frame stiffness, working out of a simpler measuring method and instrument;
- development for the actual neutral temperature (ANT) measurement in rails of CWR tracks
- development in the measurement of HC faults’ depth, increasing the measuring accuracy
- traditional inspection on foot done by patrolmen, track-masters and section engineers should be replaced by inspection on foot with hand-held computers (PDA) and video inspection, and later only video inspection so that the workers do not stay on the track.

By inspection on foot (with hand-held computers) or by video inspection numerical data can be obtained for the forming measuring numbers of the 4 main components of superstructure (rail, fasteners, sleeper and ballast), and from the 4 measuring numbers a constructional qualifying number (e.g. MAD number) can be calculated, besides the track geometrical qualifying number (TQI). The 2 qualifying numbers (geometrical and structural state) can in combination determine the real state of the track.

7.7 Summary

The aim of this Chapter is the evaluation of compatibility issues between the outputs of monitoring and examination techniques and degradation modelling inputs for tracks. Since the focus of D2.2 document (Degradation and intervention modelling techniques), is on track geometry quality and degradation, compatibility gaps and recommended potential solutions to address them refer solely to the plain line. Table **7-3** summarises the conclusions of this Chapter.

Table 7-3 Summary of compatibility gaps and suggested solutions in plain line

Links to other tasks / Asset type	D2.1	D.2.2	D2.2	D4.1	D4.1	D4.1-D4.2	D4.2
	Degradation Parameter	Model Type	Model Input	M&E Technique	M&E Output	Compatibility Gap	Potential Solutions*
Track and turnout	Geometrical deterioration	TU Graz	Determinat. of TQI	Track geometrical meas. car	TQI	None	--
Track stiffness	Deterioration		Stiffness measurem.	Track stiffness meas. car	Track stiffness	No unified European operational size limit	Measuring coach of Trafikverket
Track frame stiffness	Loss of frame stiffness		Frame stiffness measurem.			No unified European operational size limit	Recommendation for measuring method
Rail	Wear		Rail wear measurem.	Profile measurem. by laser	Wear of 45°	No unified European operational size limit	Inspection on foot will be replaced by vehicle based inspection in the future
	Corrugation				Balanced vert. wear		
Rail	RCF (HC, Squat, etc.)			Visual inspection		No unified European operational size limit	
			Eddy current measurem.	Eddy current measurem.	Rail surface crack quantificat.		
			Video inspection	Video inspection	Size of squat area		
Rail	Internal cracks		Crack length	Ultrasonic measurem.	Crack length	None	
Rail	Inclination		Rate of inclination	Rail diagnostic meas. car	Rate of inclination	No unified European operational size limit	
Rail	Equivalent conicity		Rail head profile	Rail diagnostic meas. car		None. In draft CR INS TSI there are already limit values in operation	
			Rail inclination				
			100 m average of track gauge				
Rail	Actual neutral temperature (ANT) in rail		ANT measurem.	Measurem. Barkhausen noise	C°	Further developm. of the measuring method	
Rail	Forces from trains		Measurem. of shear forces	Strain gauge	Vertical and lateral wheel forces	No unified European operational size limit	
Fasteners	Looseness, missing, loss of clamping force		Inspection on foot, Video inspection	Inspection on foot, Video inspection	Number of loose or missing fasteners	No unified European operational size limit	

Sleeper	Crack, Break		Inspection on foot, Video inspection	Visual inspection, Video inspection	Number of cracked or broken sleepers	No unified European operational size limit	Inspection on foot will be replaced by vehicle based inspection in the future
	Deteriorated fixing of fasteners				Number of loose fasteners		
Ballast	Conta-mination		Conta-mination %	Visual inspection Drifting (cutting between sleepers)		No unified European operational size limit	
	Crushing			Labour examination			

8. Retaining Walls

8.1 Introduction

Retaining walls are designed for a service life based on consideration of the potential long-term effects of material deterioration on each of the material components comprising the wall. Permanent retaining walls should be designed for a minimum service life of 50 years, whilst temporary retaining walls should be designed for a minimum service life of 5 years (Hunt, Hearn and D'Agostino 2011). However, according to the Eurocode BS EN 1990:2002 "Basis of structural design", a minimum of 120 years is considered the design working life for retaining walls. Overall, the required design working life must be specified for the individual structure in accordance with the requirements for technical approval by the concerned authority/body.

