INNOTRACK

Integrated Project (IP)

Thematic Priority 6: Sustainable Development, Global Change and Ecosystems

D6.4.2 Models and monitoring methods for LCC and RAMS relevant parameters

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

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Glossary

Abbreviation/acronym	Description
DeCoTrack	Degradation Cost of Track
Final state	The estimated state and cost for the railway system, after the contract ended.
FMECA	Failure Mode, Effects and Criticality Analysis
LICB	Lasting Infrastructure Cost Benchmarking
LCC	Life Cycle Cost
MART	Mean Active Repair Time
MDT	Mean Down Time
MMH	Mean Maintenance Hour
MTBCF	Mean Time Between Critical Failure
MTBF	Mean Time Between Failures
MTBSAF	Mean Time Between Service Affecting Failure
MTTF	Mean Time To Failures
MTTM	Mean Time To Maintain
MTTR	Mean Time To Restoration/Mean Time To Repair
MWT	Mean Waiting Time
Origin state	(current situation) is the condition and cost for the railway system before the contract starts.
PPM	Passenger Performance Metric
RAMS	Reliability, Availability, Maintainability and Safety
RCF	Rolling Contact Fatigue
ROI	Return on Investment
S&C	Switches and crossings
Stratoforce	Strain TO Force way side detector
TETrAS	Technical and Economical Track Assessment
VTISM	Vehicle Track Interaction Strategic Model

1. Executive Summary

It is vital to be able to measure and monitor the asset management process for the railway infrastructure. Key values for RAMS (Reliability, Availability, Maintainability and Safety) and LCC (Life Cycle Cost) need to be developed and transformed to a railway user environment that can be adapted for operation and maintenance. The use of LCC and RAMS is in its infancy and furthermore very few use LCC and RAMS in their contracts. LCC and RAMS as a concept and method is not clearly defined or adapted for railway facilities which, unlike the industry have assets in geographic extent, affected by climate and the traffic that operates the track. One value e.g. the MTBF (Mean Time Between Failure), can vary with the seasons, the tonnage that operates over the asset, distance, etc. It is therefore too early to go out and recommend the values to be measured and how. Key values for RAMS and LCC needs to be developed and transformed to a railway user environment.

Periodic reporting of key figures must be ensured for different kind of organisations e.g. client/contractor organisation even if maintenance is outsourced. Arrangements for this must be developed as well as methods and tools for exchange of key data between parties involved in the railway system, i.e. infrastructure managers, traffic companies, supplier, contractor, etc. Also methods to measure and monitor changes that affect the operation of the assets of which the supplier or the contractor have no influence needs to be developed.

The development can be accelerated by the parties learning from best practice, e.g. by enhanced cooperation between the partners involved in infrastructure asset management and by starting the use of method and tools already in use.

Such methods and tools are DeCoTrack, VTISM and TETrAs. Some equipment for monitoring traffic characteristics are Stratoforce, Argos and DafuR-system and there are also some templates and handbooks describing how to implement e.g. LCC and RAMS.

Finally, when the objectives are developed for the future activities, they must be in harmony with the objectives of the ERRAC white papers regarding transport.

These main targets of this project and the future needs to be taken into account are:

- Reduced life cycle costs by 30%
- Improved travel time by 25-50%
- Doubling of passenger traffic and triple-freight by 2020
- Reduction of noise to 69 dB for freight and 83 dB for high speed traffic
- Increasing safety - reduced fatalities by 75%
- Increased axle loads
- Increased speeds
- Improved RAMS

2. Introduction

It is vital to be able to measure and monitor the asset management process for the railway infrastructure, see Figure 1. LCC and RAMS technology are two acknowledged methods for assisting the optimisation process. Key values for RAMS (Reliability, Availability, Maintainability and Safety) and LCC (Life Cycle Cost) needs to be developed and transformed to a railway user environment and be adapted for operation and maintenance.

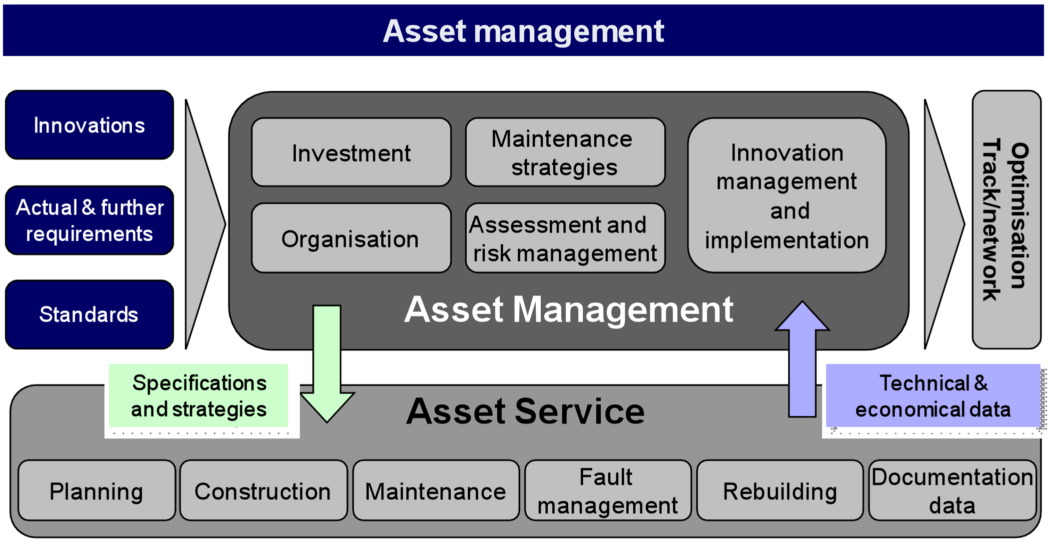


Figure 1: The optimisation process of assets needs RAMS and LCC relevant data

This report is included in InnoTrack sub-project 6 LCC and covers the subject of using RAMS and LCC in contracts.

Earlier finding's in INNOTRACK shows that LCC and RAMS is in an infancy state of use in the railway transport industry. The ability to measure and monitor the transport system and the asset management process are also affected by how the organization is structured. The organisation for asset management can be:

1. Included in a "One entity railway" operating both traffic and track, i.e. different in-house departments are planning, operating, maintaining the traffic, and constructing, renewing and maintaining the infrastructure. The organisation has internally the opportunity of getting control over both of traffic and infrastructure management, i.e. volumes of train traffic, traffic mix, type of vehicles and their maintenance standard and asset conditions and degradation rates.
2. "One entity Infrastructure manager", i.e. managing the operation and maintenance, renewal and new investment of infrastructure assets. Such an organisation is dependent on traffic statistic from Traffic Operating Companies.
3. A client/contractor organisation, i.e. buying all or parts of new investments, renewal and operation and maintenance from external or internal contractors.

