MAINLINE

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

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

Theme SST.2011.5.2-6.: Cost-effective improvement of rail transport infrastructure

Deliverable 4.1:
Report on assessment of current monitoring and examination practices in relation to degradation models

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PP	Restricted to other programme participants (including the Commission Services)	
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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.

The project 'MAINtenance, renewaL and Improvement of rail transport iNfrastructure to reduce Economic and environmental impacts' (in short MAINLINE) is a project within the EU's 7th Framework Programme. It has been part funded on the basis of the contract SST.2011.5.2-6 between the European Union represented by the European Commission and International Union of Railways (UIC) acting as coordinator for the project.

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; DB Netz AG, 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.

Work Package 4 in the MAINLINE Project

The main objectives for WP4 are:

- to clarify what inputs the degradation 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 take-up of the proposed approaches by infrastructure managers.

Table of Contents

List of figures

List of tables

Glossary

Abbreviation / acronym	**Description**
ACFM	Alternating Current Field Measurement
BCMI	Bridge Condition Scoring Index
DfD	Document for Discussion
DIC	Digital Image Correlation
DM	Degradation Mechanism
DoW	Description of Work
DTM	Digital Terrain Model
EM	Electromagnetic
EU	European Union
GPR	Ground Penetrating Radar
GPS	Global Positioning System
INSAR	Interferometric Synthetic Aperture Radar
IPI	In-place Inclinometer
LiDAR	Light Detection and Ranging
M&E	Monitoring and Examination
MEMS	Micro Electro-Mechanical Systems
MFL	Magnetic Flux Leakage
MPI	Magnetic Particle Inspection
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
PEC	Pulsed Eddy Current
RSHI	Rock Slope Hazard Index
RT	Radiographic Testing
SAR	Synthetic Aperture Radar
SSHI	Soil Slope Hazard Index
TDR	Time Domain Reflectometry
ToF	Time of Flight
UT	Ultrasonic Testing
WP	Work Package

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Network Rail (NR), United Kingdom
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1. Executive Summary

1.1 Background

Assets need to be monitored and examined for deterioration to ensure that timely action is taken for them to remain fit for service. Monitoring and Examination (M&E) systems thus form a crucial part of the integrated asset life cycle management system that is envisaged to be developed within MAINLINE Project. M&E techniques range from the most common basic visual inspection by trained personnel to the remotely operated real-time continuous monitoring systems. The techniques need to be compatible with other parts of the asset management system and also need to be cost effective and reliable.

1.2 Objective

WP4 of MAINLINE aims to review currently used M&E techniques with a view to identifying and addressing gaps in compatibility between M&E systems and degradation models, and provide validation of improved approaches via case studies. This report D4.1 within WP4 is aimed at reporting the results of a review of M&E techniques.

The main objective of this report is to review currently applied M&E techniques as they apply to various degradation mechanisms in the types of railway assets considered within MAINLINE. This task is carried out with a view to identifying gaps and improving in a cost effective way the compatibility between such techniques and degradation models.

1.3 Work carried out

D4.1 is a report on the review carried out within Task 4.1 (of WP4) which is an assessment of current M&E practices with a view to identifying key gaps. This review was based mainly on inputs from industry practitioners, a review of relevant projects, and relevant experience from other industry sectors.

This report integrates individual reports from MAINLINE partners involved in WP4 and perspectives gained from the debate following the Document for Discussion (DfD) (see Appendix) circulated earlier on. The Monitoring and Examination techniques reviewed throughout this report relate to the selected assets (as determined in D2.1) explored for the purposes of the project. These are: (i) cuttings, (ii) metallic bridges, (iii) tunnels with concrete and masonry linings, (iv) plain line and switches and crossings, and (v) retaining walls. Currently used Monitoring and Examination practices as they apply to these types of assets are described in individual sections of the report.

Although the focus of this review is on currently prevalent M&E techniques, emerging techniques have also been taken note of and discussed.

1.4 Conclusions

Each of the M&E techniques reviewed throughout this report offers a number of different capabilities and their applications vary significantly in terms of time, cost, applicability, compatibility, validation and credibility. Despite recent advances in sensor technologies and NDT, visual inspection as a technique plays a crucial role in the M&E process and in many cases forms the main technique used. There is need to optimally incorporate M&E techniques based on their strengths in an integrated asset management system capable of providing accurate and reliable outputs in a timely and cost effective manner.

The review of M&E techniques also shows that for many of the rail assets, it is Examination or Inspection (these terms are synonymously used for the purpose of this report) that is usually undertaken first. This is followed by Monitoring as required or decided using such Inspection reports.

It is envisaged that this review of available M&E methods that includes the pros and cons of each technique will help assess the suitability of these techniques in relation to the degradation mechanisms affecting the selected types of rail assets. The report also enables the identification of gaps to be addressed within Task 4.2 of MAINLINE.

2. Introduction

2.1 The drivers for advanced asset management tools in the rail sector

Growth in demand for rail transportation across Europe is predicted to continue, with midterm projections by the European Commission expecting rail freight and passenger traffic to rise by approximately 13% and 19% respectively between 2000 and 2020 (European Commission 2006). This predicted increase in traffic on existing elderly rail infrastructure across Europe 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. In addition these maintenance and renewal interventions need to take account of the need for reduced economic and environmental impacts. The residual life of each historic asset varies and is difficult to predict, as is the consideration that needs to be given to the environmental impact of past events in the life of the asset. It is also crucial to find a balance between the natural desire for lower cost solutions and the real need to achieve the lowest life cycle cost.

In order to address these issues, the MAINLINE (MAINtenance, renewal and Improvement of rail transport iNfrastructure to reduce Economic and environmental impacts) project has been prepared for the purposes of work programme topic SST.2011.5.2-6.: “Cost-effective improvement of rail transport infrastructure”. The project brings together leading railways, contractors, consultants and researchers from both Eastern Europe and the emerging European economies. The development of a tool to assist railway administrators to contribute to a more cost efficient and effective improvement of European railway infrastructure based on whole life considerations is the principal objective of the MAINLINE project. The project draws heavily on the experience of the members of the consortium, relevant recently completed research projects such as INNOTRACK (2010) and Sustainable Bridges (2007) and on-going research at both national and international levels. Although MAINLINE focuses on certain asset types, the management tools to be developed will be applicable across a broader asset base, highlighting the potential and adaptability of the project.

2.2 Definitions/Descriptions of key terms used in this report

Asset

Asset covers in this report all railway civil engineering structures, earthworks and tracks, i.e. all earthworks, bridges, tunnels, culverts, retaining walls and tracks (incl. rails, sleepers, ballast, switches and crossings).

Bridge (Network Rail 2004)

A structure of one or more spans greater than or equal to 1800 mm, whose prime purpose is usually to carry traffic over an obstruction or gap, but excluding culverts. An ‘Underline Bridge’ is a bridge carrying one or more operational tracks.

Earthwork (Network Rail 2004)

Earthworks include embankments, cuttings or natural slopes (soil or rock). Any local support, bolting or netting of Rock Cuttings is classified as part of the Rock Cutting for examination purpose. Any reinforced soil wall less steep than seventy degrees is classified as earthwork.

Cutting (Network Rail 2004)

Cutting is an open excavation to permit a railway or road to maintain its level or gradient through high ground.

Rock Cutting (Network Rail 2004)

Rock cutting is an excavation where the predominant mode of slope failure is along a discontinuity within the rock mass.

Tunnel (Network Rail 2004)

A structure provided to allow the railway or services to pass under higher land, buildings and/or water, which has been excavated without removing the surface of the land. The term includes the bore, any associated shafts, portals, inverts and drainage systems within or attached to the structure of the tunnel. The term also applies to any other type of construction that needs to be examined as a tunnel.

Retaining wall (Network Rail 2004)

Any structure built to support ground at a higher level on one side than the other, including any associated strutting or anchors. The term excludes the following: water retaining structures; wing walls, abutments and piers forming parts of bridges or culverts; platform walls; coastal defences and river protection works.

Monitoring

The dictionary meaning of ‘Monitoring’ is to watch and check a situation carefully for a period of time in order to discover something about it.

Monitoring generally includes the following:

- Measuring and recording quantitative information periodically or continuously regarding the extent and nature of degradation of the asset. Examples of such information are: the locations and dimensions of areas affected, the length; width and depth of cracks; information from NDT using appropriate instrumentation.
- Continuously monitoring the condition of an asset with the aid of data loggers and remote monitoring techniques and automatic alarm systems, should monitored parameters go beyond pre-determined limits.

According to the FP6 Project ‘Sustainable Bridges’ (2007), monitoring is the act of acquiring, processing, communicating and archiving information about the actions on and the action effects of a structure over a period of time with a high level of automation. Monitoring is based on transducers for sensing physical or chemical quantities (measurands), programmable electronic equipment for acquiring, processing and communicating data and algorithms that define how data acquisition, processing and communication is performed (Feltrin 2007). A monitoring system may consist of data acquisition, processing, interpretation, visualisation and archiving modules.

‘Monitoring’ is defined by Network Rail in UK (Network Rail 2004) as: “Continual or regular checking by observation or measurement to verify and establish changes in the condition or environment of a structure.”

Within MAINLINE, Monitoring will include the activities/processes mentioned above.

Examination and Inspection

Within MAINLINE, the terms Examination and Inspection are used synonymously.

The dictionary meaning of ‘Examination’ is to look at or consider something carefully to discover something. Within MAINLINE, Examination is an event that includes making an observation, taking measurements and recording such information regarding the condition of an asset.

‘Examination’ is used by Network Rail in UK (Network Rail 2004) in the following contexts:

- ‘Visual Examination’ of bridges:

An examination to identify changes in the condition of a structure carried out from a safe observation location, without using access equipment but using permanent ladders and walkways, binoculars and hand-held lighting where necessary.

- ‘Detailed Examination’ of bridges:
  A close examination of all accessible parts of a structure, generally within touching distance, of sufficient quality to produce a record which includes the condition of all parts of the structure, the uses to which the structure is being put, recommendations for remedial action, and any other relevant facts.

- ‘Additional Examination’ of bridges:
  An examination of a specific part of a structure in detail, or to monitor a particular defect, condition, movement or component of a structure following an incident or report, which is carried out in addition to Visual and Detailed Examinations.

- ‘Examination’ of earthworks:
  The visual examination of an earthwork to determine whether signs of slope instability are present;

- ‘Cyclical Examination’ of earthworks:
  The planned visual examination of an earthwork to determine whether signs of instability are present;

- ‘Special Examination’ of earthworks:
  A visual examination of an embankment or cutting undertaken where there is concern regarding stability.

Where relevant, a detailed examination will involve the exposure and examination of hidden critical elements which are defined as primary structural members that cannot be observed from at least one side throughout its extent and it is not protected by a material which is known to preserve the condition of the part.

In the FP6 Project ‘Sustainable Bridges’ (2007), inspection was defined as the on-site, mostly non-destructive examination to establish the present condition of a structure. Furthermore, the terms of inspection and monitoring were linked into the term ‘inspection monitoring’, which is any long term monitoring activity that is performed with the goal to increase the efficiency and effectiveness of the bridge inspection process (e.g. inspection scheduling). Finally, for the purposes of the same project, investigation was defined as the collection and evaluation of information about a structure through inspection, monitoring, testing, modelling and document search activities (Feltrin 2007).

In the rail industry, the term ‘Inspection’ is commonly used as a conformity check compared to the system design of the asset. Inspection measures the system integrity, which is described as the ability of a system to perform its intended functions without being degraded or impaired by changes or disruptions in its internal or external environments. The implementation to railroad maintenance is checking that all parts are in a state that they can handle any possible (but not necessary present) stress with a relevant safety margin. Inspection is carried out according to well defined standards and regulations and the results are documented and checked against given limits.

Within MAINLINE, the term Examination or Inspection will include the activities/processes mentioned above.

Other industry sectors have their own take on Inspection, Examination and Monitoring activities. For example, in the offshore oil and gas sector, there are standards that distinguish between Monitoring and Inspection but not between Monitoring and Examination. Inspection is an activity carried out periodically and used to assess the progression of damage[1] in a component. Inspection can be carried out by means of technical instruments (NDT) or by a visual examination (DNV 2012).The same document describes Monitoring as an activity carried out over time whereby the amount of damage is not directly measured but is inferred by the measurement of factors that affect that damage.

Assessment (Network Rail 2004):

The determination of the safe load carrying capacity of a structure taking into account the physical condition and location of the structure; the term includes site inspection with site measurements and the carrying out of any calculations and checks.

Assessed Category (Network Rail 2004):

The categorisation of load capacity utilisation of the critical element of a structure; this term applies to assessments carried out using limit state or permissible stress principles.

Site Investigation (Earthworks) (Network Rail 2004):

A comprehensive sequence of desk-based studies and site work leading to the development of an understanding of site conditions and failure mechanisms; the term includes engineering geological and geomorphological mapping, in-situ and laboratory testing and the installation and monitoring of piezometers and movement instrumentation. The soil/rock and groundwater parameters obtained shall be sufficient for an evaluation and/or design of remedial works.

Evaluation (Network Rail 2004):

The appraisal with regard to condition, use and location of all relevant information and circumstances relating to a structure to establish whether action is required to ensure that the level of safety and serviceability of the structure remains acceptable.

2.3 Monitoring and Examination (M&E) in an integrated asset management tool

Monitoring and examination systems form a vital part of any integrated asset life cycle management system. In recent decades, the traffic loads, volume and speeds on the European railway network have greatly increased due to the demands of the continually growing economy and higher transport efficiency. Rail networks across Europe are therefore getting busier with trains travelling at higher speeds and carrying more passengers and heavier axle loads than ever before. The combination of these factors has put considerable pressure on the existing infrastructural assets leading to increased demands in inspection and maintenance. These assets need to be monitored and examined for degradation to ensure that timely action is taken for them to remain fit for service. Monitoring techniques range from the most regular and widely used visual inspection to the remotely real-time continuous monitoring systems using electronic sensors and wireless communication. Effective inspections 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. Even when no action is taken after an inspection, a complete and objective record of what was found is vital to permit the next inspection to measure or assess any deterioration or other changes during the intervening period (McKibbins, Elmer and Roberts 2009).

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:

[1] In MAINLINE, 'damage' is defined as the loss of performance of an asset caused by accidental events such as collisions, overloading or design and construction errors and is measured in terms of visual appearance or reduction of functionality.

- 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 seeks 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 builds on work carried out in two EU Projects "Sustainable Bridges" (Sustainable Bridges 2007) and "Innotrack" (Ekberg and Paulsson 2010) as well as the UIC project on 'Monitoring track condition to improve asset management' (UIC 2010). Other sources of state of the art knowledge include: 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; and a report on the French national research project MIKTI (MIKTI 2010).

This report takes note of research on structural health monitoring and other monitoring and examination techniques identified in relevant projects. The task involves perspectives from industry practitioners some of whom are participants of MAINLINE and have contributed to this report. Cognisance is also taken of the SMARTRAIL project that is a FP7 Project that commenced concurrently with MAINLINE and is undertaking relevant work.

2.4 Participants in WP4

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

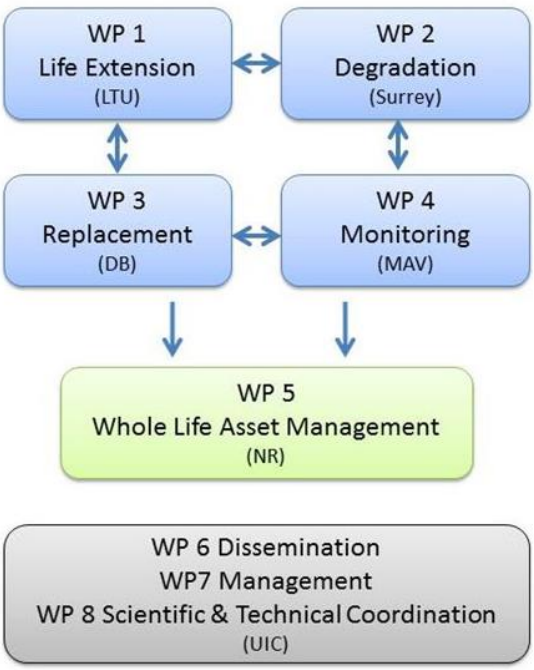

Figure 2.1. General organisation of the project.

UIC, Surrey, MAV and NR are listed below. DB is Deutche Bahn AG (Germany) and LTU is Luleå Tekniska Universitet (Sweden) (DoW MAINLINE).

Table 2.1. 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 INFRASTRUCTURE LTD (NR)	UK
4	SINCLAIR KNIGHT MERZ (SKM)	UK
6	TWI LIMITED (TWI)	UK
8	LULEA TEKNISKA UNIVERSITET (LTU)	UK
10	MAV MAGYAR ALLAMVASUTAK ZARTKORUEN MUKODO RT (MAV)	HU
14	DAMILL AB (DAMILL)	SE

2.5 The selection of assets

The MAINLINE partners have drawn up Table 2.2 in the DoW which lists the major rail assets described above; it also ascribes a score to a number of factors relevant to research into deterioration/damage models. Because there are different levels of knowledge between Western Europe and Eastern Europe and the developing economies, the values quoted in Table 2.2 have been simplified to 2, 5 and 8, with (in terms of either existing knowledge or the chance of a successful research outcome) 2 meaning poor, 5 meaning fair and 8 meaning good.