The majority of large masonry retaining walls on the railway network were built in the mid- to late nineteenth century. The stability of these walls is difficult to quantify due to various uncertainties associated with the design, quality of construction and soil properties. Assessment methods are unable to predict when a failure of a retaining wall might occur, thereby relying on monitoring the growth of cracks or bulges.

Even though the performance of a retaining wall is generally governed by the interaction between the ground and the structure itself, there is not sufficient information to capture the effect of the damage and deterioration mechanisms affecting these structures in terms of time profiles and reliability model input parameters.

However, one way forward is generating datasets of monitoring and examination information in order to develop empirical models by utilising these field inspection data.

8.2 Current Monitoring and Examination Practices

8.2.1 Introduction

While various techniques are applicable for monitoring and examination purposes of retaining walls, visual inspection is the most dominant method with applications varying from the traditional concrete gravity and cantilevered retaining walls to the mechanically stabilised types of walls.

According to the Ontario Structure Inspection Manual (US Ministry of Transportation 2008), retaining walls tend to be inspected every two years (biennially), although the inspection interval may be increased to four years if the retaining wall is in good condition and the engineer believes that its condition will not change significantly before the next inspection. A survey that was carried out for the purposes of MAINLINE (MAINLINE.2.1 2012) concluded that the majority of inspection activities are conducted visually or using geodetic surveys. The same survey reports that condition monitoring of retaining walls is periodic (not continuous) with quarterly or yearly intervals usually being used.

Visual inspection offers the advantage of low cost, whilst enabling the direct collection of data for viewing and analysis without necessarily the need for advanced technically sophisticated crew. However, limitations related to accessibility due to obstructions or the “human factor”, that is often encountered (Qasrawi 2000), lead to a gradual shift towards the use of more advanced technologies, such as automated monitoring, terrestrial laser scanning, the use of Ground Penetration Radar (GPR) and sensor technologies.

The use of terrestrial laser systems, also referred to as light detection and ranging (LiDAR) systems, has recently gained increasing attention. LiDAR systems can be used to make multi-point measurements over a large area of the wall. The output of the technique is a digital image (3D environment). However, some challenges still lie within this advanced method of monitoring. In particular, the ability to select a scan density means that excessive and unnecessary quantities of data may be collected. In addition, in order to capture the movement in an efficient way, several scans may be required which inevitably increases the cost and time consumption of the task. Finally, in comparison to visual inspection, there is a more extensive need for technically sophisticated survey crew. However, continuous work is carried out towards assessing the readiness level of LiDAR systems for the task of automated retaining wall monitoring (Laefer and Lennon 2008).

The use of GPR as a geophysical method that can use radar pulses to image the subsurface in the case of retaining walls or soils has also been explored in recent years. GPR is one of a number of remote sensing geophysical methods utilized to study subsurface archaeological and geological deposits, alongside such methods as magnetometry, electrical resistivity, and electromagnetic conductivity. The operating principles of various existing GPR radar are based on the same principle: a transmitting antenna is placed in contact with the ground, emitting short pulses towards the ground (Faize and Driouach 2012). Although this technique presents several advantages, challenges such as the controlled positioning of antennas on the wall face or the trade-off between the time required for data acquisition and data density need to be taken into consideration.

Furthermore, solutions that offer innovative automated monitoring systems providing near real-time retaining wall monitoring have recently been developed. These systems can provide settlement, rotation, and displacement measurements of wall movements 24 hours a day on very regular intervals. Automated monitoring systems can incorporate a number of sensors, tiltmeters and vibrating wire crackmeters, which enable the measurement of horizontal/vertical wall movements, wall displacements and rock extension contractions respectively. However, the cost of the technology as well as the time and cost associated with the sensors, at least on a short-term basis, are factors to be considered.

Other instruments and technologies used for the inspection of retaining walls are inclinometers, thermocouples, moisture sensors and fibre optic strain gauges. A summary of the most commonly applied Monitoring and Examination techniques in relation to the main degradation mechanisms or symptoms of/factors affecting degradation is provided in Table 8-1. For further information please refer to MAINLINE deliverable D4.1 (MAINLINE.4.1 2013).