The type of organisation will affect the infrastructures manager's possibilities to steer the maintenance process, see Figure 2. A client/contractor organisation will make it difficult to obtain good control of the maintenance process. The activities within the dotted box can be included in purchased maintenance and might be impossible to control by the infrastructure manager depending on the kind of contract, e.g. lump sum performance contracts.

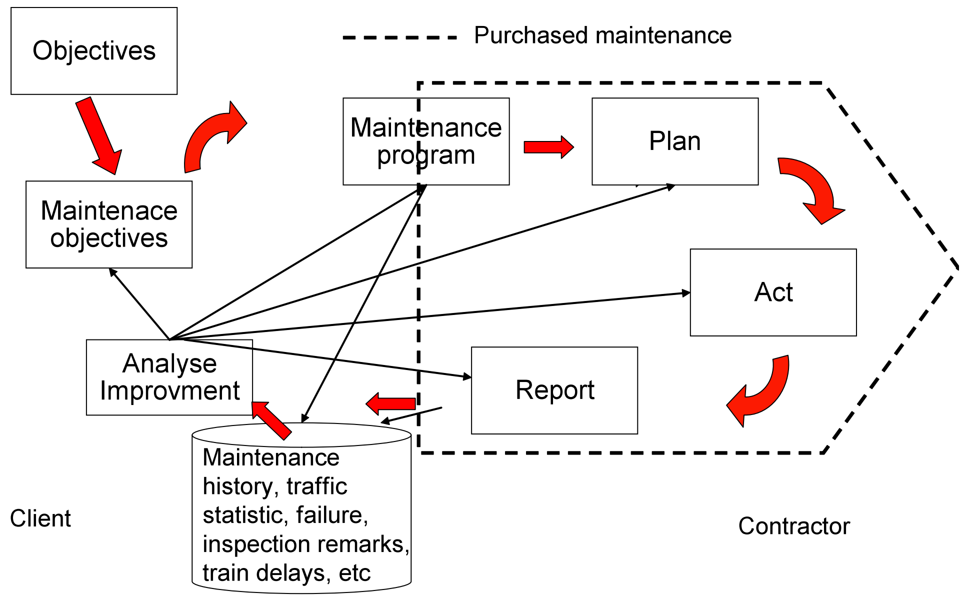


Figure 2: Maintenance process (Åhrén, T and Nissen A, (2005), "The black Box" PowerPoint presentation, www.jvtc.ltu.se)

It is necessary that the suppliers selling products/assets with LCC commitments will get feedback from the maintenance process i.e. how the stipulated maintenance strategy is conduced. The supplier also has to receive data for failure statistics and inspection notes as well as information on changes in traffic, i.e. how the assets are operated

Therefore this report has restraint from the ambition of forming detailed guidelines of how to use LCC and RAMS in contracts. This report will focus on key values and tools that are already in use, as a first step for future monitoring key values for LCC and RAMS.

The perspective for the life cycle costing will be the situation when the infrastructure manager must take a decision to make a change due to e.g. decreased availability or reliability, or implementing a new innovation on an already existing railway section/line/subsystem.

2.1 Information acquisition

Information about how RAMS and LCC are used in contracts was obtained from following sources:

- Deliverable 6.4.1
- Results from WP 6.4.1 questionnaire
- Discussion and telephone conversation with infrastructure managers and suppliers.
- Previous related reports from INNOTRACK.
- Documents, handbooks and templates from e.g. Network Rail, ProRail and Voestalpine
- Scientific papers, reports

2.2 Aim and objectives

The aim is to derive a definition of national and international key values for LCC and RAMS in contracts.

The objective is:

- Definition and monitoring methods required to audit arrangements

2.3 Activities/method

1. Review current information from earlier work in INNOTRACK and gathering those key values in use
2. Review of parameters in use by the UIC project Lasting Infrastructure Cost Benchmarking, LICB
3. Assembling current information to a template
4. Description of current situation and tools in use

2.4 Organisation and Resources

The organisation and resources for this work package are given in Table 1. Banverket is responsible for the delivery of WP 6.4 which includes deliverables D6.4.1 and D6.4.2.

Table 1. WP 6.4 Organisation and resources

Workpackage	**6.4 – RAMS and LCC in contracts/wordings/policies**							
Participant id	UIC	VAS	BV	ADIF	Alstom	OBB	DB	CORUS
Person-months per participant	1,96	0,30	2	0,5	0,50	1	1	0,4

A reference group was selected, in order to conduct a broader survey. Participants in the reference group were Balfour Beatty, Carillion, České dráhy, Network Rail, ProRail, Speno and VAE.

3. Monitoring Measures for LCC and RAMS

This chapter will suggest how to introduce monitoring measures for LCC and RAMS in contracts for substructure, switches and crossings (S&C) and track (i.e. permanent way/superstructure). The result is summoned up in a template, see Annex 2.

Type of organisation and contract, and contract forms will not be regarded. Focus will be on the operation and maintenance phase.

3.1 Management process

The process starts, see Figure 3 with new demands from customers and stakeholders or when the IM reaches a critical point in the management of infrastructure where:

- Cost for corrective maintenance has increased over a level of 20 % of the total maintenance cost, meaning that the IM starts to lose control of the maintenance (Wireman, 2004).
- Asset has reached its technical life time or the standard is decreasing and needs to be renewed, modified or replaced.
- The duration of the maintenance contract has reached its finalisation and it is time to purchase a new contract for e.g. operation and maintenance.
- Maintenance costs are too high.
- Failure rate has increased.
- Unavailability causes train delays.
- Etc.

The optimisation process can address single components, modules, sections, lines or the whole network. Due to the increasing numbers of dependencies the complexity of the analysis strongly grows from the component to the network. A pre-analysis may be useful to focus on the main issues or parts.
Before a decision can be taken, the current situation (Origin state) is described and objective formed for a future/expected performance (Final state). In order to estimate the future performance and cost. Low resolution models can be used that has a more global overview of the railway system and economic outputs. They are used to predict the impact on the whole rail system of changes to the sub-systems of trains, traffic and track. Different alternatives can be:

- prolong life length,
- modify,
- renew,
- replace with new construction.