Table 2.2. Estimation of current knowledge and potential for improvement according to DoW; values express the chance of successful research outcome (2=poor, 5=fair and 8=good) (D2.1 MAINLINE)

Component of elderly rail infrastructure	Relevant degradation mechanisms	Current knowledge level	Potential to increase knowledge	Success in 3 years Deterioration models	Availability of validation data
Earthworks					
Sub grade (natural ground)	Bearing capacity failure, lack of shear strength, settlement	8	2	5	5
Cuttings	Soil Erosion, Creep deformation, Stability Rock Erosion, Freeze/thaw	5	8	5	5
Embankments	Erosion, Creep deformation, Stability	5	8	5	8
Bridges					
Masonry	Freeze/thaw, Water percolation, Foundation settlement, Deformation, Fatigue	5	8	2	5
Metallic	Corrosion, Fatigue, Cracking, Dynamic effects	8	8	5	8
Concrete (reinforced, pre-stressed or post tensioned)	Concrete Carbonation, Sulfate attack, Chloride ingress, Alkali silica reaction, Freeze/thaw Reinforcement General (carbonation) corrosion, Pitting (chloride induced) corrosion, Fatigue	8	5	5	8
Tunnels					
Unlined	As for rock cuttings	5	5	2	5
Masonry lining	As for masonry bridges	5	5	2	5
Concrete lining (including sprayed)	As for concrete bridges	8	5	2	5
Metallic lining	As for metallic bridges	8	5	2	5
Other structures					
Retaining/sea walls (masonry, concrete, steel sheet piling)	Stability (plus those for specific materials mentioned above)	5	5	5	5
Drainage / Culverts	Blockages, Crushing due to overloading. For culverts also same as for bridges	8	5	5	5
Track					
Ballasted plain line (rail, sleepers and ballast)	Wear; Also same as for bridges	8	5	2	5
Switches & crossings	Mechanical wear, Dynamic effects	5	8	5	5

Based on benchmarking of the DoW focus areas the following asset types are identified as the key focus areas:

- Cuttings,
- Metallic bridges,
- Tunnels with concrete and masonry linings
- Plain line (total track superstructure) and switches and crossings
- Retaining walls

For the above mentioned assets there is a high probability for knowledge increase within a 3 year period and useful validation data is available.

For all asset types listed in Table 2.2, and in particular the 5 mentioned above, degradation and associated performance characteristics and limit states are addressed within WP2. Furthermore, their temporal and spatial characteristics as well as sensitivity to load evolution and effects of climate change are addressed.

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.

Each asset type is addressed within Deliverable 4.1 of MAINLINE in individual chapters as listed below:

- Chapter 3, Cuttings
- Chapter 4, Metallic bridges
- Chapter 5, Tunnels with concrete and masonry linings
- Chapter 6, Plain track and Switches and Crossings
- Chapter 7, Retaining walls.

2.6 Monitoring and Examination Techniques

Monitoring and examination techniques/systems pertaining to the selected assets, as mentioned in the answers to the questionnaire carried out for the purposes of WP2 of MAINLINE, involve:

- *Embankments*: Visual examinations, cyclical examinations, special examinations, site investigations, inclinometer readings, strain gauges measurements, displacement meter readings, geodetic measurements.
- *Metallic bridges*: Visual examinations, detailed examinations, additional examination, monitoring, strain gauge measurements, hammer tapping, depth gauges, structural assessments, ultrasonic testing (uncommon), deformation measurements by extensometers, visual inspections supported occasionally by Non-Destructive Testing (NDT)/partially destructive testing, measurements by laser scanning, acoustic emission monitoring, bond tests, use of torque spanner, dye penetrant testing, emerging electromagnetic techniques.
- *Concrete and masonry lined tunnels*: Visual and detailed examinations, periodic inspections as per relevant manuals.
- *Plain line, switches and crossings*: regular inspections in relation to loading, periodic visual inspections, recording car, ultrasonic NDT, switch blade deflector.
- *Retaining walls*: Visual examinations, detailed examinations, geodetic surveys, fracture monitoring using “tell-tales”.

3. Cuttings

3.1 Introduction to the M&E techniques applicable

Embankments and cuttings form civil engineering structures known as earth structures, linear assets or earthworks are an important means of physically forming the trafficked surface of transport infrastructure. Infrastructure cuttings are excavations in existing ground, with side slopes and a trafficked surface. Infrastructure cuttings provide passage for rail, road and canal traffic across natural ground to maintain the required vertical alignment (Perry, Pedley and Brady 2003). Cuttings require maintenance, and the need to undertake it has become increasingly apparent as the materials within these structures age.

Landslides and rockfalls, like most natural hazards, cannot be prevented but the effects thereof can be mitigated using sound engineering judgement (Perry, Pedley and Brady 2003). It is impossible to avoid all areas with uneven topography and inevitably when rail are constructed in mountainous terrains, cuttings into natural slopes are required to obtain a suitable alignment.

Such disruptions of the naturally stable slopes can result in unstable conditions and if proper engineering measures are not taken to prevent slope failures such events can cause destruction of the infrastructure and even loss of life. Suitable engineering measures are available for even the most extreme slope conditions but since slopes consist of natural geological materials these conditions can change with time due to geomorphologic and hydrologic processes. If the conditions on which engineering designs were based change during the design life it is possible that the engineering measures will no longer be adequate and the hazard of a landslide or rockfall will then increase.

Monitoring of the cuttings is vital to prevent the occurrence of landslides and rockfalls. There are some important parameters to be considered during monitoring, which are listed below.

Physical parameters:

- Slope height
- Failure frequency
- Slope angle
- Launching features
- Ditch catchment

Climatic conditions:

- Annual precipitation
- Seepage/water
- Aspect

Geological conditions

- Undercuttings
- Durability/ weathering
- Inter bedded/ character
- Joint conditions
- Slope
- Vegetation
- Tension crack

Like in several other railway systems, regular visual examinations are among the most cost-effective means used to ensure the safety and long life of cuttings and their immediate environment. Visual inspection is a straightforward procedure that can be used by any properly trained person to make a reasonably accurate assessment of the cutting. The inspection involves careful examination of the surface and all parts of the cutting, including its adjacent environment.

Even though manual measurement techniques and visual inspections offer the cheapest form of monitoring, the limitations involved and the fact that they cannot carry specific monitoring tasks, have led to the development and application of a wide range of new M&E techniques practices.

3.2 Damage and deterioration mechanisms

The CIRIA Report C591 (Perry, Pedley and Brady 2003) describes the main mechanisms for soil cutting deterioration as the following:

- *Presence of water*
- *Weathering*
- *Long term creep*
- *Excavations*
- *Failure of supporting structures and services*
- *Erosion*
- *Mining subsidence*
- *Landslides*
- *Vegetation*

Whereas soil strength and stiffness are the governing factors for soil slope stability, rock slope stability is largely dependent on discontinuities within the rock mass, their orientation, and persistence and strength parameters. The following factors are listed in the CIRIA Report C591 as being the principal influences on loss of performance in rock cuttings (Perry, Pedley and Brady 2003):

- *Weathering*
- *Presence of discontinuities*
- *Construction method*
- *Climatic influences*
- *Vegetation*
- *Failure of slope support systems*

3.3 Visual examination of soil cuttings

In UK, Network Rail uses the Soil Slope Hazard Index (SSHI) to record the condition of its soil slopes in cuttings, embankments and natural slopes. This involves an operator using a hand-held electronic device to answer predefined questions about the observed condition of the slope including drainage, vegetation coverage and animal burrowing (which is found to have a marked impact on the stability of some slopes). The cuttings are divided into sections approximately 100 m (actually 110 yards) long for inspection purposes and the hand-held device uses GPS technology to record the location of any observed defects.

An algorithm is used to aggregate the individual recorded defects into an overall score for the 100 m section of cutting, but the underlying details of the defects are also retained and transferred to a central database.

3.3.1 Key advantages of the technique and notable issues

Advantages

- The system is quick and easy to use.
- The standardised format ensures consistency of reports.
- The database retains all the observations.

Disadvantages

- The process requires trained engineers to walk the length of the cuttings.
- The inspections are slow compared with vehicle-based observation of other asset types.

3.4 Visual examination of rock slopes

It is necessary to monitor the slopes for signs of deterioration to allow for efficient and economic maintenance of these assets. The most recent practice is considered to be the process of hazard assessments. This process involves an initial prioritisation of all rock slopes followed by more detailed assessments of those slopes with identified problems. While this approach has been used in the past, there are also shortcomings which are presented below.

Rock Slope Hazard Index (RSHI) was originally developed by Transport Research Laboratory (TRL) for the Scottish Office and has subsequently been used by Network Rail in UK. Principal authors include Matheson and MacMillan (MacMillan and Matheson 1997). The original intention of this system was to produce a database of the rock slopes in Scotland along with related hazard index values. The system has been used in Scotland, Wales and parts of the Highway Agency (HA) network. Modified versions of the system have also been adopted by Network Rail and Tarmac.

The RSHI system was designed for two main purposes:

- To populate a rock slope database
- To assign a 'hazard index' to each of the slopes.

3.4.1 Key advantages of the technique and notable issues

Advantages

- There is previous experience of use in the UK, particularly in Scotland and on the Network Rail infrastructure. Versions of the system are already in use by Network Rail (UK) which means the system is likely to be used in the future which should aid long-term viability.
- The system has already been in use, which means that a number of existing slopes have previously been rated, allowing the scores from new surveys to be compared with previous surveys.
- Relatively quick process to complete inspection (typically 20 to 30 minutes per slope).
- Contains mainly quantitative measures which should reduce subjectivity and increase consistency.

Disadvantages

- The RSHI system was originally developed for slopes in relatively hard igneous and metamorphic rocks in Scotland. As a result it does not deal well with weak rocks and interbedded sedimentary rocks found throughout most of England.
- The RSHI system is perceived to be a 'black-box' system, as the results can currently only be processed by TRL's approved suppliers. One possible way around this disadvantage is an agreement with TRL
- Presently inspectors need to attend a several days long course run by one of TRL's approved suppliers before they can use the RSHI system.

- The majority of the 50+ data items recorded in this process is ‘static’ in that they describe the geometry and geology of the cutting which will vary very little with time. Less than 10 items record ‘variable’ data such as the condition of the drainage and the dilation of fissures in the rock.
- The algorithm which creates the out-turn RSHI score from the defects is very complex and therefore the drivers for any given score are not obvious. This makes the RSHI score unusable as a condition modelling parameter.
- The algorithm includes the addition of some factors and the multiplication of others making the out-turn score highly volatile with values ranging from 0 to more than 10^9 and some aspects of the observations can dominate the score.

3.5 Inclinometers

Vertical inclinometers are instruments for measuring relative horizontal displacements affecting the shape of a guide casing embedded in the ground or structure. Inclinometer probes usually measure displacement in two perpendicular planes; therefore, displacement magnitudes and directions (vectors) can be calculated (Machan and Bennett 2008). Monitoring is made to verify performance and to identify whether unstable conditions are developing (Mikkelsen 1996) (Cornforth 1973).

Inclinometers are used to measure lateral ground movements in abutments, foundations, embankments, structures, and consolidation induced settlement in embankments and foundations. Measuring settlement by the vertical movement of inclinometer casings has now largely replaced the earlier method using Internal Vertical measurement devices. Thus, the same installation is now used to measure both settlement and lateral movement. (Machan and Bennett 2008).

Critical to landslide investigations is the determination of the depth and thickness of slide shear zones: the magnitude, rate, and direction of landslide movement. The inclinometer casing is installed in vertical boreholes. Usually, one to four borings, depending on the landslide size, are made along the central axis of the landslide to develop a model of the landslide for stability analyses. Inclinometers are the most commonly used instrument types when attempting to measure small levels of ground creep or shear zone movement, particularly between 0.1 and 0.5 in. (3 and 13 mm). Traversing-type inclinometer probes are usually used to determine the depth of landslide shear displacement. In-place Inclinometer (IPI) probes can be used, where the depth of the shear zone is already known, and the goal of the instrumentation is to determine the rate of movement. This method is typically combined with automated data acquisition. To improve the capability of identifying shear zone movements when the depth of the shear zone is not accurately known, a string of fixed IPI sensors can be installed.

Figure 3.1. Inclinometers measurements

Digital inclinometer probes have recently been introduced by several manufacturers with Micro Electro-mechanical systems (MEMS) accelerometers being positioned within the inclinometer probe. MEMS are designed to integrate small sensors on a single chip but this type of inclinometer needs further validation through usage and evaluations.

3.5.1 Output from the technique

Inclinometer casings are installed with slip joints or in compressible foundations providing the ability to measure settlement. Casings may be installed in drill holes with butt joints in abutments or completed embankments if no significant settlements are anticipated. The inclinometer installations are monitored at predetermined intervals which are used again in all future surveys of the casing. Inclinometer deflection devices consist of a servo accelerometer probe, cable, cable reel, and a digital readout unit. The data collected using a manual type readout unit are collected on a field data sheet and formatted to facilitate quick conversion to computer coding or entered onto tape if a tape unit recorder is used.

3.5.2 Key advantages of the technique and notable issues

The main advantages of this technique are considered to be:

- cost
- easy to use
- fast reading

Disadvantages of the method include:

- the battery drop in power,
- the probe may not function properly

3.6 Light Detection and Ranging (LiDAR)

LiDAR stands for light detection and ranging, which describes the method of determining three-dimensional data points by the application of a laser. It is a Remote Sensing technique, using either ground-based (Terrestrial Laser Scanning (TLS)) or airborne systems (Airborne Laser Scanning (ALS)); in some military contexts it is known as LaDAR (Laser Detection and Ranging). LiDAR systems use laser technology to pulse a laser and measure the time and phase pattern of the reflected light from the target object. This technology is rapidly developing, and gradually moving from being a research tool to almost an everyday piece of surveying equipment.

The aspects of degradation that can be monitored using this technique are:

- Washout
- Slip
- Scour
- Rockfall

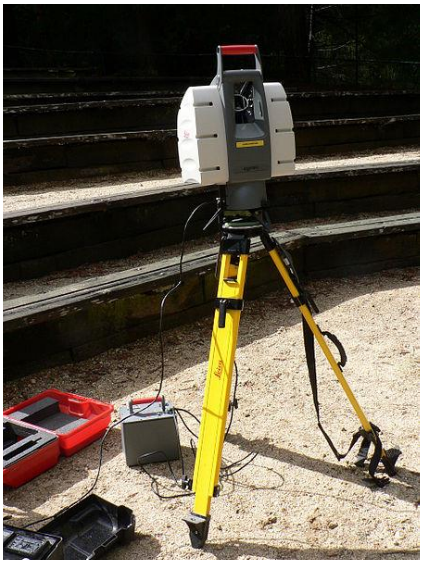

Figure 3.2. The LiDAR can aim its laser beam in a wide range: its head rotates horizontally while a mirror tilts vertically.

3.6.1 Output from the technique

Light Detection and Ranging (LiDAR) is used to measure distance from a target by measuring the time and phase change and pattern of the reflected laser light from the object. The distance measurements can be used to build a Digital Terrain Model (DTM). DTM's generation by LiDAR is used to identify areas that are likely to flood as well as classify the earthworks adjacent to the track by calculating gradients of the defences and adjoining slops. The current embankment inspection procedure also requires the manual determination of the angle and the height for each of the chain lengths (Roswell and Owen 2009). Network Rail has used LiDAR technology for the development of DTMs for embankments and cuttings on an experimental basis.

3.6.2 Key advantages of the technique and notable issues

Main advantages surround these points:

- High quality DTM's for the whole of the Rail Network
- Flood prediction
- Vegetation coverage
- Geometric calculations

While disadvantages include:

- Cost
- Many errors and factors creep into the reading of the scan due to movement

3.6.3 Current Status of the technique and expected developments

LiDAR is applied in several industries and occasions to generate DTMs for objects, e.g. topographic surfaces, road mapping, buildings, military target identification (Roswell and Owen 2009). The information is then used to host subsequent applications such as building layouts and volumes, establishment of flood prone areas, slope angles and heights and so forth.

The technology is also used for deformation monitoring, particularly in the open pit mining industry and for a movement of rock falls of mine benches, cliffs, dams and tunnel stability in underground mining (Rosser, et al. 2005, Alba, et al. 2006, Haneberg, et al. 2009)

The generation of DTMs with LiDAR systems can be very supportive to rail industry monitoring. The potential for monitoring of embankment movement, tunnel deformation, vegetation coverage and other applications can benefit the railway sector.

Future research needs to be carried out to try to merge two separate scans to provide an accurate estimation movement.

3.7 Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) technology can be readily installed to provide indication of rock falls; the aspects of degradation that can be monitored using this method are:

- Rock fall detection.
- Slip
- Scour

TDR technique can be used to identify rock strikes along chain fencing to detect rockfall activity. Furthermore by running a cable near the track side if rocks evaded the fence, the vibrational activity can be detected by this cable and indicate a possible serious threat.

3.7.1 Output from the technique

More specifically, Brillouin Optical Time-Domain Reflectometry (BOTDR) is a distance or strain measurement derived from the pulsing of light along a fibre optic cable (a single strand). It measures time and phase changes of the reflected light to determine the position of disturbance. The key advantages of this technique as well as noteworthy issues entailed are outlined below.

3.7.2 Key advantages of the technique and notable issues

Advantages:

- Rock fall detection
- Long measurement range over several tens of kilometres
- Deformation monitoring of cuttings
- Vibration analysis, train location, wheel flats, wash out development
- Blocked drains

Disadvantages:

- Cost
- Long-time required for the measurement

3.7.3 Current Status of the technique and expected developments

An early application of this technology was the detection of movement/vibration near the fibre optic cable. Vibration disturbances and cable movements cause reflection of Rayleigh waves. Time and phase change of the reflected waves can pinpoint the position of the vibration. The accuracy of the location of the vibration is determined by the system software used. Runs of up to 40km can be monitored using just one monitoring station (and possibly even greater with the use of repeaters).

This technology can also be used to monitor displacement/strain. Fibre optic cables are anchored at regular intervals along a tunnel wall or roof, and the system is regularly monitored. Analysis of the received back scatter can pinpoint the place and the degree of movement. This technique has been trialled in several mine roadways and rail tunnel applications as well as embankments (Shi, Sui and Zhang 2006, Mair 2008). As described above this technique of monitoring the displacement of the fibre optic cable has been applied to the monitoring of soil nails used to stabilise moving embankment (Amatyya, et al. 2008).The readings can be used to analyse the stress built up on each of the soil nails.

3.8 Interferometric methods

Interferometry is the method of comparing two separate Synthetic Aperture Radar (SAR) scans to determine the phase differences between the waves in the scan. Using this phase difference, changes in position are measured. The accuracy depends on the system being used; airborne, satellite, and ground. The interferometric analysis provides data on object displacement by comparing phase information, collected in different time periods, of reflected waves from the object, providing a measure of the displacement with an accuracy of less than 0.01mm.