Table 8-1 Monitoring and Examination (M&E) techniques and Degradation Mechanisms (DM) affecting retaining walls[4]

MAINLINE Project **WP4: Monitoring and Examination Techniques** **D4.1: Report on assessment of current monitoring and examination practices in relation to the degradation**								
DM / M&E	**Water presence**	**Erosion**	**Differential settlement**	**Vegetation**	**Undermining**	**Fatigue deterioration**	**Corrosion**	**Creep**
Visual Inspection	✓	✓	✓	✓	✓	✓	✓	✓
Automated Monitoring			✓		✓			✓
Ground Penetrating Radar		✓		✓	✓	✓	✓	
Light Detection and Ranging	✓		✓	✓				✓
Inclinometers			✓		✓			✓

8.2.2 Data necessary to the retaining walls maintenance

One of the main objectives of structural inspection is to identify maintenance, repair and rehabilitation needs of structures in order to maintain them in a safe condition and protect and prolong their useful life. However, as urban densification continues to grow and above ground space increases in value, the task of structural inspection becomes more challenging; in the case of retaining wall systems, they need to be installed deeper and under greater difficulty. The installation geometries will, therefore, increasingly complicate the use of traditional inspection and maintenance.

Documents including information on the geology, on the nature and the geometry of retaining walls, updated reports of the structure’s state, detailed recordings of damages and history

[4] DM here refers to Degradation Mechanisms or Symptoms of/Factors affecting Degradation

reports of completed interventions are documents that an Infrastructure Manager needs to have for maintenance purposes.

It has to be noted that a number of Infrastructure Managers agree that there is substantial lack of retaining walls data, which inevitably makes the challenge of maintenance and intervention a harder task. However, output data generated by the most commonly applicable monitoring and examination techniques are summarised in Table 8-2.

Table 8-2 Output of the main techniques applied in retaining walls' inspection

	M&E Technique	M&E Output
Retaining walls	Visual Inspection	Viewing data on settlement, deformation, erosion, vegetation, etc.
	Inclinometers	Lateral movement
	Tiltmeters	Wall displacement
	Thermocouples	Temperature
	Time domain reflectometry moisture sensors	Moisture content
	Light Detection and Ranging (LiDAR) Systems	Digital images (3D)
	Fibre optic strain gauges	Wall loading and temperature
	Ground Penetrating Radar (GPR)	3D imaging data
	Automated vision systems (incl. sensors and crackmeters)	Wall horizontal/vertical movement, wall displacement, rock extension contraction etc.

8.3 Degradation and Intervention Modelling Techniques

The performance of a retaining wall is governed by the interaction between the ground and the structure itself. Therefore deterioration may arise as result of changes in the ground conditions as well as deterioration of the structure itself. MAINLINE deliverable D2.1 (MAINLINE.2.1 2012) provides more information on the degradation mechanisms applying to Retaining Walls.

The main damage and deterioration mechanisms affecting retaining walls are:

- *Differential settlement*
- *Soil parameters*

  Time and environmental conditions can cause deterioration to a retaining wall by altering the loading from the retained earth.
- *Groundwater*

  Pore water pressure can build up behind the retaining wall leading to overturning
- *Vegetation*

  The growth of bushes and saplings near the wall can cause root damage and can affect the water content of the adjacent soils and cause geotechnical instability
- *Material and structural degradation*

  Depending on the construction material, the retaining wall structure itself may deteriorate via concrete chemical attack, steel corrosion, fatigue deterioration and so forth.

While the key mechanisms associated with the deterioration of retaining walls have been identified, there is still a considerable lack of knowledge with respect to the behaviour of these mechanisms and their aggressors. Furthermore, not enough information is available to capture the degradation time profiles under a range of operational scenarios.

The lack of available degradation modelling techniques for retaining walls may be attributed to the fact that there is still high uncertainty in regard to degradation mechanisms affecting retaining walls while, simultaneously, a huge gap between modern and historical methods of assessment of these assets is evident. In fact, the vast majority of railway retaining walls were originally designed to resist forces that were calculated purely from total-stress-based theories. However, earth pressure theory has been substantially developed since the majority of retaining walls were designed; nowadays, the effective stress analyses have replaced these traditional assessment methods (Hough 2001). A detailed description of such analyses is beyond the scope of this report but further information has been presented in Section 8.4.2 of this report.

8.4 Identified gaps in regard to Monitoring and Examination systems and guidance for optimum performance

8.4.1 The limitations of visual inspection

While visual inspection is often seen as a fast and cost-effective method of assessing the condition of a structure enabling the direct collection of data for viewing and analysis, limitations associated with this type of assessment need to be taken into account. In particular, limitations could be a result of inaccessibility due to obstructions, hazardous conditions of deficiencies of a scale not visible to the eye. In addition, the “human factor”, that is often encountered (Qasrawi 2000) when visually inspecting a structure, is an additional gap that needs to be considered.