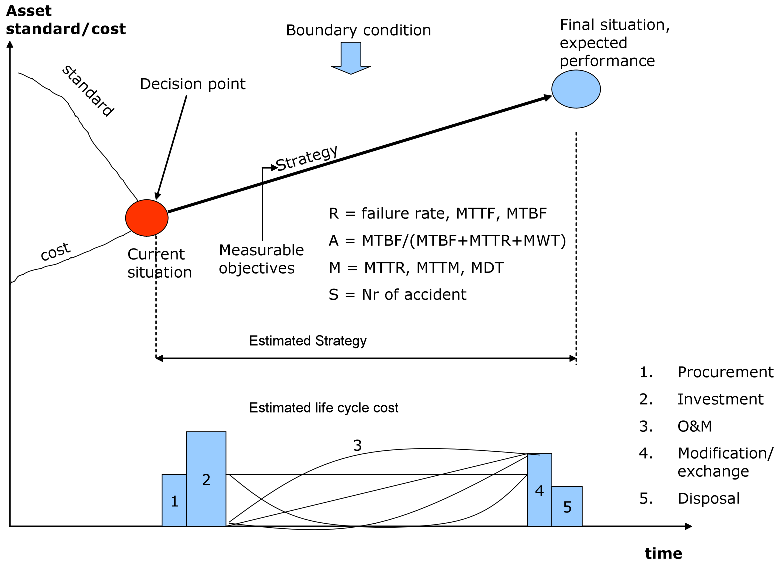


Figure 3: Management process

In order to reach the objectives, the reliability, availability, maintainability and safety values for each alternative must be specified, estimated and calculated. The result is then used to form a strategy. The cost can be divided into cost for procurement, investment, operation, modification and disposal. The cost during the O&M-phase can follow different curves, e.g. increase with age and use, or be constant, see Figure 3. The curves for the cost during the operation phase will be different depending on the chosen maintenance strategy and can be altered by changes in boundary conditions.

The objectives should be formulated strategically - i.e. what you want to achieve in the long term -, tactically - how best to achieve them-, and operationally, - i.e., how to implement them in the short term (daily activities/routines). They should also be measurable and possible to monitor. It is also vital that it will be possible to monitor changes in boundary conditions.

3.2 Origin state (current situation)

Origin state is often equal to alternative “Zero”, do nothing, continue as usual. When defining the origin state, the following must be known, see also Annex 2 Template:

- Scope for the contract, e.g. Line A between City X and Y.
- Duration for the contract.
- The system/subsystem/component’s standard:
    - What kind of substructure. Amount of cuttings, slopes, curvature, etc.
    - Maximum speed, maximum allowed axle load.
    - Permanent way, single/double/triple track, track components and track parameters.
    - Density of S&C (see LICB – Glossary, see Annex 1), type of S&C.
- The system/subsystem/components age and condition e.g. could be expressed in failure rate as function of age and use or by track quality index.
- The availability of the track – expressed in delay time or non-available time.
- Current maintenance strategy, condition based, predetermined. Amount of corrective maintenance.
- Current traffic situation in Million Grosse Tonnes (MGT). Kind of traffic that is running on the line. Number of trains per type and their maintenance condition. Information about variation of traffic mix. Used track capacity.
- Cost for maintenance actions, minimum level preventive, corrective maintenance and cost for inspection, based on average costs for operation and maintenance and major changes over a 10 year period. Also if possible expressed as a function of use and age.
- Which are the cost drivers – caused by failures, caused by wrong maintenance demands/requirements/strategy.
- Which are the failure drivers which cause non-availability?
- Down time cost.
- Risk.
- Redundancy.
- Type of climate.

3.3 Final state / Objectives

The origin state describes the current situation and areas for improvement. The demands from e.g. the stakeholder combined with the origin state forms the basis for the work of finding realistic objectives.

These objectives shall take into account possible future needs for the European Railway like defined in the ERRAC White Paper like:

- Reduced life cycle costs by 30%,
- Improved travel time by 25-50%,
- Doubling of passenger traffic and triple-freight by 2020,
- Reduction of noise by 5 dB to 10 dB,
- Increasing safety - reduced fatalities by 75%,
- Increased axle loads,
- Increased speeds.

These requirements can only be achieved if the RAMS of the infrastructure will be improved and the wheel-rail interface, and the behaviour and characteristics of the vehicles optimised.

Different strategies of reaching the objectives pin point different alternatives that must be evaluated. A first rough evaluation can be implemented e.g. with so-called "low resolutions models".

3.4 Measures

Most commonly used key values to describe RAMS (see Annex 3) are: failure rate, MTBF (Mean Time Between Failure), MTTF (Mean Time To Failure), MTTR (Mean Time to Repair), train delay caused by infrastructure failures, hazard rate, number of derailment and number of accidents. Some other key values for RAMS are MART (Mean Active Repair Time), MMH (Mean Maintenance Hour), MTTM (Mean Time To Maintain), time for maintenance, MTBCF (Mean Time Between Critical Failures), MTBSAF (Mean Time Between Service Affecting Failure), MWT (Mean Waiting Time), and PPM (Passenger Performance Metric). IMs use key values on system, subsystem and component level while manufacturers and contractors use them on a component level. Most of these values are reported into different databases owned by the infrastructure manager. In general the feedback of technical performance of the track to the supplier of the components or modules does not exist. This is an important gap for a faster optimisation of the infrastructure.

LCC is partly used to find cost drivers in investment projects. Most commonly key values for LCC are cost for corrective and preventive maintenance mainly on subsystem level. The impact of using LCC is to get decision support for changing equipment and maintenance strategy.

These have been compiled in a template, see Annex 2.

3.5 Traffic Characteristics

There are different ways of monitoring how the track is operated. Traffic data (amount of vehicles, type of vehicles, tonnage etc) can be reported directly in the train management system by the traffic operating companies. Another way is to monitor and measure the traffic by way side equipment, i.e. wheel impact monitoring system. Other system of tracking traffic data are Stratoforce, DafuR or Argos (see chapter 3.6.4 - 3.6.6). In the future more data needs to be collected, e.g.