The interferometric radar products provide a unique solution to the problem of monitoring small movements in ground or structures, allowing remote, long range, continuous real-time measurement of large areas. More specifically, Interferometric Synthetic Aperture Radar (INSAR) systems use an active microwave imaging sensor to capture images. INSAR monitors the rock fall aspect of slope degradation mainly used for imaging and topographical modelling.

A number of innovative instruments based on ground-based radar interferometry are currently available. The main applications of these instruments are in monitoring of slopes and structural movements as well as landslide monitoring in order to prevent accidents and interruptions of service.

3.8.1 Installation

- Installation time takes approximately an hour.
- Measurements are taken between the ground surface and the satellite.
- A couple of images are taken at one time; can only be used when the satellite is located above the target area.
- Cannot be used as a surveillance camera

3.8.2 Output from the technique

- Ground-based radar inteferometry is regularly used to monitor movement. The INSAR ground - commercial system consists of a mobile trailer unit, with a short wavelength multi pass dish unit that performs multiple scans and interferometry on the acquired readings. Any change in the scan readings results to a warning of impending rock fall or movement being given.
- The technique is mainly used in the mining industry.

3.8.3 Key advantages of the technique and notable issues

The biggest strength of this technique is the remote sensing capability at a distance of up to 1km for static and dynamic monitoring. In addition, these systems are deemed to have accuracies of 0.1mm at 850m or more distance, which indicates the great potential of this technique. In addition, readings are not prone to reflection of the vegetation which means that a true picture of the ground surface is provided. Other advantages may include real-time simultaneous mapping of deformations and fast installation and operation independently of weather conditions.

However, the accuracy of this technique is dependent upon the system's capabilities, the satellite's location and ground parameters. In various cases corner reflector installation may be required.

3.8.4 Current Status of the technique and expected developments

- The possibility of the system identifying rocks being placed on the tracks (vandalism)
- The use of long wave length radar system to see through vegetation offers great potential.

3.9 Resistivity measurements

Resistivity is a material property that describes how strong a material opposes the flow of an electrical current. In general terms, it is the normalised measure of electrical resistance. For the non-homogeneous porous material found in cuttings, the resistivity is influenced by several factors, such as porosity, saturation, pore fluid resistivity, matrix resistivity and pore space.

Field soil resistivity measurements are often conducted using Wenner four pin methods and a soil resistance meter. The Wenner method requires the use of four metal probes or electrodes, driven into the ground along a straight line. Soil resistivity is a simple function derived from the voltage drop between the centre pairs of pins, with current flowing between the two outside pairs. This technique monitors the presence of water and ground density and contributes to the process of defining the geological aspect of degradation.

3.9.1 Installation

The installation time required for the Resistivity measurement is approximately a couple of hours, although, this depends on the surface being tested.

3.9.2 Output from the technique

- Graph with pins spacing against the soil resistivity.
- Soil resistivity generally decreases with increasing water content and the concentration of ionic species.

3.9.3 Key advantages of the technique and notable issues

- The method is used in many geotechnical and geological related applications to help identify soil or rock layers.
- It can support the prediction of rock fall locations and locations where previous instability has occurred.

On the other hand, it needs to be noted that resistivity measurements require regular site visits and ensuring that cables and electrodes are kept in location.

3.9.4 Current Status of the technique and expected developments

- Resistivity Measurement is used to indicate the sub surface strata. The technique can be used and incorporated with other forms of geophysical assessment (such as conductivity, microgravity) to build up a 3D model of the subsurface conditions.
- Furthermore, wireless technologies could remove the necessity of regular site visits, with cables and electrodes being buried to avoid vandalism and animal tampering.
- Variable success is achieved when on/near the permanent way due to the interference of the metallic track and typically large number of buried/surface services.

3.10 Global Positioning System (GPS)

Global Positioning System (GPS) is the method of using a land based unit to receive time stamped signals from satellites orbiting the earth. From these signals the time of flight from the corresponding satellite can be determined, which in turn can be used via geometric triangulation to define the exact position of the unit on the earth surface. GPS monitors the movement aspect of slope degradation.

3.10.1 Installation

The installation of GPS is simple and takes approximately an hour. However, this depends on the signal strength and the availability or the need to install a receiver.

3.10.2 Output from the technique

- The output can be in the form of map or image of the earth surface
- GPS is a reliable method of providing a surface image of the cutting. This can assist in monitoring changes in surface and sudden landslips.

3.10.3 Key advantages of the technique and notable issues

GPS coordinates can be linked to databases to record the engineer’s line reference coordinates and calculate the mileage. Handheld GPS are used to record field data tied to specific position/coordinates on the system.

Even though GPS technology has gone through a remarkable progress during the last decade, limitations linked to the coverage due to the geometry of earthworks are still a major weakness of this technique. Furthermore, reliable positional accuracy requires signals to be received from a number of satellites. This however is not always possible due to geometries or obstructions (e.g. it cannot be used in tunnels).

3.10.4 Current Status of the technique and expected developments

- Even though GPS can provide accurate logging systems for earthworks movement, concerns about satellite coverage due to the geometry of earthworks may prevent this technology from being applied in many occasions.
- Leica have recently developed two units, the GMX 901(one frequency receiver) and GMX902 (two frequency receiver), which have been specifically designed for the monitoring of dams, bridges and buildings.

3.11 Other Techniques used

- **Video and Image analysis**
  Video and Image analysis is well known and widely applied in many occasions. Objects, for example, can be recognised automatically in varied orientations and rules can be applied to determine whether the object meets them. This technology is widely used in manufacturing for potting defects, sorting and so forth. Video cameras could be used as an affordable way of monitoring cuttings or embankments for large scale movements and rock falls.

- **Acoustic monitoring**
  Acoustic monitoring is a developing technology in seismic analysis used to determine rock boundaries and hence oil traps below the earth surface. It can be used to monitor large earth movements, rock falls and washouts.

- **Micro Electro Mechanical Systems (MEMS)**
  This is a developing technology commercially driven by Geotechnical Companies. MEMS accelerometers are basically new inclinometers allowing stacking of in situ inclinometers in bore hole. They can also measure soil temperature as well as moisture.

3.12 Summary Table

Table 3.1 Monitoring and Examination (M&E) techniques and Degradation Mechanisms (DM)[2] affecting cuttings

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

Section 3. Cuttings

DM / M&E	Water presence	Washout	Long term creep	Scour	Failure of supporting structures	Erosion	Landslides and rockfalls	Vegetation
Visual Inspection	✓	✓	✓	✓	✓	✓	✓	✓
Inclinometers			✓		✓		✓	
Laser Scanning (e.g. LiDAR)	✓			✓	✓		✓	✓
Time Domain Reflectometry	✓						✓	
GPS-based methods			✓		✓		✓	
Interferometry							✓	
Acoustic Monitoring		✓			✓	✓	✓	
Video/image Analysis		✓		✓	✓		✓	✓

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

4. Metallic Bridges

4.1 Background

The inspection of metallic bridges has been the focus of several projects to date. Railways 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 (Bell 2004), 13 of 17 railway owners perform annual inspections. The frequency depends on the level of inspection carried out and the asset owner. The frequency of thorough inspection may differ between 2 and 10-12 years depending on the country. Other levels of inspection could be from once in 6 months to once in 8 years.

A guideline for inspection and condition assessment for railway bridges based on the technical research carried out within the project Sustainable Bridges was developed. Based on the state of the art, this FP6 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 in Sustainable Bridges Project surrounded the fact that in most of the 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 there is also an Appendix with a detailed tool-box of non-destructive testing. UIC recommendations for bridge maintenance procedures are given in UIC 778-4R (2009).

Furthermore, valuable lessons were learnt from the FP6 Project Sustainable Bridges in regards to monitoring of railway bridges. A report from the project (Feltrin 2007) provides valuable guidelines to monitor tasks carried out on railway bridges. It 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 is 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.,* for the Sustainable Bridges project (Sedlacek, Hechler and Lösche 2007).

Condition assessment of bridges comprises two main phases: (i) “in situ” inspection of the structure and (ii) evaluation of condition (Casas 2004). During the first phase, all the 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 in a major inspection. The main disadvantage of standard inspection is that a deterioration process can start just after an inspection has been carried out. Advanced inspection, using advanced sensors allows a continuous inspection for the whole service life of the structure. Therefore, the continuous condition assessment of a bridge is possible (Casas and Cruz 2003).

4.2 Introduction to the M&E techniques applicable

Testing and monitoring of the actual condition of a structure and its true behaviour are a necessity for an enhanced assessment of a bridge. A range of monitoring and examination practices have been applied to reduce uncertainties associated with the bridge assessment, such as cross section properties, material properties and load (Leander, Andersson and Karoumi 2010).

The main method used in bridge inspection is the external visual inspection. However, in order to meet the demands set for railway bridges, a more refined inspection needs to be carried out to assess not only the external but also the internal condition. The physical principle and its applicability to the investigated material as well as the choice of an appropriate sensor determine the applicability and accuracy of Non-destructive testing methods for detection of defects.

The bridge stock needs to be maintained in a safe and serviceable condition. The performance of a bridge, as of any structure, shall be monitored during and after construction; the bridge shall also be adequately maintained as mentioned in Eurocode EN1997-1 s4.1(1)P. Serviceability, as set out in BA 57/01 (The Stationery Office 2007) and Eurocode 7 is typically defined as “the ability of structures to fulfil, without restriction, all the needs which they are designed to satisfy”. The verification of serviceability is expressed in Eurocode 7 by the use of limiting design value of the effect of actions (e.g. displacement, distortion). Eurocode 7 has been widely adopted across most of European countries. Serviceability limit states are defined, according to EN1990 s1.5.2.14, as “states that correspond to conditions beyond which specified service requirements for a structure or structural member are no longer met”. Serviceability is therefore the main drive behind any inspection regime for a bridge. There are two main classes which inspections may be considered as falling into (Tilly, et al. 2008): (i) inspection for condition assessment and (ii) inspection for strength assessment. However, examination is still the most common approach for the condition assessment of metallic bridges. Inspections for condition are usually limited to the visual observation and monitoring of defects, which is sometimes supported by on-site testing. Inspection should provide data on bridge geometry and dimensions, as well as evidence of any visible deterioration.

Metallic bridges are generally robust and typically show evidence of distress in advance of structural failure provided it is known where to look at. The routine process of periodic visual inspection and more detailed inspections on a less frequent basis, supported by additional investigations, is a potentially adequate strategy to ensure fitness for continued service (The Stationery Office 2007). There are many tests that should be carried out to ensure the serviceability of the bridge structure such as: material identification, yield strength, ductility, compressive strength, notch toughness, fatigue resistance, weld quality, weldability, and state of stress (dead load and residual). In addition to visual assessment, many methods are used to monitor and test steel and locate defects. Such techniques are known as non-destructive testing (NDT) and they do not actually damage the material when applied.

4.3 Damage and deterioration mechanisms

Fatigue/fracture plays a major role in undermining bridge resistance and is a dominant factor in causing damage or failure short of total collapse as underlined in MAINLINE’s D2.1 report. It is also worth noting that scour is a very important contributor to bridge collapse. Buckling is the other factor that plays a role, albeit at a smaller scale compared to fatigue. Deterioration in metallic bridges occurs as a result of environmental factors (temperature, precipitation, humidity, wind) reacting with the bridge materials, thus leading to a reduction in geometric or material properties. Corrosion is the most obvious manifestation of the influence of environmental factors on metallic bridges. The water presence as well as the existence of discontinuities needs to be considered thoroughly in order to assess the condition and the deterioration mechanisms of metallic bridges.

In order to address the issues mentioned above, a number of monitoring and examination techniques have been adopted, with the most common ones being the visual examinations, detailed examinations, monitoring, hammer tapping, strain gauge measurements, laser scanning, ultrasonic testing and other methods described in the following subsections.

4.4 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. Routine inspections serve to document sufficient field observations/measurements and load ratings needed to:

- Determine the physical and functional condition of the structure.
- Identify changes from the previously recorded conditions.
- Determine the need for establishing or revising a weight restriction on the bridge.
- Determine improvement and maintenance needs.
- Ensure that the structure continues to satisfy present service and safety requirements.
- Identify and list existing problems.
- Identify and list concerns of future conditions.
- Identify any inventory changes from the previous inspection

4.4.1 Network Rail's *'Bridge Condition Scoring Index'*

In the UK, the observations of bridges owned by Network Rail are known as 'examinations'. These are generally made at two levels: a brief, annual 'visual examination' and the six-yearly 'detailed examination'. There are other categories of examinations including: 'underwater', and 'bridge-strike' for example.

In the detailed examination all parts of the structure are accessed nominally *"within touching distance"* and representative minor elements of the structure are graded using the Bridge Condition Marking Index (BCMI). This allows the 'severity and extent' of defects to be recorded by assigning a letter-number code as shown in Table 4.***1*** below.

Table 4.1 Severity and extent ratings for metal (Network Rail)

Severity rating	Definition
A	No visible defects to metal
B	Corrosion/loss of section< 1mm deep
C	Corrosion/loss of section 1mm up to 5mm deep
D	Corrosion/loss of section > 5mm up to 10mm deep
E	Corrosion/loss of section > 10mm but not through section
F	Corrosion/loss of section to full thickness of section
G	**Choose most extensive from:** Tears, fracture, cracked welds Buckling, permanent distortion or displacement

Severity rating G relates to a condition that would normally merit immediate notification to Network Rail if known to be a new defect.

Extent	Definition	
1	No visible defects	
2	Localised defect due to local circumstances (such as isolated damage caused by a single bridge strike or isolated water leakage)	
3	Percentage of surface of the element occupied by defect	< 5%
4		5% up to 10%
5		>10% up to 50%
6		> 50%

Table 2C.14: Severity and extent ratings for metal

The scores for all the minor elements of a bridge are aggregated by a standard algorithm to give a condition score, between 0 and 100, for the whole structure with the score for the groups of minor elements also recorded. This quantitative score reflects the condition of the visible parts of a structure determined by detailed visual examination. It is not a safety index and does not reflect structural adequacy.

In summary, the BCMI is derived as a result of non-judgmental recording of defects by the bridge examiners providing a consistent and quantitative indication of the visible condition of the structure.

4.4.2 Key advantages of the technique and notable issues

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 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. However the difficulty still lies within the inspection of the structure inside the material.

Other advantages are: low cost, immediate data for viewing and analysis, little skill required from the operator. Disadvantages: uncontrolled offset affects the field of view and the crack’s width and length.

4.4.3 Current Status of the technique and expected developments

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.

The BCMI examination method was originally paper-based with word-processed formats for each inspection report. This is now moving to electronic data collection but still relying on the visual observations of trained examiners.

With about 40,000 bridge decks examined by Network Rail on a six-year cycle, the BCMI database now contains a very large body of actual bridge condition observations. This must constitute one of Europe’s largest repositories of bridge condition data and has been used to model probable condition variation over time.

4.5 Optical Fibre Monitoring

Optical fibre monitoring has been used for the monitoring of a wide range of bridges in terms of material and structural form, including metallic bridges. A variety of optical fibre sensors also exist, including discrete point sensors (Fabry-Perot and Fibre Bragg Grating) and distributed sensors (e.g. Brillouin). 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. Recent examples of applications using optical fibre monitoring systems in the UK include the Mount Pleasant Bridge (Canning 2008) as well as applications on steel bridges (Glisic, Posenato and Inaudi 2007) and (Inaudi 2009).

The durability of optical fibre monitoring systems, when adequately installed and protected, is of the order of decades and hence particularly suitable for medium-to-long term monitoring and management of structures. An additional benefit of optical fibre monitoring systems is that once installed, they can provide improved information for the assessment of bridges in terms of structural behaviour and measured load levels (rather than those assumed in design). 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. Similarly, limited research has been undertaken on optical fibre monitoring of the track (Kluth, et al. 2006).

Figure 4.1. Optical fibre monitoring

4.5.1 Installation

The installation of an optical fibre monitoring system would typically take place on an existing installed structure, and hence can require extensive safety and access arrangements. However, the sensors and associated equipment are relatively light (other than the data acquisition equipment which is usually located at more easily accessible locations such as bridge abutments). Installation typically requires at least a single day often with a commissioning period (e.g. controlled load test) to confirm adequate operation.

4.5.2 Output

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 that can be produced 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.

Continuous monitoring over weeks, months, and years can also be used to monitor long-term degradation. However, accurate specification of the monitoring system is then required to avoid superfluous amount of data.

4.5.3 Key Advantages and Issues

The main advantages of optical fibre monitoring are:

- Lightweight, durable, inert to most chemical hazards and sensitive to several parameters.
- Flexible - can access into previously inaccessible and harsh environments.
- System is immune to many kinds of external noise due to the electrical isolation of the sensors (link between the sensor and the detector is dielectric, containing only glass fibre). Therefore significantly improved reliability and sensitivity of measurements such as in high voltage environments.

- Fitting a structure with a comprehensive sensor network capable of continuously gathering information on all relevant structural parameters offers a better way of assessing its real behaviour.
- Monitoring of hidden critical structural elements.
- Possible to develop time-lapse information rather than just seeing degradations that are relative to the original state or the state at the previous inspection.
- Performance data can be used in finite element analysis models of the bridge to provide a more realistic assessment.

The main issues/limitations are:

- Continuous monitoring over long periods of time generates unmanageable and often unnecessary amount of data. Thus advanced algorithms must be developed for intelligent processing and data reduction such that predetermined parameters (e.g. peak strains) are stored.
- Although durability is good, sensor redundancy should still be considered due to the very long typical service life of a bridge.

4.6 Dye penetration testing

Dye penetrants are used to detect defects which are opened to the surface of a homogeneous material. The most common application is checking for cracks in welds (McCrea, Chamberlain and Navon 2002).

Penetrant processes are divided into two basic groups, visible and fluorescent. Visible penetrants are those that contain a very bright dye, usually red, which, after developing, is viewed under bright white light. Fluorescent penetrants contain a dye, which fluoresces under filtered ultra-violet ray (black light).