A solution, which is increasingly implemented recently, is to assist visual inspection of retaining walls with the use of supporting technologies, incorporating the use of optical instruments, computer-based picture stores/libraries and remote camera systems. Automated monitoring systems utilising integrated innovative systems with the use of a wide range of tiltmeters, crackmeters and sensors can provide sufficient information on a 24 hour-basis and regular intervals and, thus, offer design and construction engineers a peace of mind during difficult projects.

8.4.2 Lack of data to support degradation reliability models

The lack of availability or the slow uptake of degradation modelling techniques for retaining walls may be attributed to the lack of available data for this purpose or even the fact that there is a significant gap between modern and historical methods of assessment of these assets. Uncertainties in regard to the mechanisms affecting the condition of retaining walls as well as lack of sufficient inspection data have been the main factors of the absence of reliability models.

As part of a project, a comparison was carried out between modern and historical methods of assessment in order to highlight those areas requiring particular attention in the assessment and maintenance of retaining walls (Hough 2001). Total stress analyses are used for short term considerations while the effective stress assessment theory is applied for longer term considerations. It is evident, since most of railway retaining walls are more than 100 years old, that any assessment of the stability of the retaining walls requires the latter.

The results of the comparison of the two assessment theories, as carried out by Hough (2011), are indicative of the extent to which gravity walls of the nineteenth century were considerably under-designed by modern standards. Modern factors of safety against sliding, for example, were found reduced by 8 times in comparison to the original design.

In order to bridge the gap of lack of degradation modelling techniques, inspection field data can be collected and used to develop empirical models for the deterioration of retaining walls. The success of this approach will depend on the amount and quality of data provided by different Infrastructure Managers, as well as the standardisation process which will be required to validate the model.

8.4.3 Need for advanced and specialised technical skills

The recent technological advancements have been reflected in condition monitoring through the development and implementation of inspection techniques such as automated monitoring systems, laser scanning, ground penetrating radar and so forth. This implementation of automated and remote sensor technologies, however, has introduced some new challenges for Infrastructure Managers.

Overall, inspection technologies such as LiDAR sytems or automated monitoring systems require more advanced and specialised technical crew skills. Furthermore, the ability to select different applications and scenarios, for example a scan density in the case of LiDAR systems, means that excessive and unnecessary quantities of data may be collected and stored. The latter may have a counterproductive effect on the assessment process of the structure, especially due to the increased time and cost associated with the handling, storage and analysis of the data.

In other cases, such as the application of GPR systems, the challenge lies on the controlled positioning of antennas on the wall face as well as the trade-off between time required for data acquisition and data density. For the effective interpretation of the inspection data required for maintenance and intervention purposes, the need for advanced technically sophisticated crew is evident.

While railway industry is highly depending on these technological developments, further guidance needs to be provided to the Infrastructure Managers in regard to the application of advanced monitoring techniques. In addition, the development of decision support system tools, which will integrate various monitoring techniques and offer efficient, well-structured and non-complicated guidance to decision makers, may also be an effective approach for the monitoring and examination of retaining walls.

8.4.4 High short-term cost of laser and sensors technologies

As mentioned in the previous section, the implementation of advanced technological systems for the inspection of retaining walls has both a direct and indirect impact to the time and cost of the process. At the same time, the frequency and range of applications of these technologies can have a major impact on the cost of the systems. The cost of purchasing and installing a number of sensors to capture data related to ground movement, structure temperature, moisture content, wall loading and 3D digital images, seems to be a limitation, as Infrastructure Managers are often concerned by the short-term impact rather than the long-term costs/benefits.

However, if the cost of the technologies is assessed on a whole lifecycle (long-term) basis, the opportunity to increase their attractiveness and applicability may be more feasible. In order to achieve this, further work to compare different inspection and maintenance strategies based on a life cycle evaluation need to be carried out. Such an evaluation, as the one proposed in MAINLINE deliverable D5.4 (MAINLINE.5.4 2013) for the development of MAINLINE's Life-Cycle Assessment Tool (LCAT), should quantify all associated costs, including direct economic costs, availability parameters and environmental impact costs.