- Type of train and their maintenance standard – Yaw stiffness/wheel profiles
- Static and dynamic axle loads
- Speed

3.6 Models and Tools

During the project, a number of models, tools, manuals and templates have been identified. Some of these are useful in efforts to get the key values and measures of RAMS and LCC and shortly described in this chapter:

- Two low resolution models have been discussed within InnoTrack during the evaluation of a new slab-track system. Low resolution models have a more global overview of the railway system and economic outputs. They are used to predict the impact on the whole rail system of changes to the sub-systems of trains, traffic and track. Other low resolution models for vehicle track interaction as a method for determining track degradation are described in InnoTrack deliverable D1.3.2. There are also high resolution models with more detailed mechanistic modelling approach, see D1.2.6. One of those models, used by DB is TETrAs (Technical and Economical Track Assessment).
- Systems for monitoring and measuring traffic and tracking changes; three of these are Stratoforce, DafuR and Argos.
- One Handbook for using LCC and RAMS in contracts
- Templates, amongst these one for procurement, a spreadsheet for FMECA and a spreadsheet for determining the costs of planned and unplanned unavailability.

3.6.1 DeCoTrack – Degradation Cost of Track

DeCoTrack (Degradation Cost of Track) is a model for prediction of railroad track degradation.

The model simulates changes in degradation rate of the track due to changes in traffic characteristics. The inputs include for example parameters such as axle load, annual tonnage, speed, the mix of vehicle types and vehicle maintenance conditions. Outputs from the model are both service life of track and the estimated degradation cost. When developing the model, results from research studies reported mainly from Europe and North America were combined with classical mechanical engineering theories, and empirical data from the last 20 years of railway transports in Sweden. By establishing compatible interfaces between the different input sources, information became easy to adapt to the model which was gradually implemented into easy-to-use software.

The main focus of the model is to estimate changes in maintenance and in the track degradation rate when the traffic is changed. Therefore it is tuned to reflect the current situation after which future changes of traffic are simulated. The tuning is made by a set of key parameters for the studied track section:

- A value of the curve radius, r (m), where wear exceed fatigue as the dominant rail degradation mechanism. This corresponds to the break point in Figure 4. This parameter sets the relative weighing between k_u (coefficient for fatigue) and k_s (coefficient for wear)in the described mechanisms.
- An estimated service life of track with the current traffic volume. It is expressed as accumulated tonnage (MGT) at a free selectable curve radius.
- Annual maintenance costs that are supposed to be independent of traffic volume, from now on labelled $\mathbf{C_{ob}}$.
- Annual maintenance costs that are supposed to be dependent of traffic volume and proportional to tonnage. Such areas include costs for track reinvestment, ballast, inspections, costs due to accidents/derailment and other unspecified track components, This cost is from now on labelled $\mathbf{C_T}$.
- Annual maintenance costs that are supposed to be dependent on traffic volume and especially influenced by both axle load and tonnage. Typical costs include rail replacement, rail maintenance, tamping, turnouts and ties. The factor is from now on labelled $\mathbf{C_{ax}}$.

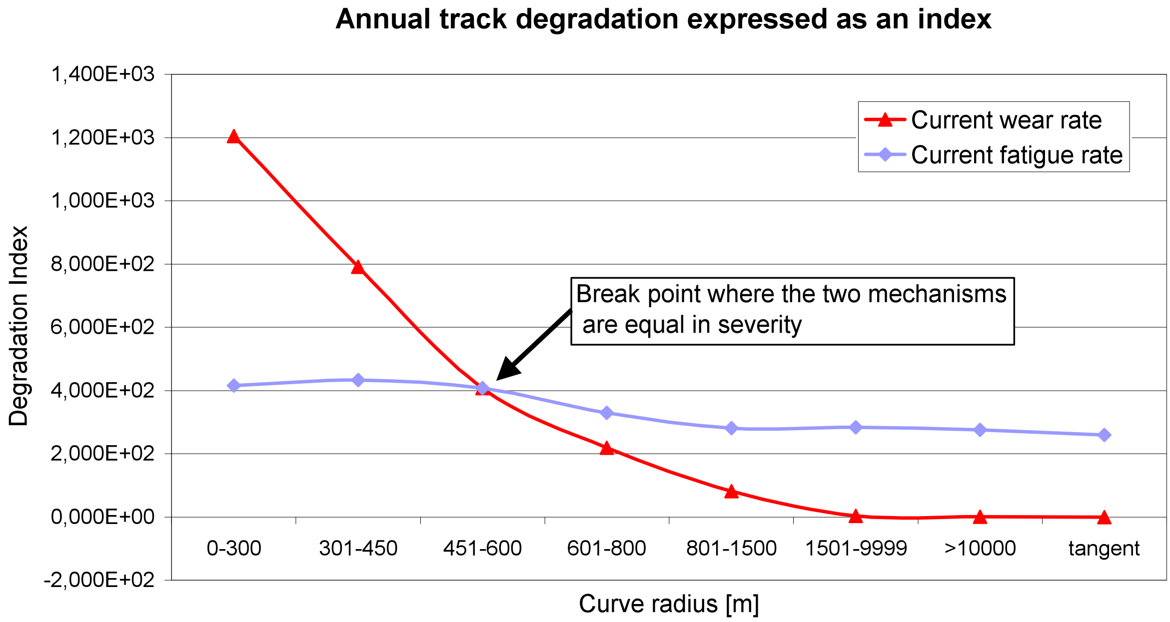


***Figure 4**: Wear and fatigue mechanisms as a function of curve radii. The degradation index corresponds to a relative degradation rate.*

When the key parameters are given, it is assumed that the current traffic has run unchanged for several years so that it can be expected to reflect the current maintenance volume. The key parameters are used for controlling the relative position between the plots in Figure 3 and to relate them to the actual rail life length. Entered maintenance costs make it possible to convert mechanical data into economical data and to distribute costs along the studied track section based on the underlying mechanical mechanisms.