Both categories are sub-divided into three groups, depending on the penetrant removal method: (i) water washable—penetrant is soluble in water achieved by adding emulsifiers during manufacturing, (ii) post-emulsified—penetrant is not soluble in water but it is made so by the addition of an emulsifier as part of the cleaning process, and (iii) solvent removable— penetrant can only be removed using a suitable solvent. A key part of the process is the developer, whose function is to assist development of the penetrant indications, in order to make them more readily visible.

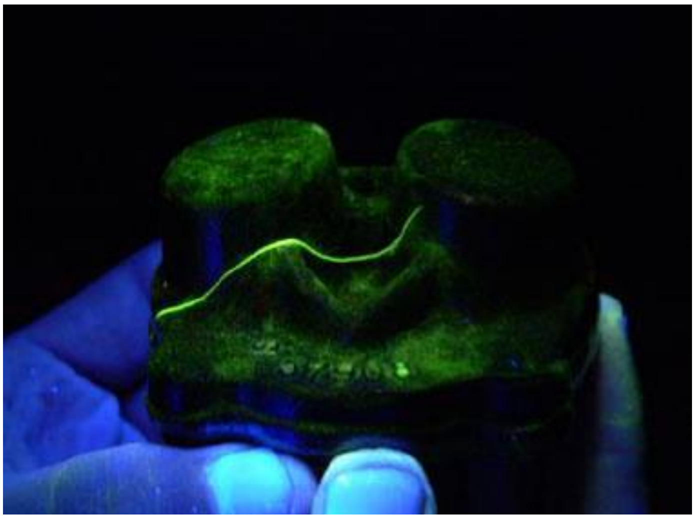

Figure 4.2. Liquid penetrant used to detect crack in parts

4.6.1 Output from the technique

The process of crack detection using penetrants consists of three stages, which need different equipment and application, if it is to be automated:

- pre-cleaning
- application of the penetrant and developer
- observation

The application of the process starts with the pre-cleaning of the parts to receive the penetrant. It is vital that the surface is clean particularly when dealing with in situ materials, such as bridge stanchions. The penetrant is then applied in sufficient quantity to thoroughly wet the area under inspection and prevent drying. The ideal temperature for testing is between 15 and 40 °C, as higher temperatures lead to evaporation of the penetrant's lighter fractions, while lower temperatures slow down the whole process. Allowed penetration time is up to 20 min, and after a specified time, the excess must be removed from the surface. The process must be quick and efficient to ensure a clear background can allow efficient inspection. The penetrant can then be dried in warm air (80 °C, when possible), to make way for the developer. The developer forms a thin absorbent layer, of uniform appearance, without contamination or discoloration. Then, the inspection can take place under the appropriate lighting conditions. After the application of the developer, time should be allowed for indications to develop in the cracks.

4.6.2 Key advantages of the technique and notable issues

Advantages:

- Simplicity of all stages
- no sophisticated equipment required
- low cost

Disadvantages:

- Three stage process involving a variety of equipment and activities-difficult to automate
- The inspection process relies completely upon the experience and observing skills of the tester, combined with the visual acuity and intelligence;
- The method requires particular conditions for observation—suitable type of lighting, weather or enclosure dependent;
- Surface cleanliness to avoid restricting the capillary action of the developer.

4.7 Ultrasonic Testing (UT)

Ultrasonic testing equipment has been extensively used by the rail industry. 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. A pulse generator is used to generate an electric wave, which is amplified and converted to mechanical vibrations by a piezo-electric crystal probe and transmitted through the material under test. The reflected signal is then picked up by the probe, converted back to an electric wave and registered as an echo (Dawson, Clough and Silk 1991). If a void lies directly in the pulse path, the instrument indicates the time taken by the pulse to circumvent the void by the quickest route. It is thus possible to detect large voids when a grid of pulse velocity measurements is made over a region, in which voids are located.

4.7.1 Output from the technique

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.

4.7.2 Key advantages of the technique and notable issues

Advantages:

- 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.

Disadvantages:

- 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 expensive when used on large structures.

4.8 Radiographic testing (RT)

There are three basic methods available under this process (McCrea, Chamberlain and Navon 2002):

- X-radiography—electromagnetic radiation of very short wavelength, emitted by electrons, the velocity of which is suddenly reduced,
- Gamma radiography— electromagnetic radiation of very short wavelength (shorter than X-rays) emitted by the nuclei of decaying radioactive substances and
- Neutron radiography—neutrons (uncharged atomic particles, similar in mass to protons) that when beamed through a component become differently attenuated and may be used to produce radiographs.

4.8.1 Output from the technique

These types of radiation are capable of acting on photographic plates and ionising gases. Rays can be reflected, refracted, and attenuated, as well as produce fluorescence or secondary beta radiation. The principle of this method is that X-rays or Gamma rays passing through an object (up to 25 mm thick) are absorbed differently by flaws or discontinuities. Cracks, voids and inclusions can be viewed as shadows imaged on film. The method is used to detect and locate subsurface discontinuities within the material (cracks, porosity, voids, and separation) and dimensional variations.

4.8.2 Key advantages of the technique and notable issues

Advantages:

- Portability of the equipment and its purposeful design for field use (Gamma radiography only);
- film radiography yields a permanent record of results and is compatible to computer analysing techniques;
- Large areas can be covered with one inspection.

Disadvantages:

- Access to opposite sides is required and monitoring of scattered radiation is necessary;
- density or thickness variations of 1%-2% only can be sensed;

- in X-radiography voltage, exposure time and focal spot size are critical;
- Gamma radiography requires special mechanisms for storage and extension of source;
- sensitivity decreases with material thickness (Gamma rays being less sensitive to material thickness compared to X-rays and Neutron rays);
- extensive expertise is needed to implement tests and interpret results;
- Gamma source is uncontrollable and decays in time, so testing duration has to be monitored;
- racks must be parallel to beam;
- source and film geometry and alignment are critical;
- high risk activity, extensive personnel training needed;
- need to clear the whole site, while operating the equipment;
- most items of equipment are produced as stand-alone, with no inter-faces provided to other equipment;
- equipment is mostly very bulky and heavy.

4.9 Acoustic emission

Acoustic emission testing tools can detect and locate incipient and active cracks in stressed structures as well as crack propagation, locating the tip of known cracks, remote, long-term and underwater monitoring (McCrea, Chamberlain and Navon 2002). Example components include welded and riveted connections if proper filtering of fretting noises can be achieved, welded connections, sockets, web and flanges, pin and hanger assemblies.

4.9.1 Output from the technique

Description and specification of energy released at deformation or crack sites using this method is sensed by the piezoelectric transducer. This information is processed and recorded by digital counters, computer filtering, magnetic storage, graphic tape recorder and meter indication. Interpretation of the results is carried out on the basis of comparative or differential analysis of emission count rate, amplitude and frequency spectrum and differences in signal arrival times.

4.9.2 Key advantages of the technique and notable issues

Advantages:

- Highly portable; inexpensive transducers permanently attached to bridge structures offer the potential for long term and remote monitoring;
- Monitors response to applied loads;
- Capable of locating the source of failure;
- Internal source of elastic waves;
- Cracks less than 0.003 mm in length can be detected.

Disadvantages

- Acoustic coupling requires clean smooth flat surface and the removal of thick coatings;
- Transducer arrangement is critical to the results;
- ‘Noise filtering’ waveguides are required in high noise areas;
- Extensive expertise is required to plan, test, and interpret results;
- Lack of ability to intensify the elastic wave field;
- Measurements cannot be repeated;
- Signals are transient and random in time (standard noise reduction methods cannot be used);
- Several simultaneous measurements are required for verification and orientation and determination.

4.10 Magnetic Particle Inspection

Magnetic particle inspection (MPI) is a process used to detect surface and slightly subsurface discontinuities in ferroelectric materials. A magnetic flux is created in the substrate and metallic dust in suspension sprayed onto the area of interest. The suspension is then drawn towards the flux leakage at a discontinuity (i.e. a crack) and provides a visual indicator.

4.10.1 Installation

The general location of the installation has to be first identified by a combination of visual examination and other techniques such as acoustic emission monitoring. Prior to application of the suspension, cleaning of the area is required to provide a dry surface and remove debris.

Creation of the magnetic flux could be problematic if the area of interest is in close proximity to other electrical services associated with the railway such as overhead electrification, signalling and telecommunication cables. Even though the cost of this method is relatively low, it is dependent upon the number of locations to be tested, and access and safety arrangements.

4.10.2 Output

The output of this method is a visual indication of the severity and extent of a crack, usually shown by photographs with a scale. For the measurement of crack growth over time by a series of inspections, a scaled photograph is particularly useful along with a general photograph and sketch showing the overall location on the bridge.

4.10.3 Key Advantages and Issues

The main advantages of magnetic particle inspection are:

- Speed and simplicity of the test.
- Low cost.
- Smaller cracks that can be imperceptible to the naked eye (particularly when unloaded and hence closed) can be identified at an early stage.
- Standards are available for this method.

The main issues are:

- Supply of electricity usually required.
- Presence of thick paint layer can affect results.
- Can only detect surface or near-surface flaws.
- Interpretation is not always simple and can require advanced skills and experience.

4.11 Monitoring using Strain Gauges

The strain gauge has been in use for many years and is the fundamental sensing element for many types of sensors, with the most common type being the electrical resistance strain gauge, while applications of vibrating wire strain gauges are also available. Strain gauges are one of the most precise systems to get local strains needed in the fatigue assessment of fatigue critical details. Gauges are in fact the only system recommended to evaluate dynamic effects on the stress distribution of the structure strain. Preliminary assessment and previous experience, resulting from full-scale testing and fatigue failure analysis of already detected damages shall be analysed. In addition, the choice of cross sections to be assessed is based on this analysis (Sedlacek, Kammel, et al. 2007).

While there are several methods of measuring strain, the most common is using a strain gauge, a device whose electrical resistance varies in proportion to the amount of strain in the device. The most widely used gauge is the bonded metallic strain gauge. This gauge consists of a very fine wire or, more commonly, metallic foil arranged in a grid pattern. The grid pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction. The cross sectional area of the grid is minimized to reduce the effect of shear strain and Poisson Strain. The grid is bonded to a thin backing, called the carrier, which is attached directly to the test specimen. Therefore, the strain experienced by the test specimen is transferred directly to the strain gauge, which responds with a linear change in electrical resistance. Electrical resistance strain gauges operate on the principle that as the foil is subjected to stress, the resistance of the foil changes in a defined way.

A fundamental parameter of the strain gauge is its sensitivity to strain, expressed quantitatively as the Gauge Factor (GF). Gauge factor is defined as the ratio of fractional change in electrical resistance (R) to the fractional change in length (strain) (L), as shown in the equation below (Sedlacek, Kammel, et al. 2007):

$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon}$$

Strain gauge measurement involves sensing extremely small changes in resistance. Therefore, appropriate selection and use of the bridge, signal conditioning, wiring, and data acquisition components are necessary for reliable measurements.

Ideally, the resistance of the strain gauge should change only in response to applied strain. However, strain gauge material, as well as the specimen material to which the gauge is applied, also responds to changes in temperature. By processing the gauge material (at manufacturing level) and using two strain gauges in the bridge, the effect of temperature can be nevertheless minimized.

Strain gauges are available commercially with nominal resistance values from 30 to 3000 Ω, with 120, 350, and 1000 Ω being the most common values.

4.12 Fatigue monitoring

4.12.1 Fatigue fuse

The fatigue failures are usually initiated at weld joints, bolt or rivet holes and at sharp changes in section. The fatigue crack can be detected visually or using one of the techniques listed below:

- Magnetic particle testing
- Dye penetrant testing
- Eddy current testing
- Ultrasonic testing

Once the crack is detected it is necessary to know how rapidly it is growing, so that a decision can be made on whether immediate action is required or not. The fatigue fuse is attached to the component to be monitored and needs to be sufficiently thin and flexible so that it does not affect its structural behaviour. The fuse contains a sharp edged slot which acts as a crack initiator. Once attached, cyclic loading of the component initiates cracking at the tips of the slop. As these cracks grow they fracture the conducting strips printed on the surface of the fuse. Measuring the rate at which the crack grows, along with analysis of the structure, allow to predict the future behaviour of the crack.

4.12.2 Fatigue sensing

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 CrackFirst system was developed through the collaboration of TWI Ltd., FMB, Micro Circuit Engineering Ltd., UMIST and Caterpillar Peterlee (A division of Caterpillar (UK) Limited) in a project funded by the DTI's LINKSensor and Sensor Systems for Industrial Applications Programme. This system is ideal for the bridge monitoring in cases where fatigue of steel welded structures present a structural performance concern.

At the heart of the CrackFirst system is a fatigue sensor, which, when installed on a welded steel structure, indicates the portion of the design life that has been consumed and that enables engineers to estimate its remaining life. The sensors, when suitably located, are subjected to the same loading history as the structure and provide an accurate record of cumulative weld fatigue damage. The sensor comprises a steel coupon attached adjacent to a critical joint. Stress cycles cause fatigue crack growth in the coupon that is detected electrically. For a typical fillet welded joint the sensor output provides the proportion of the fatigue design life that has been used (Dore and Tubby, 2011).

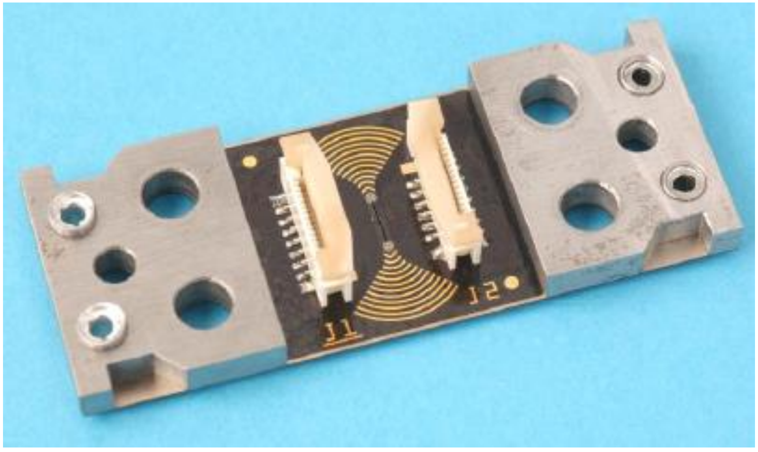

Figure 4.3. CrackFirst sensor (copyright TWI)

The principal advantage of the sensor is that it provides information on the rate at which the fatigue design life is being expended and it can, therefore, be used to set inspection intervals according to usage rather than elapsed time. On completion of its development, the CrackFirst sensor system was licensed to Strainstall UK Ltd who have since further developed the sensor electronics and monitoring software making the system commercially available (Dore and Tubby, 2011).

4.13 Laser Scanning

Laser scanning and in particular the method of terrestrial laser scanning is one of the most effective spatial data collecting methods and can provide high accuracy and fast implementation in large measurements. Terrestrial laser scanning, or LiDAR, is based on the fact that light travels in a straight line at a known speed. The technique is a non-contact method for taking physical surface measurements, allowing visualizations of scanned surfaces in a digital 3D environment.

Some traditional measurements with extensometer are being replaced by laser measurement due to the high precision in large dimensions (from 1 to 200m), although the technology is limited by climate conditions (e.g. dust environment). More information about this technique can be found in section 3.6 as well as in subsequent sections (section 5.7 and section 7.5) of this report.

4.14 Summary Table

Table 4.2 Monitoring and Examination (M&E) techniques and Degradation Mechanisms (DM) affecting metallic bridges[3]

MAINLINE Project WP4: Monitoring and Examination Techniques D4.1: Report on assessment of current monitoring and examination practices in relation to the degradation				Section 4. Metallic Bridges			
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	✓	✓	✓				
Dye Penetration Testing		✓	✓	✓			
Fatigue Monitoring			✓				
Acoustic Emission	✓	✓	✓				
Magnetic Particle Inspection		✓	✓				
Laser Scanning		✓	✓	✓	✓		✓
Monitoring using Strain Gauges			✓		✓		✓

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

5. Tunnels with concrete and masonry linings

5.1 Introduction to the M&E techniques applicable

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)

Monitoring can be achieved by carrying out discrete repeated observations and measurements of phenomena at suitable times, or gathering such data using a more continuous automated approach, such as by installing suitable dedicated monitoring instrumentation and logging devices.

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 is the most cost-efficient form of monitoring and is generally very effective (McKibbins, Elmer and Roberts 2009).

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 is now a viable alternative to applied instrumentation in certain circumstances. The applicable inspection techniques for tunnels with concrete and masonry linings are described in the following sections.

5.2 Damage and deterioration mechanisms

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 interaction between parameters that undergo change over time, where the rates of change may vary.

A brief introduction to the key mechanisms affecting lined tunnels is provided in this section; the damage and deterioration mechanisms are more thoroughly described in Task 2.1 of MAINLINE and are the focus of the Project’s D2.1 report. The CIRIA guide C671 on the inspection, assessment and maintenance of tunnels provides detailed information on the main deterioration mechanisms for lined tunnels (McKibbins, Elmer and Roberts 2009).

Main structural deterioration mechanisms:

- Geotechnically driven faults
- Repair and enhancement activities
- Operational loading
- Water ingress
- Vegetation

Masonry lining

The majority of masonry deterioration mechanisms are related to the presence of water and chemical contaminants. A key mechanism that is particularly relevant to tunnel structures is sulphate attack as sulphates are often present in the groundwater, soil and rock that surround tunnel linings. If left untreated masonry deterioration can result in structural instability and failure, for example the fall of bricks or stones onto the track or passing trains.

Concrete lining

In the case of tunnels with concrete lining, problems may include cracking and spalling, reinforcement corrosion, sulphate and acid attack and freeze thaw damage. Similar to the case of masonry linings, a particularly relevant mechanism for concrete tunnel structures is sulphate attack as sulphates are often present in the surrounding ground and groundwater. Concrete deterioration may lead to a loss of strength, for example by a reduction in the effective section thickness or loss of reinforcement, and thus has the potential to cause structural failure.

5.3 Visual Inspection

It is necessary to continually update knowledge on asset condition and performance of tunnels, 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. 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. In order to comprehend condition and performance related problems and take action when necessary, inspections need to provide detailed, objective and accurate information (McKibbins, Elmer and Roberts 2009).