8.5 Summary

While the key mechanisms associated with the deterioration of retaining walls have been identified, there is still a considerable lack of knowledge with respect to the behaviour of these mechanisms and their aggressors. The absence of available degradation modelling techniques for retaining walls may also be attributed to the fact that a huge gap between modern and historical methods of assessment of this type of asset is evident.

Due to lack of sufficient inspection data to support the development of degradation reliability models and the high short-term of cost laser and sensors technologies, decision support system tools (on a whole lifecycle basis) are required to enable the integration of various monitoring techniques and offer well-structured guidance to decision makers.

9. Conclusion

This report, Deliverable D4.2, draws on the output generated from Monitoring and Examination practices in the rail industry and their uptake as inputs to degradation models. Key data gaps and compatibility issues have been identified and feasible solutions have been suggested to address them in an effective way. Data consistency and cost-effectiveness are at the foremost of priorities in this report, which provides guidance as to what additional information could be captured or what alternative methodologies could be followed to enable a good compatibility in data interpretation.

Five different types of railway assets were considered: (i) cuttings, (ii) metallic bridges, (iii) tunnels with concrete and masonry linings, (iv) plain line, and (v) retaining walls. It has been concluded in Deliverable D4.1 that visual inspection as a technique plays a vital role in the inspection process and in most cases forms the standard assessment in the industry. However, more advanced inspection techniques, incorporating sensor technologies, non-destructive testing and automated monitoring instrumentation is being increasingly developed, with projects like MAINLINE presenting their huge potential.

Nevertheless, an efficient integrated asset management system must ensure that the various inspection techniques are not considered in isolation leading to information that is not used in an optimal way or surplus to requirement. This report has identified specific issues in relation to inspection practices and the uptake by degradation models.

The lack of data for validation purposes across Europe, difficulties in integration of models using different types of data and the effect of climate change on earthwork stability have been identified as the main issues in regard to cuttings. In order to overcome these gaps, solutions, such as the development and implementation of a generalised algorithm (across Europe), the incorporation of monitored data into deterioration models and inputting climatic region-specific data into deterioration models respectively, have been suggested in this report.

In metallic bridges, compatibility issues have been presented related to the key degradation phenomena of corrosion and fatigue. The report suggests that monitoring procedures need to be further enhanced and probability-based models to be developed in order to address the lack of monitoring for key exposure parameters and the coating performance. Furthermore, in regard to fatigue, measurements need to focus at points with maximum damage; optical sensors are considered as an effective potential solution. Finally, existing or future models need to take into account the combined effects of these two degradation mechanisms.

The lack of consistent and reliable data for validation purposes of the degradation models is also one of the identified gaps in the case of tunnels with concrete and masonry linings; this issue applies in the majority of rail related European Research and Development Projects. In order to overcome the lack of data across Europe, a generalised framework could be developed and utilised to be applicable to different regions and railway networks within Europe. In addition, the lack of models for masonry lined tunnels and the high cost associated with continuous monitoring of the asset are limitations that need to be overcome. Potential solutions to address these gaps could be the use of field inspection data to develop empirical models and monitoring specific required parameters to generate necessary output.

Finally the use of decision support systems for data and control management purposes could also bridge the gap of cost and time associated with excessive data.

Combining plain line degradation models and inspection output data in an efficient and cost-effective way, in order to minimise maintenance costs, is a challenging task that was also explored in this report. The main identified gaps are the lack of modelling techniques for the track super-structure and switches and crossings, as well as the need for standardised database and decision support tools. Suggestions to address these issues, mainly focused on using vehicle-based inspection and automated inspection systems, have been made in this report.

Finally, in regard to retaining walls, where the lack of sufficient inspection data to support the development of degradation reliability models is evident and the high short-term of cost laser and sensors technologies is an additional challenge, decision support system tools (on a whole lifecycle basis) which will integrate various monitoring techniques and offer well-structured guidance to decision makers could be an effective way forward.

This report has explored a range of potential solutions to address the identified gaps in an efficient and cost-effective way. A suitable geographical coverage across Europe was ensured through the involvement of experts from both Western and Eastern European countries in the preparation of the document. A comparison of European best practice methods has been carried out to offer reliable conclusions in regard to solutions to compatibility gaps between monitoring and examination systems and degradation models.

However, in order to further explore the benefits regarding the use and cost-effectiveness of the suggested solutions, a validation exercise is required, which is expected to promote the uptake of useful and cost effective approaches by the rail sector.

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