The model converts mechanical degradation to economic terms by a linear conversion between technical life and annual traffic-related maintenance cost. In mathematical terms this is expressed as:

(1) $$C_{tr} = C_T(ref) * \frac{T}{T(ref)} + C_{ax}(ref) * \sum_{\substack{\text{curve} \\ \text{radius}}} L * \frac{\max(e_u, e_s)}{\max(e_u(ref), e_s(ref))}$$

where:

C_{tr} = Annual traffic-dependent maintenance cost

C_T = Annual maintenance cost, tonnage but not axle load dependent, for example track replacement costs

C_{ax} = Annual maintenance cost, both axle load and tonnage dependent

T = Annual tonnage

ref = Reference year, e.g. current situation

L = The normalised part [0-1] of total track length having a given curve radius interval

e_u = Degradation index due to fatigue and dynamic forces

e_s = Degradation index to wear

Formula (1) expresses that all costs are relative to current conditions and they are distributed along track according to the curvature. Noticeable is that the tonnage-dependent cost C_T includes track replacement although the technical life of track is governed by wear and/or fatigue mechanisms as described. Such a statement is based on estimates of the fact that track replacement cost not necessarily is proportional to time between replacements. The amount of work and the component volume might vary and any effects of asset values and interest are not included. The later in spite of the fact of a technical life reaching 40-50 years. Such considerations have to be taken when the reinvestment costs are distributed into annual track reinvestment amounts.

The total maintenance cost of track is calculated by the following formula:

(2) $$C_{tot} = C_{ob} + C_{tr}$$

where

C_{tot}= Total annual maintenance cost

C_{ob}= Annual maintenance cost, traffic independent

C_{tr}= Annual maintenance cost, traffic dependent (= $C_T + C_{ax}$)

From the model a plot of annual track consumption can be presented. The degradation, expressed as % of track life per year, is plotted against curve radius, Figure 5. A value of 5% means for example that the track is to be replaced after 20 years in service. The two plotted lines represent two traffic situations where “Current traffic mix” reflects 22,5 ton axle load trains and “Future traffic mix” reflects 25-ton axle load trains. All other parameters such as annual tonnage, track standard and vehicle type are assumed to be unchanged. The plots are based on the worst case in the wear/fatigue diagram in Figure 4. On tangent track and in shallow curves it is rail fatigue that restricts the track life and in curves it is rail wear. Track degradation increases in the “Future traffic mix” scenario on all curve radius >600m due to the increased axle load while the degradation in curves is unchanged as wear is assumed to be proportional to the total (unchanged) tonnage.

The model also can produce a plot, Figure 66, where the annual traffic dependent maintenance costs are distributed on the curve radii of a track section. The calculation is based on expressions (1)+(2) and the diagram reflects costs due to track degradation weighted with track length and with added traffic non-dependent costs and purely tonnage dependent costs. The shown example is based on same data as Figure 4. All freight tonnage is moved from 22.5 to 25 ton axle load. The total cost increase is +4.2%

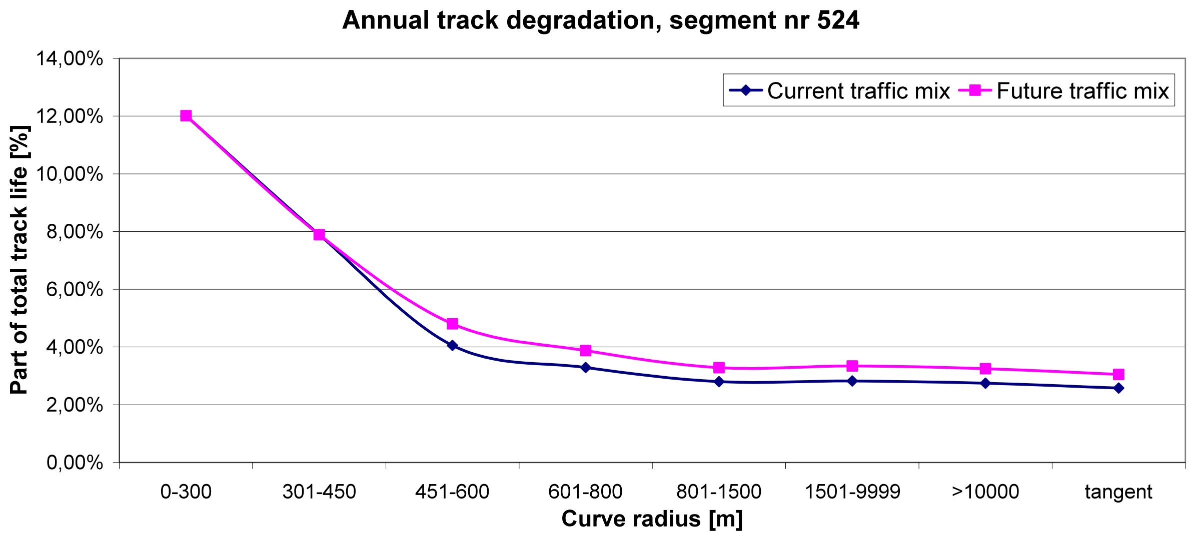


Figure 5: Annual track consumption expressed as % of total track life

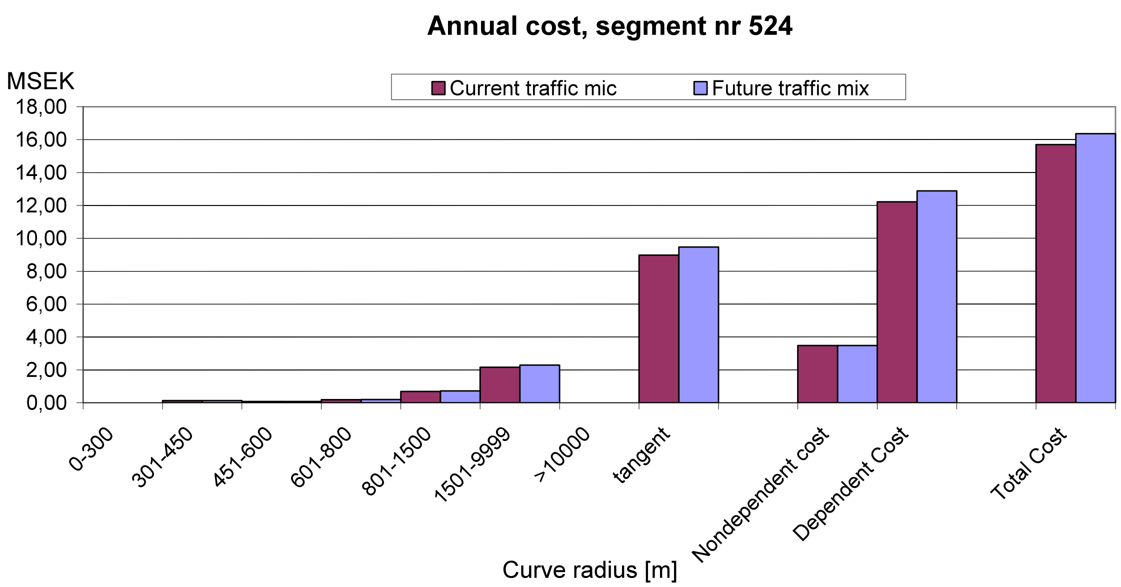


Figure 6: Annual degradation costs related to curve radius.
An increase of +4.2% in total cost.