5.4 Ultrasonic Inspection

The use of ultrasound is a commonly used technique for the detection of defects in tunnels. The location and size of defect such as porosity, voids and cracks can be detected by moving the ultrasonic probe across the surface of the structure and observing a trace on a monitor. More about the technique is described in section 4.7.

5.5 Eddy current

Eddy-current testing uses electromagnetic induction to detect flaws in conductive materials (Peters and Day 2003). A circular coil carrying current is placed in proximity to the component to be inspected. The alternating current in the coil generates changing magnetic field which interacts with the component and generates Eddy currents. Variations in the phase and magnitude of these currents are monitored either using a second 'search' coil, or by measuring changes to the current flowing in the primary 'excitation' coil. The presence of any flaw causes a change in Eddy current and a consequent change in the phase and amplitude of the measured current.

Visual inspections are often used to monitor the condition of permanently installed monitoring equipment or monitoring aids, i.e.:

- monitoring of fractures using dated mortar tabs which are monitored to ensure that the tabs do not fracture;
- surveying of previously installed survey points within the tunnel to monitor distortion and overall movement of the tunnel.

5.5.1 Output from the technique

Eddy current testing can be used for:

- Crack detection
- Material thickness measurements
- Coating thickness measurements
- Conductivity measurements for:
    - Material identification
    - Heat damage detection
    - Case depth determination
    - Heat treatment monitoring

5.5.2 Key advantages of the technique and notable issues

Advantages:

- Provides a faster scanning speed than the conventional ultrasonic testing (UT)
- Requires no liquid coolant
- Can detect very small cracks in or near surface of material
- Physically complex geometries can be investigated
- Can be used to make electrical conductivity and coating thickness measurements
- Portable devices
- Immediate feedback

Some of the limitations of Eddy current inspection include:

- Only conductive materials can be inspected
- Surface must be accessible to the probe
- Skill and training required is more extensive than in other techniques
- Surface finish and roughness may interfere
- Reference standards needed for setup
- Depth of penetration is limited
- Flaws such as delaminations that lie parallel to the probe coil winding and probe scan direction are undetectable.

5.6 Thermal Imaging

The use of infrared cameras to examine building structures is a well-known approach within the civil engineering industry. This technique is used to detect differences in surface temperature profile arising from defects within the structure. 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). The principle of the technique is based on the fact that good thermal conduction will exist in structures without voids or air gaps and they therefore appear relatively cold on the camera. Where there are voids or air gaps heat transfer from the surface is less efficient and thus the surface therefore appears hotter.

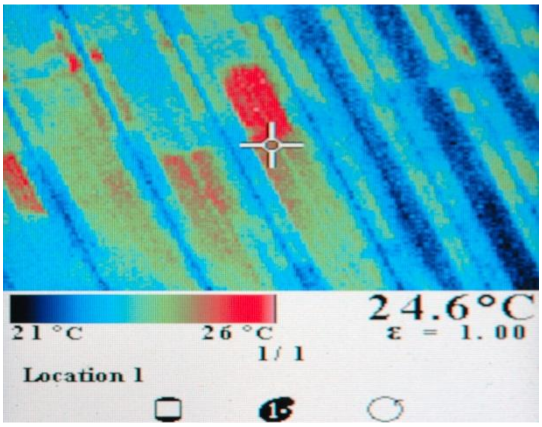

Figure 5.1. Thermal imaging technique (copyright TWI)

5.6.1 Output from the technique

Thermal imaging instruments are able to measure radiated infrared energy and convert this data into corresponding maps of temperatures. A true thermal image is a grey scale image with hot items indicated in white and cold items in black. Temperatures between the two extremes are shown as gradients of grey. Some thermal imagers have the ability to add colour, which is artificially generated by the camera's video enhancement electronics, based upon the thermal attributes seen by the camera. Some instruments provide temperature data at each image pixel. Cursors can be positioned on each point, and the corresponding temperature is read out on the screen or display. Images may be digitized, stored, manipulated, processed and printed out. Industry-standard image formats, such as the tagged image file format (TIFF), permit files to work with a wide array of commercially available software packages.

5.6.2 Key advantages of the technique and notable issues

This technique is able to inspect relatively large areas at a time and therefore has the potential to carry out rapid inspection of large sections of a tunnel. However, even though it can detect large defects such as void, the method is not capable of detecting small defects such as cracks.

5.7 Laser scanning

Laser scanning, which is a method mainly implemented for geometrical surveys purposes, uses a time of flight approach or a frequency modulated beam to measure the distance from the emitter to the point of reflection.

It has been used for many applications such as in nuclear fuel processing, surveying, mining, quarrying and archaeology. Laser scanning is mainly used to detect deformation of tunnels’ components.

5.7.1 Installation

- It depends on the size of tunnel being measured. Stations need to be installed to reflect the beam at certain points.
- A number of shots need to be taken.
- Time to install varies between half a day to a day

5.7.2 Output from the technique

Output files can be received through the installed software, with a number of images being linked together at the station points. These images can then be used to observe and detect deformation issues.

5.7.3 Key advantages of the technique and notable issues

Advantages:

- Scan speed up to 100,000 points per second
- In the case of continuous moving laser heads, scans can be taken at a speed of 1-2 meters per second.

Limitations:

- The wavelength of the laser lies within the visible spectrum; this means that it is only possible to measure whatever the human eye can see.
- Furthermore, the laser cannot measure effectively through water, glass or smoke, as the laser beam is subject to light diffraction while passing through these materials.

5.7.4 Current Status of the technique and expected developments

The conventional laser scanner (Leica, Z+F, Faro) is the most well developed system using this approach. The scan speed has steadily increased up to about 50-100,000 points per second whilst maintaining its accuracy.

5.8 Ground Penetrating Radar (GPR)/Georadar

5.8.1 Introduction to the M&E technique applicable

Ground-penetrating radar (GPR) is a geophysical method that uses radar pulses to image the subsurface. This technique can provide a considerable amount of information on masonry tunnel condition and construction and is deemed to be one of the most well-established techniques because of its rapid data acquisition and versatility. Ground penetrating radar (GPR) is a similar technique to the seismic imagery reflection. It uses electromagnetic waves that propagate and refract in heterogeneous medium in order to scan, to localize and to identify quantitative variations within electric and magnetic properties of the soil. GPR frequencies usually range from 10 MHz to 2.6 GHz. When using lower frequency antenna (between 10 and 100 MHz) investigated depth will be higher (more than 10 m), however resolution remains lower (Faize and Driouach 2012).

Ground penetrating radar (GPR) is one of a number of remote sensing geophysical methods utilised to study subsurface archaeological and geological deposits, alongside such methods as magnetometry, electrical resistivity, and electromagnetic conductivity. The operating principles of various existing GPR radars 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).

GPR operates in the same manner as navigational radar systems, in that it sends pulses of electromagnetic (EM) 'radar' waves into the ground in order to identify the shapes, sizes, and locations of subsurface features. When the transmitted EM wave encounters changes in subsurface materials, the properties of the wave are altered, and part of the wave is reflected back to the surface, where data on its amplitude, wavelength, and two-way travel time are collected for analysis. The data are collected in traces, each of which displays the total waveform of all waves collected at one surface location. When arranged in their relative positions, series of traces can produce a number of different types of images showing variations in subsurface properties in the vertical and horizontal dimensions.

5.8.2 Output from the technique

GPR can be used to determine lining thickness, detect features beyond the lining such as timbers, counterforts, shafts, and to characterise changes in geology. 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 and can be followed up by targeted drilling or by detailed geophysics from the top, once the suspect location has been identified.

Individual lines of GPR data represent a sectional (profile) view of the subsurface. Multiple lines of data systematically collected over an area may be used to construct three-dimensional or tomographic images. Using this non-destructive method, data may be presented as three-dimensional blocks, or as horizontal or vertical slices. Horizontal slices (known as "depth slices" or "time slices") are essentially plan view maps isolating specific depths.

5.8.3 Key advantages of the technique and notable issues

The most significant performance limitation of GPR is in high-conductivity materials such as clay soils and soils that are salt contaminated. Performance is also limited by signal scattering in heterogeneous conditions (e.g. rocky soils).

Other disadvantages of currently available GPR systems include:

- Interpretation of radiograms is generally non-intuitive to the novice.
- Considerable expertise is necessary to effectively design, conduct, and interpret GPR surveys.
- Relatively high energy consumption can be problematic for extensive field surveys.

5.8.4 Current Status of the technique and expected developments

This non-destructive method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and detects the reflected signals from subsurface structures. GPR can be used in a variety of media, including rock, soil, ice, fresh water, pavements and structures. It can detect objects, changes in material, and voids and cracks (Daniel D.J. 2004). It is also used for the monitoring of tunnels and bridges.

5.9 Time-of-Flight Camera

A Time-of-Flight Camera (ToF camera) is a range imaging camera system that resolves distance based on the known speed of light, measuring the time-of-flight of a light signal between the camera and the subject for each point of the image. The camera has each of its individual pixels as an independent time of flight distance ranger, so it is similar in operation to having many laser rangefinders work in parallel. The method of ToF can detect open joints, flaking of wall and missing brickwork.

5.9.1 Installation

- Time to install: half a day
- Four Components to the ToF: Illumination unit, optics, image sensor, driver electronics (signals) and computation/interface.

5.9.2 Output from the technique

- A TOF based camera emits an infra-red light, hitting a target. The light then bounces back to the sensor which then calculates the distance that it took to travel back and forth.
- The individual pixelated data produced by these infra-red lights bounce off the target and then are extrapolated to produce the target's equivalent image

5.9.3 Key advantages of the technique and notable issues

Advantages:

- Interreflection occurs due to collisions, corners or hollows. The signal can take multiple ways through reflection before returning to the receiver.
- Light scattering, for ToF cameras the secondary reflections of light reflected by near bright objects superpose the measurement from the background.
- ToF cameras can have a range of up to about 60 metres, with a distance resolution of 5-10mm.
- The number of pixels can be as large as 484 x 648 pixels.
- Time-of-flight cameras are able to measure the distances within a complete scene with one shot. As the cameras reach up to 100 frames per second, they are ideally suited to be used in real-time applications.

Limitations:

- Noise limits the performance of ToF cameras.
- The technology is very recent and performance is still not to the desired standards.

5.9.4 Current Status of the technique and expected developments

- The TOF camera is a recent development and is likely to increase in performance and size of the array quite quickly as it is essentially all solid state.
- Current applications of ToF camera: automotive, human-machine interfaces and gaming, measurement and machine vision and robotics.

5.10 Digital Image Correlation

Digital Image Correlation is a full-field image analysis method, based on grey value digital images that can determine the contour and the displacements of an object under load in three dimensions. The technique of DIC is used to detect deformation, open joints and fractures.

5.10.1 Installation

- Time to install: half a day
- DIC is a combination of single camera image correlation and two cameras photogrammetry
- Photogrammetry is a measurement technology whereby the three dimensional coordinates of an object's point are measured using two or more photographic images taken from different positions.
- The intersection of these rays from different perspectives determines the location of the image.

5.10.2 Output from the technique

- In practice, a random high contrast pattern is applied to the surface of the test object to supply a grid of unique points to correlate. This pattern then deforms or moves along with the object. The deformation under different load conditions is recorded by the digital cameras and then evaluated by the software.

- The initial image processing involves defining unique correlation areas known as areas of interest across the entire imaging area.
- These facets are tracked in each successive image with sub-pixel accuracy. Then, using photogrammetric principles, the 3D coordinates of the entire surface of the specimen are precisely calculated.
- The results are the 3D shape of the component, the 3D displacements, and the plane strain tensor.

5.10.3 Key advantages of the technique and notable issues

- Shadowing effects occur for the 3D measurements
- Lens aberrations and accuracy effects caused by the tunnel walls being curved need to be calculated for 2D measurements.
- The camera can process images at 1 per second.
- A vehicle does not need to stop to make a measurement.
- However, a notable issue of the technique is that moist and water can affect the outcome of the data

5.10.4 Current Status of the technique and expected developments

Necessary algorithms, computer hardware and high-resolution cameras are being developed to make high resolution measurements of tunnel walls.

5.11 Impact-Echo

Impact-Echo is a method of non-destructive evaluation of concrete and masonry, based on the use of impact-generated stress (sound) waves that propagate through the structure and are reflected by internal flaws and external surfaces. Impact-Echo systems can measure thickness of concrete slabs such as pavements, retaining walls, and tunnel walls. This technique is an acoustic method that can determine locations and extent of flaws/deteriorations, voids, debonding of re-bars, thickness of concrete. The method overcomes many of the barriers associated with flaw detection in concrete based on ultrasonic methods. The use of this method helps to mitigate the need for major retrofit since the deterioration can be detected at an early stage and repairs performed. While the use of frequency analysis has aided in interpreting test results provided by this technique, experience is needed in setting up optimal testing parameters, recognizing valid recorded waveforms, and analysing test results.

5.11.1 Installation

The installation using the Impact-Echo method can be carried out at the spot, assuming that the tunnel is clear.

5.11.2 Output from the technique

A short-duration mechanical impact, produced by tapping a small steel sphere against a concrete or masonry surface, produces low-frequency stress waves that spread into the structure and are reflected by flaws and/or external surfaces. The wavelengths of these stress waves are typically between 50mm and 2,000mm – longer than the scale of natural inhomogeneous regions in concrete (aggregate, air bubbles, micro-cracks, etc.). Multiple reflections of these waves within the structure excite local modes of vibration, and the consequent surface displacements are recorded by a transducer located adjacent to the impact. The piezoelectric crystal in the transducer produces a voltage proportional to displacement, and the resulting voltage-time signal (called a waveform) is digitised mathematically into a spectrum of amplitude vs. frequency.

5.11.3 Key advantages of the technique and notable issues

- Routine maintenance evaluation to detect cracks, voids, or delamination
- Delineate areas of damage and corrosions in walls, canals, and other concrete structures
- Assess quality of bonding and condition of tunnel liners.
- However, a notable issue of the method is that firing enough projectiles and targeting may be a difficult task
- Furthermore, verification may be required at selected points to increase confidence level

5.11.4 Current Status of the technique and expected developments

Impact-Echo Instruments is the world leader in developing and marketing Impact-Echo technology to evaluate concrete and masonry structures, catering to construction managers and forensic test consultants.

5.12 Other Techniques used

- **Resonance inspection**. This innovative inspection technology is not only restricted to conventional NDT applications, but is also capable of performing several inspection functions in one test. The technology can detect cracks, voids, hardness variations, and dimensional variations, bonding problems, parts with missing manufacturing processes, misshaped parts and changes in material properties (Peters and Day 2003). It is primarily suitable to inspect mass-produced components, although some high value individual components can be condition monitored to detect changes in their structural integrity.

- **Seismic methods.** Seismic methods are becoming more popular in geotechnical investigations because of their ability to give valuable information on the stiffness variations in the ground. The seismic method relies on the differences in velocity of elastic or seismic waves through different geological or man-made materials. Seismic methods can provide engineers and geologists with the most basic of geologic data via simple procedures with common equipment. Any mechanical vibration is initiated by a source and travels to the location where the vibration is recorded. However, issues with accuracy and speed need to be addressed for this technique to gain higher value and applicability for tunnels inspection.

5.13 Summary Table

Table 5.1 Monitoring and Examination (M&E) techniques and Degradation Mechanisms (DM) affecting tunnels[4]

MAINLINE Project WP4: Monitoring and Examination Techniques D4.1: Report on assessment of current monitoring and examination practices in relation to the degradation				Section 5. Tunnels				
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			✓		✓		✓	
Ground Penetrating Radar	✓		✓	✓		✓	✓	

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

6. Plain line and Switches and Crossings

6.1 Introduction to the M&E techniques applicable

A “minimum action” is the least that the responsible track engineer can do to ensure that the track remains safe on discovery of a broken or defective rail or weld. Railway Infrastructure Managers (IMs) carry out routine inspection, including both visual and non-destructive inspection techniques, such as ultrasonic or eddy current testing. The minimum actions are guidelines that specify the actions to be taken to ensure the integrity of the railway. This was one of the objectives of the INNOTRACK Project (Ekberg and Paulsson 2010), on a scientific basis of “minimum action” rules for the management of defective rails.

In order to enforce efficient rail maintenance routines, it is vital to detect rail damage as early as possible. The rail industry commonly employs ultrasonic probes mounted on special test trains in order to inspect rails fast. To improve upon the efficiency of ultrasonic systems, the use of other technologies such as eddy current probes, magnetic flux leakage detectors, alternating current field measurement sensors and ultrasonic phased array probes has been investigated (Ekberg and Paulsson 2010). General information on modern rail technology can also be found in text books by Esveld (2001) and Lichtberger (2011).

Plain line and Switches and Crossings (S&C) are critical components of a railway system. In order to ensure that they meet the condition standards required, they need to be checked both in terms of functional performance and system integrity. Monitoring the actual behaviour of the assets under the current load can offer information regarding the relative condition of the assets and the rates of possible degradation mechanisms affecting them. Measuring inputs at specified time intervals can define trends of parameters over time and check the functional performance of the components. On the other hand, the system integrity is the ability of a system to perform its designed functions without being degraded or impaired by changes or disruptions in its internal/external environment. This conformity check against the system design following well defined standards, regulations and predefined values commonly forms the inspection activity.

Over the last 20 years, automated measurements have been widely used for the M&E of plain lines and S&C. Even though the use of special trains with several sensors and cameras has provided very detailed and precise results, some issues were still unresolved such as the high cost, the need for solutions to cover every part of the track and the need to occupy a time slot during the measurement. Small two-direction vehicles, portable devices and devices integrated on regular trains or into the railway infrastructure have, therefore, been widely used over the last 5-10 years.

Track status, in general, can be described by two factors, the geometrical state and the structural state of all track components, which closely affect one another. Even more complicated, deterioration depends on weather conditions and other external conditions. However, track and turnout deterioration is not just defined by the components behaviour but by the interactions of all components and thus the behaviour of the whole structure, as described in Deliverable 2.1 of MAINLINE. It is worth highlighting though that it is not practical or economical to measure every single relevant parameter for a relatively complex mechanical system such as the S&C system.