3.6.2 VTISM – Vehicle Track Interaction Strategic Model

The Rail Safety & Standards Board (RSSB) has developed a Vehicle Track Interaction Strategic Model (VTISM) for the UK Rail Industry. VTISM is developed to predict the impact on the whole rail system of changes to the sub-systems of trains, traffic and track. This understanding is vital in helping to identify how to achieve substantial cost savings in the wheel/rail system. This will enable cost reductions to be achieved through optimising the characteristics and maintenance of the track and trains.

VTISM is bringing together:

- The vehicle dynamics code VAMPIRE
- The rail , Rolling contact Fatigue and wear codes in the whole life rail model
- The track planning application T-SPA which calculates track renewal and maintenance

To deliver a sustainable railway the cost must be understood in order to be able to optimise. VTISM provides links between inputs such as track and vehicle characteristics, and output such as rail life, wheel life and maintenance regimes to predict impact of change in one part of the system, see Figure 7.

The vision is to capture the consequences in economic terms both for train and track.

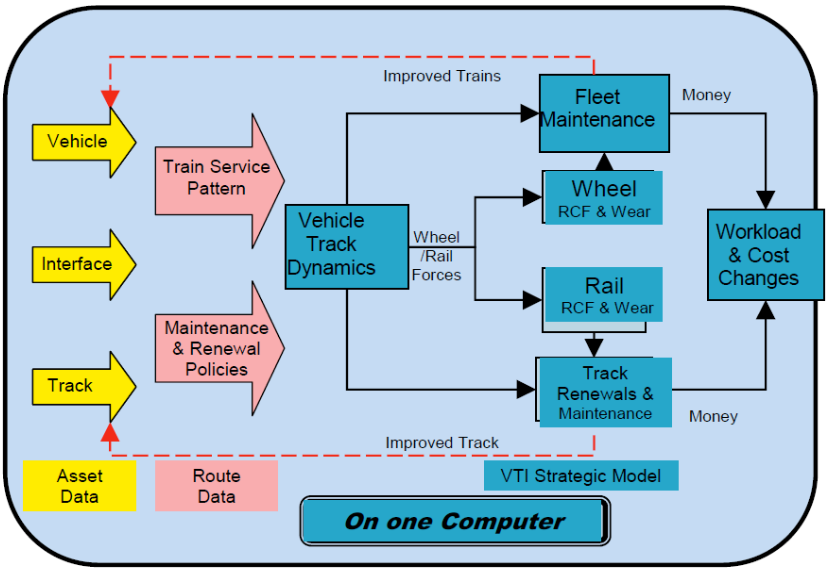


Figure 7: The vision for VTISM

VAMPIRE is a detailed model for vehicle track geometry data that can simulate wheel-rail forces and stresses. A separate run is required for each vehicle or vehicle condition that is to be included. The result is passed on to the Whole Life Rail Model that takes derived forces from VAMPIRE and a specification of the infrastructure and traffic data from T-SPA and maps them together, deriving rolling contact fatigue damage and wear damage for the prescribed total traffic flow. The output are then return to T-SPA. T-SPA takes the network definition and use detoriation models to predict future condition in terms of e.g. vertical geometry Standard Deviation (SDs). Maintenance and renewal actions are then predicted by comparing predicted conditions with standards leading to renewal and maintenance volumes prediction and corresponding costs.

VTISM can be used for several new investigations:

- Implication of tighter track quality standards on costs
- Impact of potential new renewal and maintenance methods on costs
- Impact of new wheel contact profiles on RCF and wear, and associated costs

3.6.3 TETrAs

TETrAs (Technical and Economical Track Assessment) is a knowledge based system which is able to optimise track and operational conditions. It was developed at DB and includes different simulation tools for several technical questions.

The central part of TETrAs is an object oriented data base management system, which stores all relevant data and which controls the interaction of the simulation modules. For different tasks like track loading, acoustics, ground borne vibration, rail corrugation or deterioration of components simulation models will be integrated. In most cases these models are validated using measurements.

The most important simulation tool is SiRaGe which simulates the vertical vehicle track dynamics for any track construction like slab track or ballasted tracks on soil or bridges. Figure 8 shows as an example of a model for ballasted track on a bridge.

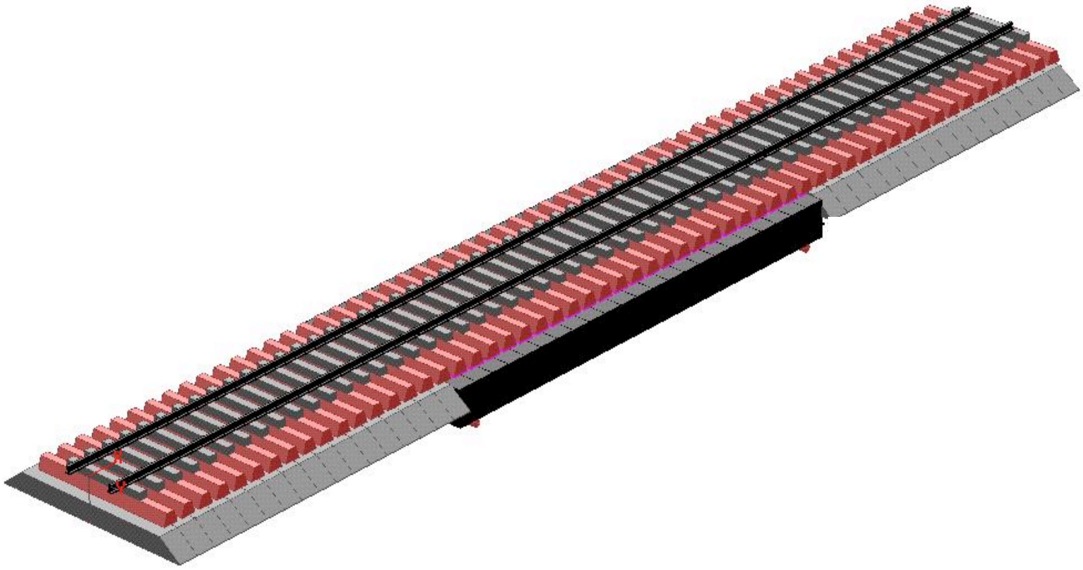


Figure 8: Track model for ballasted track on bridge

In a first step the real track has to be divided in to similar sections, like straight track, curving, crossing or bridges. Then the trains have to be classified in vehicle types, vehicle loading, types of out of round wheels or types of wheel flats.

For the different track sections and the classified loading (trains) TETrAs calculates the system values, which are either relevant for deterioration of track components like pressure, velocity or acceleration or which are relevant to prove the environmental friendliness like acoustics or ground borne vibrations. The calculated or measured system values will be classified and assessed using laws for the long-term behaviour of track components and life time and maintenance cycle derived.

The comparison of different track constructions or different operational conditions allows an optimisation regarding different aims. The assessment of the track will be carried out on the basis of classified track section and classified operational conditions:

A typical practical application at DB was the optimisation of track construction to minimize long-wave length corrugation curves or to optimise the track to obtain lower ground borne vibration.

3.6.4 Stratoforce - Strain To Force Way Side Detector

Stratoforce is developed by the researcher Dan Larsson Damill AB, in cooperation with Luleå Railway Research Center (JVTC) at Luleå University of Technology. Stratoforce is a wayside equipment that measures forces from passing trains by using different sensors. It can be stationary or mobile i.e. for temporary measurements. The stationary Stratoforce has been in operation since 2006.

The trains and vehicles passing identified in three ways (of which the first is the best option):

1. RFID car identification reader that are automatically read by an automatic train identification units (ATI).
2. Identification by train number retrieved from the Traffic Control Center.
3. Web camera which photographs the passing locomotive.

Each train (wagon, loco) has a different load pattern that makes it possible to classify passing vehicles. The output is matched against typical track degradation mechanisms on lines, where the vehicles are operating.

The monitoring station is mainly built up by a number of strain gauges mounted onto the rail. They are all placed in curves and arranged in a pattern that supports a good extraction of the different stress directions in the rail. Besides the strain gauges the station also includes a temperature and a humidity sensor. The system is normally in a standby mode waiting for trains. When a train passes the system automatically starts a logger sequence including post processing and storing of data. The monitoring computer is connected to Internet for easy distribution of data. A major part of the system development has been focused on analysis techniques for the sensor data. Output now includes:

- Axle counting
- Vertical load on each wheel
- Lateral load from each wheel (including direction)
- Angle-of-attack
- Vertical transient detection
- Locomotive identification
- Car identification (by RFID tags)
- Outdoor temperature
- Humidity
- An automatically updated top list of axles with high lateral forces (bad actors) including car and axle numbers
- An automatically updated top list of high axle load including car and axle numbers.

The monitored data is input to an extensive analysis of each train. There is a strong influence on the track forces from vehicle type, load, maintenance condition and weather (lubrication). As an example, the effect from maintenance condition is so strong that a hollow wear wheel with 2 mm wear in a 3-piece bogie can increase the lateral forces to 200-400% of their normal level (Larsson et al, 2007). It is of cause important to add that there are also other factors generating high lateral forces. Such parameters are for example high axle yaw stiffness and high cant deficiency.

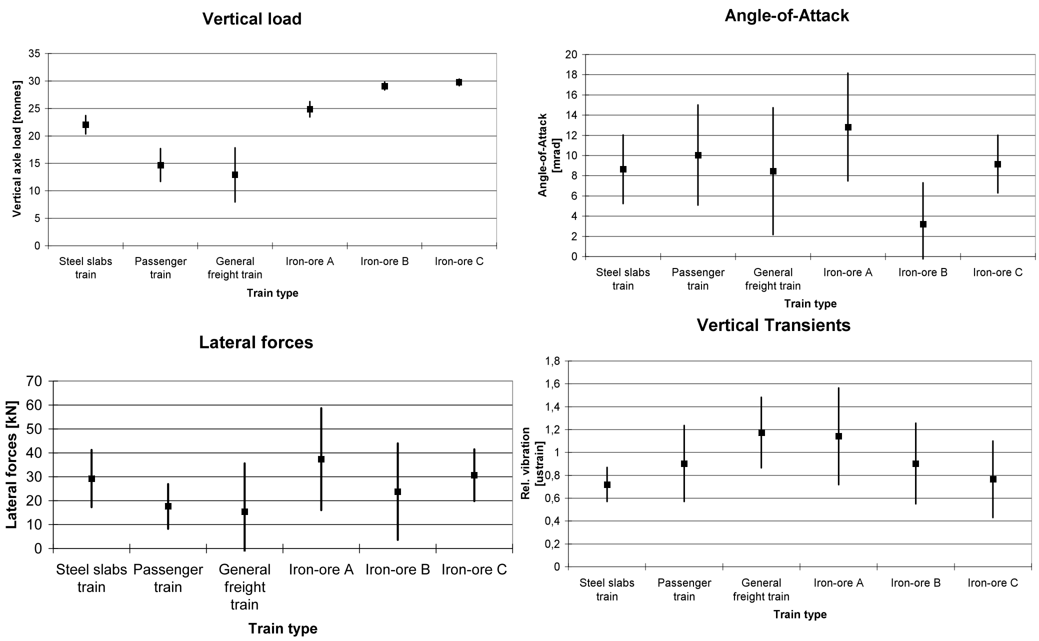
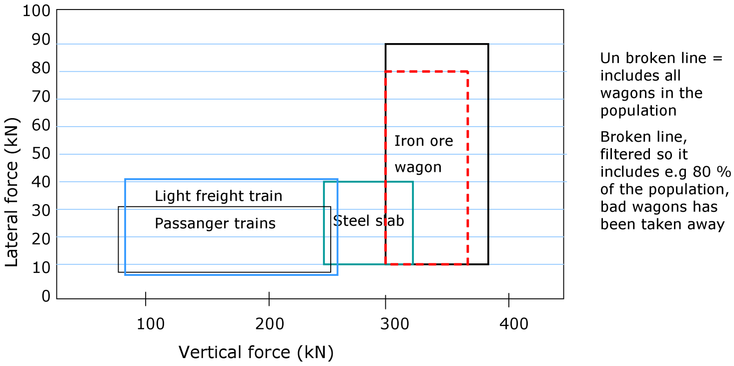


***Figure 9**: To the left; Vertical and lateral forces for 6 different train types. To the right: Angle-of-attack for 6 different train types. Vertical transients Vertical and lateral forces for 6 different train types. The bullets represent mean values while the lines correspond to +/- 1 Standard deviation.*

To compare different vehicles, plots are produce like that in Figure 9. In this presentation the diagrams represent several trains and several 100's of axles for each type. The horizontal axis in the diagram always shows vehicle type while the y-axis shows maximum lateral force, the angle of attack and the vertical transients.