Network Rail (UK) has a hierarchy of Inspections (Network Rail 2012), involving different levels of Inspection as a process and different levels of personnel:

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

Following the above hierarchy, basic visual inspections are carried out to identify immediate or short term actions required; these are generally faults that require action within four weeks. Manager track inspections include measurements of gauge, cross-level and other features; they review trends in condition, identify work to be planned and carried out and check the effectiveness of inspections and works. Cab riding inspections assess the quality of the ride for trains and identify locations that require further inspection. Detailed inspections are carried out to check the condition of specific types of track infrastructure with measurements being taken. Track geometry measurement identifies and measures track geometry faults and track geometry quality while ultrasonic inspections are carried out to identify and measure surface and internal defects in rails.

Furthermore, the concept of risk based inspection is adopted so that faults are repaired before they affect the safe performance of the track. Inspections, asset information, analysis and local knowledge must be used to (Network Rail 2012):

- plan and carry out maintenance works needed to meet the safety, performance, cost and asset life targets for the track on their route
- suggest refurbishment or renewal works when/where it is assessed that maintenance alone is not the best way to fulfil these targets

According to Network Rail (UK), the frequency of basic visual inspections varies between twice/week and once/8 weeks depending on the track category and the inspected element of the track (i.e. plain line, S&C etc.). On the other hand, Section Manager and Track Maintenance Engineer inspections are carried out every 8 weeks to 2 years, again depending on the track category and examined element. It needs to be noted, however, that the above frequencies are reviewed annually and may be changed if asset condition indicates that this is required (Network Rail 2012).

Several of the techniques described in previous sections can be used for the monitoring of plain lines and switches and crossings, in particular:

- visual inspection
- inspection using measurement tools (track gauge meter, ruler, gap meter, force meter, computer aided trolley, measuring trains etc.)
- eddy current method
- laser and camera
- ultrasonic techniques

Basic visual track inspections identify defects which, if not addressed, could affect the safety or reliability of the operation of the railway prior to the next planned inspection. Inspections on foot are carried out by walking the track within the length of the sleepers; a maximum of tracks can be inspected at one time if the right conditions are met. Planning inspections from a vehicle are conducted in addition to inspections on foot, although all S&C are mainly inspected on foot. Furthermore, train-borne inspection is used for additional observation from the vehicle; plain line pattern recognition is an alternative process for the basic visual inspection of plain line track components, whilst video inspection is an alternative for the basic visual inspection of S&C track components. Finally, advanced emerging technologies are also applied for the M&E of plain line and S&C.

An overview of the techniques most commonly used in the UK and elsewhere for the monitoring of Plain line and S&C are presented in Table 6.1 and Table 6.2 respectively.

Table 6.1. 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 6.2. Overview of techniques used for Monitoring and Inspection of S&C.

Switches & Crossings		
Parameter to inspect and/or monitor	**Method**	**Equipment**
The same as in plain line + the followings		
Flangeway clearance (check rail gauge max. behind the switchblade)	Measuring wheel or laser +camera or manual measurement	Track geometry measuring train or switch inspection train or trolley or track ruler
Check rail gauge (at the frog)	Measuring wheel or laser +camera or manual measurement	Track geometry measuring train or switch inspection train or trolley or track ruler
Back-to-back distance, check gauge of the switch	Measuring wheel or laser +camera or manual measurement	Track geometry measuring train or switch inspection train or trolley or track ruler
Switch-blade opening	manual measurement	ruler or measuring tape
Clamp gap	manual measurement	manual gap meter
Force measurements (setting force, remaining force)	measuring the forces	force meter
Rail flaw (not manganese crossing)	Ultrasonic	Trolley
Rail flaws in manganese crossing	Penetration fluid or ultrasonic	Manually applied
Rail surface defects (Headchecks, squats)	Eddy current	Trolley
Pont machine, end positions	Clearance when lock	Manual inspection
Point machine, performance	Current monitoring	Computer connected to control unit
Obstruction test	Manual test with an ostacle of 4 mm	obstacle of 4 mm
ORE Test	Examination of the wear of stock rail and switch-blade by ORE gauge	ORE gauge

Most railroad administrators own inspection trains while others buy such inspection as a service. To be effective, they should be operated in normal train speed for the lines they are supposed to serve. Examples of inspection trains in Europe include the “Iris 320” train in France and “Dr Yellow” train in Japan.

Automated inspection of S&C from a measuring train is difficult due to the complex geometry. An important aspect of inspecting switches from passing trains 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 as train has to go through the switch several times and point machinery cannot be checked. A manual intervention is still necessary.

The trend of reducing track time for inspection and monitoring trains can be exemplified by systems incorporating camera and lasers installed on customer vehicles. These systems measure rail profile, track gauge, head checks and fishplate existence. Railscan’s (Netherlands) laser scanner, which can be installed on regular trains to measure, measures track gauge and absolute x-y-z coordinated of the track based on GPS positioning.

The InnoTrans exhibition in Berlin 2012 showcased on-going developments regarding small equipment for fast manual inspection or monitoring of switches. As several suppliers present similar products, the prices of such equipment are expected to be very reasonable. Some examples include Vogel & Plötscher’s (Germany) computerised gauge, which takes all readings in a S&C while walking along it, Graw’s (Poland) trolley with laser profile scanner for S&C and equipment for ultrasonic testing and flaw detection such as the products by Radioavionica (Russia) and Geismar (France) or Metalelectro Ltd’s TrackScan (Hungary) for the geometrical measurement of plain line and turnouts.

6.2 Damage and deterioration mechanisms

There are different impacts on Plain line and S&C caused by different mechanisms consequently leading to different damages and maintenance actions. These are listed below.

Wear (Side-Wear)

Plain line and S&C wear can be monitored with optical devices by track measurement cars. Rail pad wear can be identified by monitoring the rail inclination.

Rolling Contact Fatigue (RCF)

RCF failures can be identified with eddy current measurements.

Fatigue

Indicators of an exceeded rail fatigue resistance and rail breakages may be identified using ultrasonic methods.

Corrugation

Corrugation waves are generally measured by the recording car.

Rotting

Degradation of wooden sleeper is very often the missing frictional connection or the process of rotting. The behaviour of wooden sleepers can be monitored by measuring the gauge and the rail foot distance.

6.3 Mechanised track measurement

The continuous measurement of track geometry is carried out by track measuring coaches, measuring trains, or manually pushed small trolleys.

The two most commonly used methods of the measuring technologies are:

- chord measurement
- inertial measurement

In the case of chord measurement, the longitudinal level and alignment are measured by chords of different length depending on the type of the measuring coach. The chord measurement provides distortional measuring result; an example of a continuous track measurement using track measuring train is shown in Figure 6.1**.** below.

Figure 6.1. Example of track geometrical measuring car (copyright MÁV Co)

On the other hand, inertial measurement is contact-free, and can be carried out at lengths specifically defined in EN 13848-1:

D1 3-25 m

D2 205-70 m

D3 70-210 m

A disadvantage of some inertial measurements is the fact measuring results for longitudinal-level and alignment cannot be provided for very low speeds (between 0 km/h to some km/h). However, a possible elimination of this weakness is the combination of optical chord measurement with inertial measurement, as illustrated in Figure 6.2.. Changeover from optical chord measurement to the inertial measurement is automatic in the function of the actual speed.

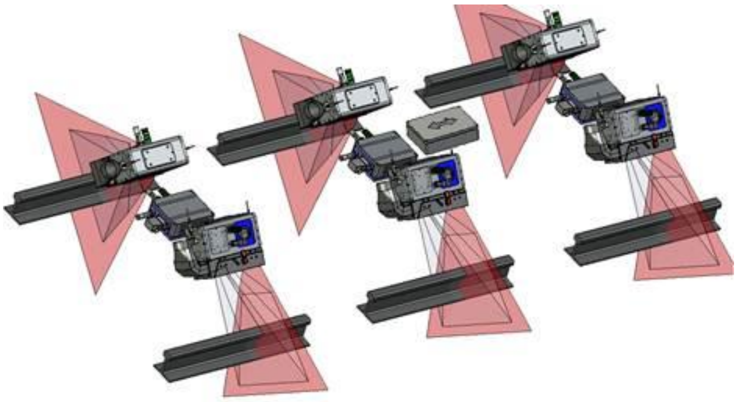

Figure 6.2. System combining optical chord and inertial measuring (copyright Tecnogamma)

For continuous track geometrical measurement, manually pushed small trolleys can also be used.

The basic types of these trolleys can be used for the measurement of:

- track gauge
- twist and
- super-elevation

Their more up-to-date versions can also measure longitudinal level and alignment. Furthermore, they are able to measure turnouts continuously as well as are fit for point-like measurements.

6.4 Eddy current measurement

Among the types of Rolling Contact Fatigue (RCF) rail faults (Head Checking, Squat, Belgrospi and tongue formation) commonly detected, Head Checking (HC) involves a high number of tasks for infrastructure managers. Defining the depth of HC cracks is not possible using ultrasonic measurement within the upper layer of 5 mm of the railhead. At the same time the depth must be known so that necessary interventions are planned and carried out (e.g. grinding, milling or replacement). For the calculation of the depth of HC faults, one possible solution is the use of Eddy Current measurement.

While the principle of this method has been presented in a previous section (see Section 5.5), it is worth underlining the fact that Eddy current measuring instruments can be mounted on measuring cars or make use of manual trolleys for continuous measurement of the damage depth, which is a parameter vital for the determination of interventions' regulations by infrastructure managers.

6.5 Gauge measurement using laser and camera

Ensuring the clearance gauge is free of obstacles forms a key operational safety aspect. Checking the clearance gauge is necessary whenever the geometry of the track is changed (correction, track adjustment, new establishments near the track, etc.). The measurement of all key points of the objects reaching into the measuring gauge is necessary. Although the "measuring gauge" is defined by Infrastructure Managers variously, 3.0m laterally from the track axis and 7.0m vertically from the top of the rails are dimensions generally used.

The most widely used solution for mechanical measurement of the clearance gauge is laser scanning. The laser strobe of the measuring device rotates and projects the laser beam, which measures the distance between the rotation centre and the laser points on the object. Throughout this process, the railway vehicle on which the laser telemeter is mounted runs at a certain speed, as shown in Figure 6.***3***. As a result, a spiral laser line is formed, which means that objects located between two consecutive spiral sections (e.g. signs) cannot be recorded using this measurement. The accuracy of laser measurement, therefore, depends on the rotating speed and the speed of the vehicle. Enhancing the rotating speed, which means more advanced and expensive instrument, or reducing the speed of the vehicle can improve the accuracy of the measurement. A commonly chosen rotating frequency is 100 Hz, in which case at a vehicle speed of 50 km/h objects of 14 cm width (size of the object parallel to the track axis) can be captured.

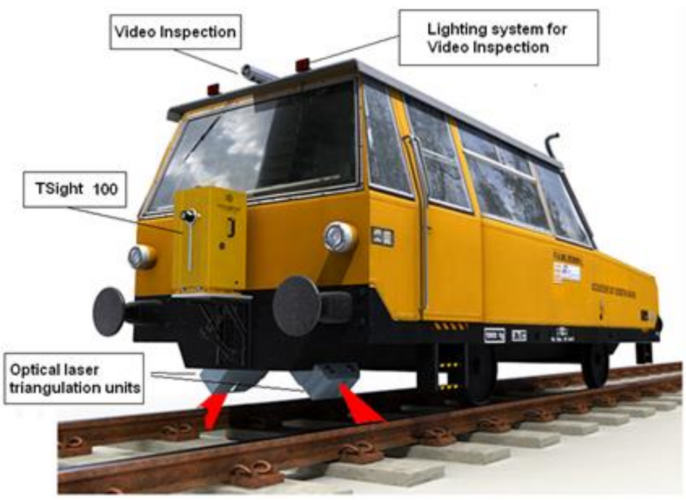

Figure 6.3 Clearance gauge measuring equipment mounted on a vehicle (copyright Tecnogamma)

Mounting the equipment on a small trolley and pushing it manually is another widely used method of clearance gauge measurement. Tracks which are not involved in the mechanised continuous measurement due to certain reasons are measured using this method.

Finally, a third method lies on the manual measurement with the aid of various tools (frame mounted on a trolley and measuring rods, or rods assembled in L-shape or measuring tapes), which may already be considered as the method of the past.

6.6 Ultrasonic and wheel probe

Ultrasonic testing has been extensively used for the inspection of rails in-service. In most cases rail inspection is performed using special ultrasonic probes mounted on the undercarriage of the test train (Ekberg and Paulsson 2010). For the continuous ultrasonic measurement of the rails in track, two solutions are well known: (i) Sperry's Roller Searching Unit (RSU) and (ii) the use of ultrasonic probes installed on a sliding frame. For the plain lines, the wheel probe was developed to detect defects along the track. Eddy-current and flux leakage sensors can be attached to the wheel. The wheel consists of a flexible tyre containing three phased array transducers (Bird and Bray 2005). The three transducers are orientated to produce three non-steered beam angles: 0°, 40° and nominally 58°. These basic non steered beam angles are then modified by the electronic steering available in the phased array system to produce focused beams in a variety of locations within the rail section. Use of phased array ultrasonic probes allowed a reduction in the required number of probes and, most importantly, allowed the system to focus and steer to the desired inspection locations. The 0° probe was used for detection of rail foot corrosion, horizontal splits and bolt hole cracks. The 40° probe for bolt hole and rail foot fatigue cracks and the 58° probe for rail head cracking. Of particular interest was the detection of gauge corner defects that are both tilted and skewed with respect to the rail axis. For ideal defect detection and sizing conditions a skewed, focused 70° ultrasonic beam was required.

Furthermore, the rail head can also contain squat defects in the centre portion of the rail head which require high beam angles for optimum defect detection. By steering and focusing the nominal 58° probe, both non-skewed beams aligned with the centre of the rail and skewed 70° ultrasonic beams for gauge corner crack detection were generated. These focused beams avoided surface waves and ultrasonic noise generated by the relatively rough rail surface.

For the classification of ultrasonic faults, the UIC leaflet 712 (rail fault catalogue) and the UIC leaflet 725 are generally used. The ultrasonic faults detected using ultrasonic measuring trains are checked on the spot by manual ultrasonic trolleys in short time periods. The speed of this mechanised ultrasonic measurement generally varies between 50 and 80 km/hr; an example of this inspection technique is shown in Figure 6.***4***.

Figure 6.4. Crack growth investigation by ultrasonic (copyright TWI)

This technique is typically employed on Sperry trains (UTU1 and UTU2 models) in many countries. Portable ultrasonic inspection units (Sperry Sticks) are used to confirm the presence of detected defects by the Sperry trains. However, the fact that many of the readings provided from the Sperry trains were ''false'' has only been partly addressed by setting more realistic detection thresholds. Eurailscout (Netherlands, Germany, etc.) and Scanmaster (Israel) test trains use sliding plate sleds to accommodate the ultrasonic probes. The Eurailshout trains incorporate pulsed Eddy Current probes to improve the system's detection capability (Ekberg and Paulsson 2010).

6.7 Examination and Monitoring of S&C

Turnouts are generally categorised into different groups depending on their loading. This classification determines the frequency of turnout examinations. The practices for S&C examination fall into 4 general types, which are described below:

a. Visual inspection:

   Carried out by patrolmen on foot according to the class of turnouts; this method does not involve measurement but only observation.

b. Simplified S&C examination

   This examination involves visual inspection of the turnout as well as measurement/checking of the operational sizes at a frequency defined by the class of the turnout.

c. Measurement of the turnouts

   Parameters such as the track gauge, guiding gauge and cross level are measured at pre-defined measuring points. During the evaluation stage, the measured values are compared against the values defined in regulations, taking into account tolerance values.

d. Video inspection in turnouts

It is worth mentioning at this point that throughout the simplified turnout examination, the operational sizes refer to:

1. switch-blade opening (to be measured)
2. check gauge of the switch (to be measured)
3. clamp gap (to be measured)
4. fitting gap (to be checked)
5. switch-blade lagging, block gap (to be checked)

6. longitudinal displacement of stock rail and switch rail compared to each-other
7. obstruction test (to be checked)
8. check gauge at the crossing peak (to be measured)

Continuous measurement of S&C is also executed by the track geometrical measuring cars, but their continuous measurement is also possible by manually pushed measuring trolleys. Certain railway companies/operators consider the measurement of turnouts using track geometrical cars as an informal process, due to the extra loading that measuring cars receive.

Regarding the method of video inspection of turnouts, a good example is its application in the Netherlands (Eurailscout VST-05). In this system the measurement of turnouts occurs at speeds of 40 km/h., while 4 vehicles continuously carry out the examination of turnouts throughout the network every 2 weeks.

Mounting sensors on the turnouts can enable the measurement of wear and the state of individual components so that intervention is executed at the most efficient time. One of the most well-known solutions for S&C monitoring is offered by the Vae Roadmaster 2000 system. In this case the switch point machine is used as sensor for irregularities in the switch. With Vae Roadmaster 2000 Light (system used for example by MAV, Hungary) it is possible to economically supervise multiple switches in a centralised signalling room. The measured local values are then transferred for further evaluation to a central or local computer.

6.8 Other techniques used

In addition to the most commonly used methods, which are presented in Table 6.1, there are a number of other techniques used recently in monitoring and examination of Plain line, S&C. These techniques are described below.

6.8.1 Magnetic Flux Leakage

The application of Magnetic Flux Leakage (MFL) sensors is mainly focused on the detection of near-surface or surface-breaking transverse defects, such as RCF cracking (Papaelias, Roberts and Davis 2009). However, transverse fissures are not the only types of defects found in rails, which can include deep internal cracks and rail foot corrosion. These defects are not detectable with the 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.

Inspection systems based on the simultaneous use of conventional ultrasonic transducers with MFL sensors have a higher probability of detecting smaller near-surface and surface-breaking defects in the rail head. However, as inspection speed increases, the performance of MFL sensors tends to deteriorate rapidly due to a reduction in the magnetic flux density. 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 variations.

Fatigue cracks can initiate from manufacturing and service-related defects such as inclusions, shelling and corrosion. Many of these defects are not detectable using MFL because the flaws run parallel to the magnetic flux lines or the flaws are too far away from the sensing coils to detect. MFL is mainly used as a complementary technique to ultrasonic inspection.

6.8.2 Alternating Current Field Measurement

Alternating Current Field Measurement (ACFM) is an electromagnetic inspection method capable of both detecting and sizing (length and depth) surface breaking cracks in metals (Papaelias, Roberts and Davis 2009). The basis of the technique is that an alternating current can be induced to flow in a thin skin near the surface of any conductor. By introducing a remote uniform current into an area of the component under test, when there are no defects present the electrical current will be undisturbed. If a crack is present, the uniform current is disturbed and the current flows around the ends and down the faces of the crack, thus allowing its detection and sizing. ACFM sensors are less affected by lift-off variation than eddy current probes and can operate even at 5mm away from the rail surface.

6.8.3 Automated vision systems

Automated vision systems can operate at very high velocities (speeds up to 320km/h are possible depending on the nature of the inspection) and are typically used to measure the rail profile and percentage of wear of the rail head, rail gauge, corrugation and missing bolts (Papaelias, Roberts and Davis 2009). SNCF, for example, operates a high speed camera inspection of its rail track network using its new “IRIS 320” car that can achieve speeds up to 320km/h. These inspections are performed every 15 days to detect visual surface defects over high speed lines as well as high standard main line. Certain advanced vision systems can be used for the detection of RCF and other types of surface damage such as wheelburns at slower inspection speeds (<10km/h). Despite the usefulness of automated vision systems, their applicability is restricted to the detection of surface features only and therefore the inspection needs to be repeated using ultrasonic sensors if internal defects are to be detected.

6.8.4 Radiographic inspection

Radiographic inspection of rails can be carried out using either gamma or X-ray sources (Papaelias, Roberts and Davis 2009). In the past radiography was carried out more often using a gamma-ray source and film to obtain a radiograph of the inspected area of a rail. With the advent of portable digital X-ray detectors, the use of X-ray sources became more commonplace. Radiography, although a particularly efficient non-destructive evaluation (NDE) method for inspecting rails for internal flaws, inherently involves health and safety drawbacks. Furthermore, the inspection is time-consuming and for that reason, it is only applicable as a means of verification in places where defects have already been detected using other non-destructive evaluation techniques or in rail areas, such as aluminothermic welds, and switches and crossings, where inspection with other NDE methods is unreliable and not very efficient in detecting transverse rail defects.

6.8.5 Long range ultrasonic (guided waves)

This is an Ultrasonics Testing (UT) method based on transmitting ultrasound as volumetric waves along a structure such as rail. Transducers are designed and installed so that the appropriate wave modes can be excited and transmitted in the structure. Girth welds and cracks or corrosion can be detected using this method; these degradation mechanisms are recorded either as reflections from fixed reference points or changes in cross sectional areas. These records are then analysed using suitable software and experienced and trained personnel. Even though Long-Range Ultrasonics 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 in the U.S. (The Pennsylvania State University), South Korea (Seoul National University of Technology) and the U.K. (TWI) (Ekberg and Paulsson 2010).

6.9 Output from the techniques

The outputs produced from the geometry measurement systems are normally in the same unit as the systems they replace, which makes the task of implementing them easier.

The systems for flaw detection and surface defects, however, are different, since they produce much more complex output that requires interpretation by skilled users. Nevertheless, the software gradually becomes more and more advanced assisting the user with the analysis process.

Monitoring systems used for local examination also require substantial time for interpretation. A typical output parameter is the time required for the machinery to move between switch positions. Another output can be the mean current, which represents the power or the energy needed.

6.10 Key advantages and notable issues

New track geometry inspection and monitoring trains are probably better than their predecessors when it comes to the quality and speed of measuring. The data output is also better structured for data processing and trending.

Moving from special measuring trains to sensors placed on regular trains will reduce the disturbances affecting traffic schedules. On the other hand, these new systems might provide less accurate readings compared to the special trains.

The computerised gauge devices for S&C inspection still need manual on-site visits but they considerably reduce the time needed to do the inspections whilst same time supporting the automatic data storing and trending of data.

6.11 Current status of the techniques and expected developments

Currently special geometry measuring trains are in use worldwide for plain line inspection and monitoring, whilst S&C are still commonly inspected by manual inspection. Video inspection techniques are increasingly applied, taking advantage of their ability for non-contact dimension measurement and detection of defects and missing components. High quality computer and camera performance, more sophisticated analysis software and reduced system cost are the main factors making this technique very promising.

Once automated inspection and monitoring techniques become available on dedicated trains, the potential of gradually enabling their application on regular trains becomes feasible. This is also driven by the need to reduce inspection cost as well as the track access time needed for maintenance. The fact that a wide range of computerised tools for S&C inspection exists is also positive. Although manual intervention is still required, the time of examinations on track is reduced, thus increasing the system availability.

Parallel to MAINLINE, another EU-funded project, AUTOMAIN, investigates “self-inspecting” switches. Intelligent monitoring of the point machine power line, extended use of permanent cameras close to the switch and fastening bolts with inbuilt load transmitters are key techniques under consideration.

6.12 Summary Table

Table 6.3 Monitoring and Examination (M&E) techniques and Degradation Mechanisms (DM) affecting plain line, switches and crossings[5]

MAINLINE Project WP4: Monitoring and Examination Techniques D4.1: Report on assessment of current monitoring and examination practices in relation to the degradation				Section 6. Plain line and S&C				
DM / M&E	Wear	Rolling Contact Fatigue	Fatigue cracking	Corrugation	Vegetation	Corrosion	Track geometry defects	Alignment
Visual Inspection	✓	✓	✓	✓	✓	✓	✓	✓
Gauge Measurement Laser Scanning	✓		✓	✓	✓		✓	✓
Eddy Current		✓						
Ultrasonic Testing	✓		✓			✓		
Magnetic Flux Leakage	✓	✓		✓				
Alternating Current Field Measurement	✓			✓		✓		
Video Inspection	✓		✓		✓		✓	

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

7. Retaining Walls

7.1 Introduction

Retaining walls are structures that are constructed to support almost vertical (steeper than 70 degrees) or vertical slopes of earth masses. According to Eurocode EN 1997-1:2004 §9.1.1(1)P, retaining structures include all types of wall and support systems in which structural elements have forces imposed by the retained material. Retaining walls are often used near the toe of a cut or fill slope, so that a flatter slope can be constructed to prevent or minimize slope erosion or failure. They can also be used to keep a toe of a slope from encroaching into a wetland area or into a stream and thus prevent potential undercutting of the toe by flowing water. Retaining wall systems represent worldwide a two billion dollar a year industry of increasing complexity and as urban densification continues to grow and above ground space increases in value, retaining wall systems need to be installed deeper and under greater difficulty (Laefer and Lennon 2008). Several techniques are nowadays available and used for the monitoring and examination of retaining walls. These vary from the more traditional visual inspection and geotechnical methods to the automated monitoring systems using advanced sensors and laser technology. The monitoring of retaining walls is a particularly important process for the maintenance and improvement of rail transport infrastructure and needs the required attention.

Retaining walls are generally classified as gravity, semi-gravity (or conventional), non-gravity cantilevered, and anchored. Retaining walls are designed to withstand lateral earth and water pressures, the effects of surcharge loads, the self-weight of the wall and, in special cases, earthquake loads. 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 the technical approval of highway structures.

7.2 Damage and deterioration mechanisms

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 D2.1 report 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.

7.3 Visual inspection

7.3.1 Introduction to the M&E technique applicable

Visual inspection refers to evaluation by means of eyesight, either directly or assisted in some way. It typically involves the search for large-scale deficiencies and deformities (Ferraro 2003). An important aspect related to the preparation for visual inspection is the review of available literature related to the structure - the retaining wall. This should include original drawings, notes and reports from previous inspections, and interviews with personnel familiar with the retaining wall to be inspected. The visual inspection may also be relevant to the behaviour and stability of the retaining wall. Even though the examination is visually based, it can be supported by measurement and simple testing to gather additional data. Routine inspections serve to document sufficient field observations/measurements and load ratings needed to:

- Determine the physical and functional condition of the retaining wall.
- Identify changes from the previously recorded conditions.
- Determine the need for establishing or revising a weight restriction.
- Determine improvement and maintenance needs.
- Ensure that the structure continues to satisfy present service and safety requirements.
- Identify existing problems, inventory changes from the previous inspection and concerns of future conditions.

Visual inspection is a very common inspection technique 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 shall be inspected every two years (biennially), although the inspection interval can 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. Degradation mechanisms, such as settlement, deformation, overturning, erosion, vegetation and undermining of the retaining wall can be observed using this monitoring technique.

7.3.2 Key advantages of the technique and notable issues

The basic principle of direct visual inspection is a thorough attention to detail. The most common tools used by inspectors include gauges, templates, micrometres, rulers, levels, chalk, illumination devices, cameras, note taking devices, and other miscellaneous equipment.

Sight limitations could be a result of inaccessibility due to obstructions, hazardous conditions or deficiencies of a scale not visible to the naked eye. When such unfavourable field conditions arise, aids may be required to permit effective visual inspection, implementing the technique of remote visual inspection.

Other advantages:

- low cost of the method;
- immediate data for viewing and analysis;
- no need for advanced technically sophisticated crew.

Other disadvantages:

- inaccessibility due to obstructions;
- the “human factor” that is often encountered (Qasrawi 2000).

7.3.3 Current Status of the technique and expected developments

Whilst inspection of retaining walls is mainly performed purely manually, there is a gradual shift towards the use of supporting technologies, incorporating the use of video camera systems with frame grabber and picture store, which is often accompanied by PC-based picture libraries, allowing additional examinations to take place off-site. Furthermore, in cases of unfavourable and inaccessible field condition, remote visual inspection which involves the effective use of optical instruments can provide efficient solutions. These instruments include mirrors, borescopes, charged coupled devices (CCD), and remote miniature cameras.

7.4 Automated Monitoring Systems

7.4.1 Introduction to the M&E technique applicable

An innovative automated monitoring system providing near real time retaining wall monitoring has recently been developed by GEO-Instruments (Geo-Instruments 2010). GEO's Early Warning System provides settlement, rotation, and displacement measurements of wall movements 24 hours a day on 15 minute intervals. Stakeholders are immediately notified via e-mail and text messaging in the event of any wall movement detected that is greater than the alarm thresholds specified by the design engineers.

The instrumentation of this automated monitoring system consists of:

- 41 horizontal electrolevel beam sensors and 10 vertical electrolevel beam sensors,
- 6 liquid level sensors to measure wall settlement/heave,
- 34 vertical tilt meters to measure cumulative wall displacement and rotation,
- 18 vibrating wire crack meters to measure rock extension/contraction.

7.4.2 Output from the technique

GEO's Early Warning System is capable of providing data which is collected every 15 minutes (user selectable), processed on one of Geo-Instruments Servers and then updated to a password protected client accessible web site. This allows the viewing of overall maps, with colour coded symbols used for each sensor. Additionally, each sensor data box can be "drilled down" to provide trend graphs for the past month (Geo-Instruments 2010).

7.4.3 Key advantages of the technique and notable issues

The automated monitoring system developed by GEO-Instruments offers the significant advantage of providing near real time monitoring of retaining walls, since measurements are carried out 24 hours a day every 15 minutes. Furthermore, stakeholders are immediately notified in the event of any wall movement that is greater than the specified thresholds. The early data of the earth movements can provide sufficient information and the use of the system can offer design and construction engineers a peace of mind during difficult projects (Geo-Instruments 2010). Despite these advantages, issues such as the expensive installation and the complicated setup that the instrumentation requires need to be taken into account.

7.5 Laser Scanning or Light Detection and Ranging (LiDAR) Systems

7.5.1 Introduction to the M&E technique applicable

As urban densification continues to grow and above ground space increases in value, retaining wall systems need to be installed deeper and under greater difficulty. The use of traditional monitoring techniques is getting increasingly complicated due to crowded sites, third-party permissions and the installation geometries. Given this, the attractiveness of terrestrial laser systems, usually referred to as light detection and ranging (LiDAR) systems, has recently gained increasing attention.

Lasers have been used for over a decade to detect defects in a wide variety of industries, while LiDAR in particular has been used for risk evaluation for a wide range of Civil Engineering subjects. LiDAR provides the capability to rapidly make multi-point measurements over a large area, which makes this technique attractive for retaining wall monitoring.

Terrestrial laser scanning, or LiDAR, is a non-contact method for taking physical surface measurements, allowing visualizations of scanned surfaces in a digital 3D environment. The technique converts ‘bounce back’ information using laser pulses to build a 3D digital model of the surface monitored. The technology is based on the fact that light travels in a straight line at a known speed (Laefer and Lennon 2008).

7.5.2 Output from the technique

LiDAR systems enable operators to quantify measurements of surface features and orientation, with reference to surrounding features, such as building or to reference targets placed within the scan area. The laser pulse is emitted in a controlled vertical sweeping motion as the machine rotates in the horizontal to sweep the scan area. Subsequent scans are merged into one model using the reference points generated from the reference targets and any alteration in position can thus be visualized and measured. Reference targets are also used where a number of scan stations are required, as in the case of sheet piling monitoring, to build a complete image of a subject area (Laefer and Lennon 2008).

The scanner can be set for slow data collection thereby increasing the point density if required. However, selecting a scan density does not mean collecting the maximum data possible. Collecting excessive quantities of data only makes storage and processing problematic, so attention needs to be drawn on this issue.

7.5.3 Key advantages of the technique and notable issues

The decreased cost and increased processing speed for terrestrial laser scanners have made this remote sensing technique much more attractive. Furthermore, the approach has two major advantages over traditional surveying:

- absolute measurements are collected, as opposed to relative ones because they are based on a global positioning registration;
- the ability of the technologies to highlight cracks in masonry.

Attention needs to be drawn on the process of selecting a scan density using LiDAR systems. A common error is in the framing of the object to be scanned. Unnecessary time, resources and effort are expended, if unessential background elements are included.

Furthermore, the quality or the intensity of the laser bounce back depends on surface characteristics and atmospheric conditions. Dust and moisture in the atmosphere degrade feedback quality and can result in void areas due to scatter.

Other disadvantages:

- high cost of the equipment;
- atmospheric conditions are a known source of error for the instruments;
- more extensive need for technically sophisticated survey crew.

7.5.4 Current Status of the technique and expected developments

Terrestrial LiDAR scanning can offer some additional benefits over traditional survey methods with respect to an objective permanent record that can be free from any large-scale subsidence that the area may be experiencing. Since the laser scanning process is non-tactile, it need not interfere with on-going earthworks, especially since there is no need to install any monitoring equipment directly onto the retaining wall. However, despite major advances in the equipment and software, the technology is not a panacea and arguably not fully ready for the task of automated retaining wall monitoring and some challenges with respect to registration and displacement monitoring still remain (Laefer and Lennon 2008).

7.6 Other techniques used

- **Ground Penetrating Radar (GPR).** The technique of GPR, which has been described in detail in Section 5.8 of this report, can also be applied in the inspection of retaining walls.
- **Inclinometers.** Inclinometers are used to measure lateral ground movements in abutments, foundations, embankments, structures, and consolidation induced settlement in embankments and foundations. Measuring settlement by the vertical movement of inclinometer casings has now largely replaced the earlier method using Internal Vertical measurement devices. Further information can be found in Section 3.5.

7.7 Summary Table

Table 7.1 Monitoring and Examination (M&E) techniques and Degradation Mechanisms (DM) affecting retaining walls[6]

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

Section 7. Retaining walls

DM / M&E	Water presence	Erosion	Differential settlement	Vegetation	Undermining	Fatigue deterioration	Corrosion	Creep
Visual Inspection	✓	✓	✓	✓	✓	✓	✓	✓
Automated Monitoring			✓		✓			✓
Ground Penetrating Radar		✓		✓	✓	✓	✓	
Laser Scanning (LIDAR)	✓		✓	✓				✓
Inclinometers			✓		✓			✓

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

8. Discussion

This report, which is the first of three MAINLINE WP4 Deliverables, provides an overview of currently available Monitoring and Examination (M&E) techniques in relation to modelling degradation processes in a selection of railway assets. This Deliverable (D4.1) reviews currently used methods, summarises the pros and cons of each technique, draws on the suitability of these methods according to the degradation mechanism and railway asset they apply to and identifies gaps and issues to be addressed in the next stage within WP4.

Monitoring and Examination techniques vary from the traditional visual routine inspection to the remotely operated real-time monitoring systems with the use of sensors and wireless communication. Each of these methods offers different capabilities and varies significantly in terms of cost, applicability, validation and credibility. Despite recent technological advances, Visual Inspection was found to be very advantageous and the most applicable technique overall. This technique is widely used in the rail industry and forms the first approach to inspection of any of the five investigated assets. In particular, the cost-effectiveness and the high applicability of visual inspection offer major advantages to this technique. The benefits of Visual Inspection seem to override the disadvantages of the technique in terms of the possibility of human error in measurements and the subjectivity in the interpretation of the results that the technique entails.

Technological developments have enabled Non-Destructive Testing (NDT) techniques to be increasingly adopted in the Monitoring and Examination of railway assets. Some of the techniques are in their infancy and research is on-going to adapt them to meet the specific requirements in their application. Ultrasonic Testing (UT) provides an accurate and reliable method, although rail foot defects and surface rail defects smaller than 4mm may be missed at high speeds. In addition, the use of ultrasonic testing is limited to speed systems of no more than 70km in order to provide reliable output. Eddy Current (EC) method is also limited to the same speed range and can be affected by grinding marks on the rail and lift-off variations, which are identified gaps of this technique. With regards to Alternating Current Field Measurement (ACFM), the inability to detect sub surface defects in track inspection and the lack of high speed system capable to employ this technique are the main issues to be taken into consideration. The method of Automated Visual Inspection offers great potential. However, the uncertainty of reliable detection of surface breaking defects at speeds more than 4km/h needs to be addressed in the future. Magnetic Flux Leakage (MFL) can only be applied for speed systems of up to 35km/h, whilst further gaps lie in the fact that cracks smaller than 4mm cannot be detected and the performance of the method decreases significantly at high speeds. Light Detection and Radar (LiDAR) systems enable data collection under a variety of environmental conditions and quick efficient storage and process of data. The need for greater resolution at high speeds led to the improvement of the laser emitters of LiDAR systems, which can use multiple beams and rotate at higher speeds. However, it needs to be taken into account that these features increase the cost of the method. In addition, this technique requires the manual determination of the angle and the height for each of the chain lengths and offers relatively low longitudinal resolution. Finally, the inability to obtain measurements from objects at oblique angles or from the surface of water is a further issue that needs to be addressed in the future. In Time Domain Reflectometry (TDR), the main gaps surround the cost aspect as well as the time required for the measurement.

Overall, a large number of M&E techniques are currently available with various applications in the rail industry as shown in Table 8.1. An efficient integrated asset management system must ensure that these are not considered in isolation leading to information that is not used in an optimal way or surplus to requirement.

Table 8.1 Monitoring and Examination techniques used for different types of railway assets

M&E \ Assets	Cuttings	Metallic bridges	Tunnels	Plain line and S&C	Retaining walls
Visual Inspection	✓	✓	✓	✓	✓
Laser Scanning (e.g. LIDAR, Clearance Gauge etc.)	✓	✓	✓	✓	✓
Interferometry	✓	✓		✓	✓
Geodetic Measurements (tools, inclinometers etc.)	✓		✓		✓
Strain Gauges/Tapping Tools		✓	✓	✓	
Video/Digital Image Analysis	✓		✓	✓	
Eddy Current		✓	✓	✓	
Ultrasonic Testing		✓	✓	✓	
GPS-based methods	✓	✓			✓
Acoustic Emission	✓	✓			
Time Domain Reflectometry	✓				✓
Electromagnetic methods (e.g. ACFM)		✓		✓	
Impact Echo			✓		✓
Ground Penetrating Radar			✓		✓
Magnetic Flux Leakage (or MPI)		✓		✓	
Radiographic Testing		✓		✓	
Optical Fibre Monitoring		✓	✓		
Dye Penetration Testing		✓			
Fatigue Monitoring		✓			
Thermography (or Thermal Imaging)			✓		
Resonance Inspection			✓		
Time of flight method			✓		

In relation to Examination activities, risk based approaches are increasingly seen as cost-effective and practical means of maintaining asset integrity. There is realisation that there is both a statutory and operational need for suitable and sufficient risk-based approaches and assessments of railway engineering infrastructure. In order to eliminate intolerable risks and reduce all remaining risks, a quantitative risk assessment is usually required. Qualitative methods have limitations: they may be subjective and may give arbitrary measurements of risk. However, in some situations, Qualitative risk assessments are the only practical options.

Overall, a quantitative risk model that provides the absolute risk, the potential risk reduction, the cost-benefit analysis, the individual risk and an assessment of as low as reasonably practicable (ALARP) is a powerful tool to the railway programme planner. However, the role of engineers in quantitative risk assessment is vital; they should be involved at every stage of the development of a risk model and need to be aware of the functionality and limitations of quantitative risk analysis (Ross and Reid 2003). Engineering input to this process is particularly essential at the earliest stage, when consideration must be given to what data is already available, its reliability and to what data can conceivably be collected.

Even though emerging M&E techniques are increasingly applied worldwide, they suffer from low uptake due to a number of factors. These factors include the fact that Visual Inspection is perceived as a relatively reliable, cost effective and accurate technique in the rail industry. Furthermore, many M&E methods have not yet been validated in a practical context, which forms another barrier in their application. Not only validation and, thus, credibility but also time and speed are key factors affecting significantly the applicability of each technique. In addition, issues such as accessibility and compatibility can have considerable effect on the attractiveness of an M&E method to rail operators/ asset managers. Some M&E techniques may require a power source that itself needs to be replaced or maintained periodically requiring the use of additional resources. Finally, the decision on which M&E technique to use is also dependent on the cost of its implementation. Some techniques may, for such and other reasons, be applied only to special cases as opposed to routine M&E. Railway operators are often unsure that emerging systems represent good value for money and their scepticism can only be overcome if the accuracy and reliability of a technique are combined with cost-effectiveness and validation provided.

9. Conclusion

This report reviews currently applied M&E techniques as they apply to various degradation mechanisms in the types of railway assets considered within MAINLINE. This task is carried out with a view to identifying gaps and improving in a cost effective way the compatibility between such techniques and degradation models in an integrated asset management decision support tool.

The report reviews currently used key M&E techniques as they apply to respective degradation mechanisms in a selection of rail assets. Five different types of railway assets were considered: (i) cuttings, (ii) metallic bridges, (iii) tunnels with concrete and masonry linings, (iv) plain line and switches and crossings, and (v) retaining walls. Visual Inspection, strain gauge and tapping tools, geodetic measurements, acoustic emission, laser scanning, fatigue monitoring, video/image analysis, ultrasonic testing and eddy current are among the most widely used M&E methods. Although there are advances in sensor technologies and NDT, this review finds that visual inspection plays a vital role in the M&E process and in many cases forms the main technique used. A combination of concerns has resulted in reduced uptake of new technologies by the rail sector.

Each of the M&E techniques reviewed throughout this report offers a number of different capabilities and their applications vary significantly in terms of time, cost, applicability, compatibility, validation and credibility. Despite recent advances in sensor technologies and NDT, Visual Inspection as a technique plays a crucial role in the M&E process and in most cases forms the main technique used. Visual Inspection is perceived as a relatively reliable, cost effective and accurate technique in the rail industry.

The review of M&E techniques also shows that for many of the rail assets, it is Examination or Inspection (these terms are synonymously used for the purpose of this report) that is usually undertaken first. This is followed by Monitoring as required or decided using such Inspection reports.

There is a need to optimally incorporate M&E techniques based on their strengths in an integrated asset management system capable of providing accurate and reliable outputs in a timely and cost effective manner.

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Appendix

WP 4, Task 4.1: Document for discussion[7]

1. Aim of this document

To discuss and agree on 1) a definition/description of the term 'Monitoring and Examination (M&E)' as used within the remit of MAINLINE, and 2) questions to be asked in the WP4 Survey on M&E techniques.

2. Introduction

It is felt that it may be useful to clarify what we will mean by M&E as used within MAINLINE. A description of M&E is suggested here based on a review of relevant standards and suggestions from rail infrastructure managers.

WP4 involves a Questionnaire based survey to assess current M&E techniques that will be investigated in relation to the degradation models considered in WP2 that require inputs from them. There have been a number of Surveys relevant to M&E in the rail sector. This document takes cognisance of some recently carried out Surveys to draw up a provisional list of questions that may be included in the WP4 Survey.

3. Monitoring and Examination (M&E) terminology

MONITORING

The dictionary meaning of monitoring is to watch and check a situation carefully for a period of time in order to discover something about it. Within MAINLINE, Monitoring includes the following:

- Observing (visually) and recording of condition of an asset at regular intervals;
- Measuring and recording quantitative information periodically or continuously regarding the extent and nature of degradation of the asset. Examples of such information are: the locations and dimensions of areas affected, the length; width and depth of cracks; information from NDT using appropriate instrumentation.
- Continuously monitoring the condition of an asset with the aid of data loggers and remote monitoring techniques and automatic alarm systems, should monitored parameters go beyond pre-determined limits.

The above description takes into account the three classes of Monitoring mentioned in Highway Structures: Inspection and Maintenance Guide (UK, 2006). These classes are Basic Monitoring, Detailed Monitoring and Extensive Monitoring.

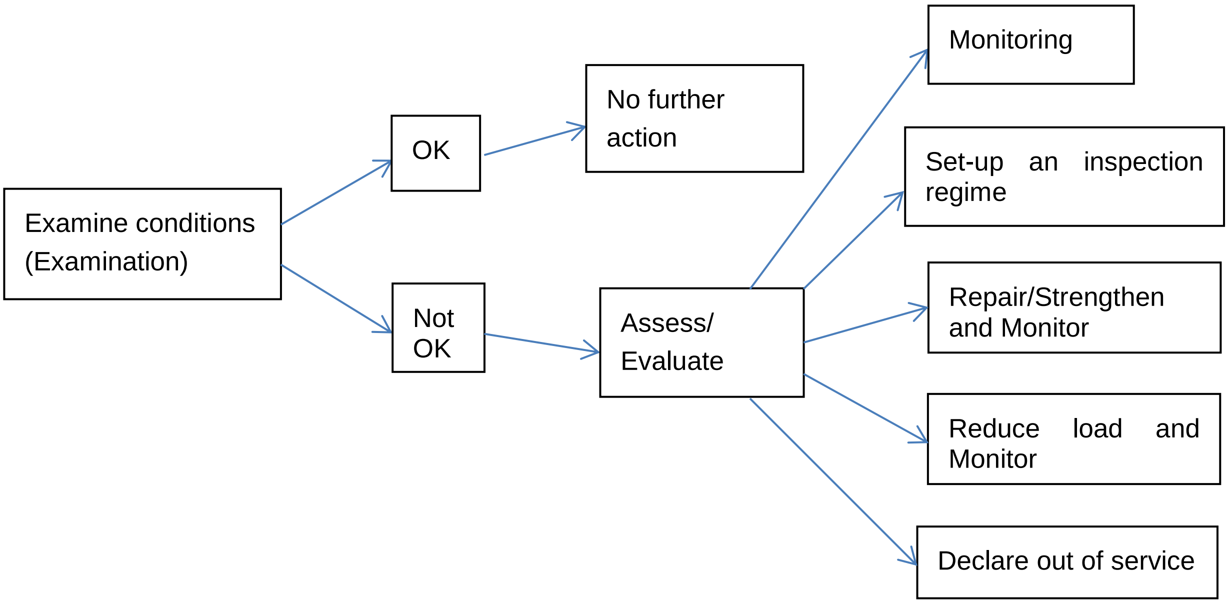
EXAMINATION

The dictionary meaning of Examination is to look at or consider something carefully to discover something.

[7] Following discussions, it was felt that a new set of Questionnaires would not add substantially to the information available from previous work and other MAINLINE Questionnaires.

Within MAINLINE, the term Examination is an event that includes making an observation, taking measurements and recording such information regarding the condition of an asset. Compared to Monitoring, Examination is a one-off event and not planned as a periodic activity; it may be done on a case-by-case basis; and it may employ techniques that are different to those used in Monitoring.

To distinguish between the two terms, consider a decision tree as below:



The 'trigger' for Examination would be some indication(s) that the asset requires attention.

The above description on what should construe as Monitoring and Examination is the result of discussion within the MAINLINE team. Of the documents/standards reviewed, none was found to compare and contrast examination with monitoring. There are several that differentiate between monitoring and inspection. Out of interest, one such description, albeit from a different industry sector (DNV, October 2012), is included here:

Inspection: An activity carried out periodically and used to assess the progression of damage[8] in a component.

Monitoring: An activity carried out over time whereby the amount of damage is not directly measured but is inferred by the measurement of factors that affect that damage.

4. WP4 Survey

4.1. Previous Surveys consulted

The following documents have been considered to draw up a provisional list of questions to be included in the WP4 Survey on M&E techniques:

- Questionnaire conducted within Mainline WP2 (November 2011)

[8] In MAINLINE, 'damage' is defined as the loss of performance of an asset caused by accidental events such as collisions, overloading or design and construction errors and is measured in terms of visual appearance or reduction of functionality.

- Questionnaire conducted by UIC Track Condition Monitoring project working group (2009)
- Questionnaire conducted by UIC S&C maintenance project (2008)

Within MAINLINE, five asset groups have been selected to focus attention on: Cuttings; Metallic Bridges; Tunnels with concrete and masonry linings; Plain line and Switches and Crossings (S&C); Retaining walls.

The questions relevant to M&E asked in the MAINLINE WP2 Questionnaire are:

Q3: How is this degradation monitored or inspected?

Q10: Do you have accessible inspection or monitoring data for this mechanism?

Q11: What key parameter(s) is/are recorded through monitoring or inspection?

Q12: Is monitoring continuous or periodic? (please state the relevant time intervals/parameters).

Monitoring and Examination techniques/systems pertaining to the selected assets as mentioned in the answers to the questionnaire appended in D2.1 of WP2 involve:

Cuttings: Visual walk-over inspections; taking down inclinometer readings, displacement meter readings, and geodetic measurements.

Metallic bridges: Visual inspection; conducting dye penetrant test, ultrasonic testing (rarely done); using depth gauges, conducting deformation measurements by extensometers, measurements by laser scanning, conducting bond test, assessment by hammer tapping, use of torque spanner, visual inspection supported occasionally by Non-Destructive Testing (NTD)/partially destructive testing, emerging electromagnetic techniques, and acoustic emission monitoring.

Tunnels with concrete and masonry linings: Visual and tactile examinations, inclinometer/ extensometer readings, periodic inspections as per relevant manuals.

Plain line and Switches and Crossings: regular inspections in relation to loading, periodic visual inspection, recording car, Ultrasonic NDT, and Switch blade deflector.

Retaining walls: Visual inspection and geodetic survey.

4.2 List of Questions to be asked in the WP4 M&E Survey

4.2.1 General questions common to all Asset types

- Does M&E involve visual observations? If so,
    - how often and how are observations recorded? Please mention the form of recording - for example, photographs are taken and saved for records.

- Does monitoring involve measuring and recording quantitative information? If so,
    - What is measured?
    - What instrumentation is involved in measurement and recording?

- Is it a continuous or periodic monitoring?

- Is monitoring done remotely or does it involve on-site M&E personnel? Or both?

- How is the output from the M&E technique used?

- What is your assessment of the reliability of the M&E technique?

- Measure of cost-effectiveness of the technique.

Below are specific questions that pertain to the different types of assets. These are mainly based on MAV inputs. The final list of questions will collate all specific questions suggested from WP4 partners. If there are specific questions that do not cover the general questions discussed above, then appropriate additions will be made to the list. If there is duplication in the specific questions that too will be removed in the final list of questions.

4.2.2 Cuttings

(Assuming sub-structure under track is also part of Cuttings)

1. What is the frequency of monitoring? Is it remote monitoring?
2. Do you have prescribed examination/measurement criteria in connection with Cuttings? If yes, then what kind of technology/methods and equipment/instruments do you use?

   What do you measure and where (e.g. where do you place the instruments/sensors on the structure)?
3. Do you have substructure database? If the answer is yes, then how do data monitored/measured get to the database? (manual input, palmtop-laptop-PC connection, scanning, usage of digital forms, editable, etc.).

4. Questions on the usage of ground penetration radar (georadar):

- Where do you use it? (main line? secondary line also? Only for lines being before reconstruction?)
- For what do you use georadar measurement (e.g. check on measurements taken by other means? Or is it part of the regular track inspection? If yes, what is the frequency?)
- What is the inspection depth?
- What kind of parameters do you evaluate from the measurement results?

4.2.3 Metallic Bridges

1. Besides visual inspection, what type of M&E instrumentation do you use? What is the frequency of such examination and in which cases is such examination applied?
2. Do you use NDT methods for the examination of bridges? If yes, what is the type of technique used? In which cases is it used? How do you use the results of such examinations?
3. Do you use a bridge condition monitoring system with sensors and other instruments? If yes, what is the typical frequency of collecting data? Do you use online, real time continuous monitoring? Do the sensors require maintenance? How are they powered?
4. What kind of degradation mechanism can be monitored by the sensors used?

5. On a scale of 1-10, what is your assessment regarding the reliability of the applied sensors or monitoring devices?
6. How do you use the output from the instrumentation involved? Are outputs used in a model to analyse degradation?
7. In what format do you store the data measured?
8. Is your monitoring system a part of an integrated infrastructure management system? What are the main features of your system?
9. How can your M&E technique be used more cost-effectively?
10. What development would be required to increase the uptake of the M&E technique?
11. Specific questions:
    a. Do you conduct measurements concerning the fatigue of structures (e.g. Barkhausen noise, etc.)?
    b. Do you conduct displacement measurements of bridges as a matter of routine or for special cases?
    c. Do you take temperature measurements of bridge structures? If so, how are these measurements used?
    d. Does your examination include a measure of corrosion protection on bridges (e.g. depth of paint layer, adhesion, etc.)? If yes, how often is such an examination carried out?

4.2.4 Tunnels with concrete and masonry linings

1. Besides the visual inspection do you execute special instrumented diagnostic/monitoring examinations?

If yes:

a) What is the frequency of examinations and in which cases are they applied?

b) What kind of instruments do you use during the examinations?

2. Do you use non-destructive testing methods for the examination of tunnels?

If yes:

a) What are the types of techniques used?

b) In which cases are NDT techniques used?

c) How do you use the results of the examinations?

3. Do you use condition monitoring system with sensors or with other instruments?

If yes:

Questions same as in the Bridge section above.

4.2.5 Plain line and Switches and Crossings (S&C)

The UIC S&C Maintenance project (2008) included an extensive questionnaire on S&C. Nine rail operators including SNCB, Network Rail and MAV answered this questionnaire. The same set of questions could be asked to those rail operators who did not participate in the 2008 questionnaire.

4.2.6 Retaining walls

1. Do you use continuous, automatic, remote monitoring (remote inspection) system to retaining walls? Please comment.

2. Do you have prescribed examination/measurement criteria in connection with retaining walls?

3. If the answer for 2 is yes, then what kind of technology/methods and equipment/instruments do you use?
What do you measure and where (e.g. where do you place the instruments/sensors on the structure)?

4. If the measurement described in point 2 and 3 is regular, then how often do you do it?

5. Do you have substructure database?

6. If the answer for Q5 is yes, then how do data monitored/measured get recorded database? (Manual input, palmtop-laptop-PC connection, scanning, usage of digital forms, editable, etc.).

7. Questions on the usage of ground penetration radar (georadar):

- Where do you use it? (Main line? Secondary line also? Only for lines being before reconstruction?)
- For what do you use georadar measurement (e.g. check on guarantee measurements taken by other means? Or is it part of the regular track inspection? If yes, by what is the frequency?)
- What is the Inspection depth?
- What kind of parameters do you evaluate from the measurement results?
- Is there an automatic evaluation for georadar measurements?

<u>References (Appendix):</u>

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