The diagrams clearly show that each vehicle have a characteristic force pattern, it can also be presented as in Figure 10 Left. That shows a picture over the different vehicles type and their ability to affect degradation on track. Combined with the amount of tonnage that rolls across the line, see Figure 10 Right, we obtain a thumb print of the traffic situation at a particular time. Stratoforce makes it possible to see if traffic conditions change.



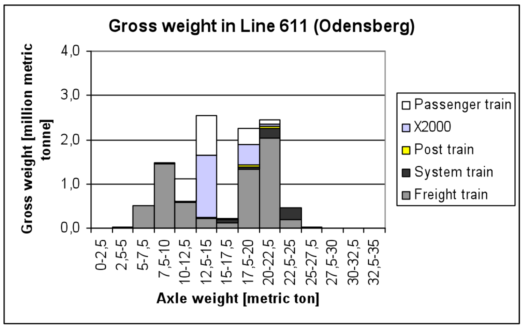


Figure 10: Left: Traffic mix and vehicles maintenance condition. Right: Gross weight

3.6.5 DafuR-System

DafuR-System is a German invention. By the application of strain gauges the DafuR system makes it possible to measure the dynamic forces between the wheel and the rail over the whole distance of a circumference of a wheelset. The connection to a data base which contains relevant vehicle parameter allows an automatic detection of vehicle types. The measured values and vehicle types are transmitted to a control centre and characteristic values like static axle load, dynamic load factor and if necessary time series of the measured forces are stored on a central server. The data will be used for the maintenance of the wheelsets, as input for the planning of preventive maintenance and for the characterisation of actual dynamic track loading. In the network of DB 23 systems are installed.

3.6.6 ARGOS System

The ARGOS-System is an Austrian invention. The main goal of local ARGOS checkpoints is to detect the dynamic condition of the trains travelling on the track at operating speeds with the highest accuracy and reliability.

ARGOS local measurement stations

Local measurement points in the track enables continuous monitoring of vehicle status and superstructure load parameters. The measurement equipment and the measurement process do not impede normal traffic. The rolling stock does not need to be fitted with any additional equipment. Nevertheless vehicle identification systems like transponders should be incorporated.

ARGOS local measuring points do not require any specific maintenance measures. Track sections equipped with ARGOS can be tamped, ground and reprofiled as with the rest of the track.

There are three types of ARGOS systems depending on usage:
Level 1: On-track derailment detection
Level 2: Automatic train monitoring (Q-force, wheel defects)
Level 3: Measurement of derailment safety (Q and Y-force, running behaviour, noise)

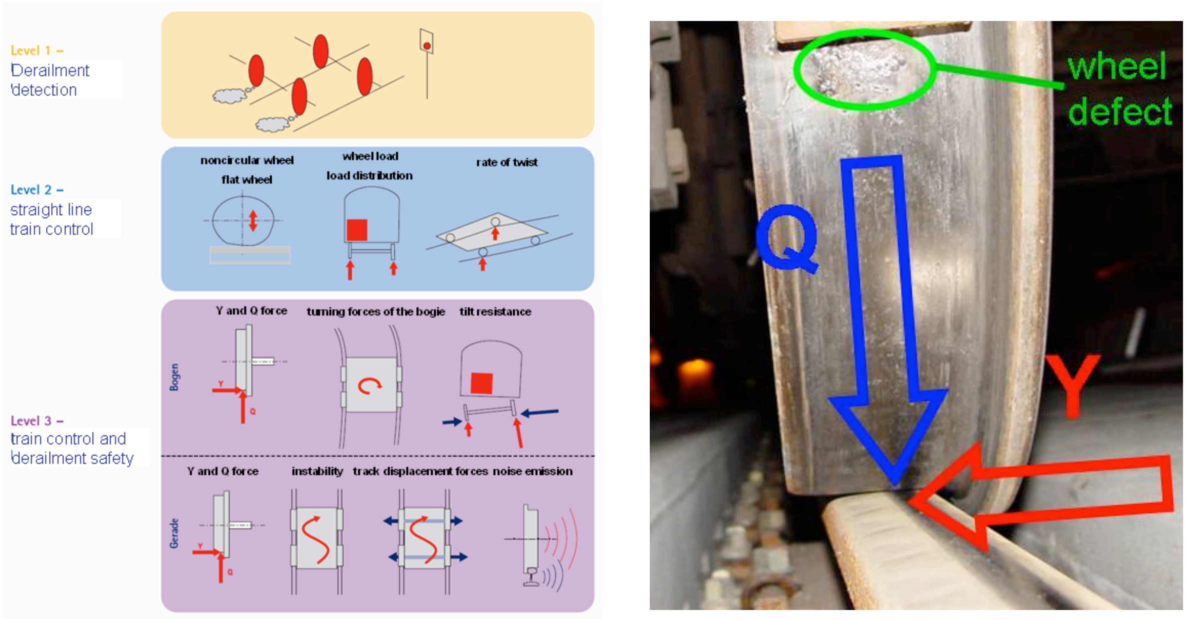


Figure 11: Functional overview of the ARGOS system and measured values

Level 1: Derailment detection

The ARGOS Level 1 system can detect rolling stock which has already derailed and give an output to the signalling system. The advantage of the ARGOS Level 1 system comes from its ability to monitor the whole area between the rails. This means that a derailment will even be detected in cases when the wheel is running narrowly over the screws and clamps of the rail. It consists of a set of four sensors in series, attached to the sleepers, to also detect jumping derailed wheels (a problem at high speeds). Extensive tests have shown that the system operates at speeds up to 300 km/h.

The Level 1 sensor consists of industrially proven force transducers, covered with a special metal plate. Through its simple and rugged construction and the logical interconnection of all four sensor elements there is no risk of an erroneous alarm.

Figure 12: ARGOS Level 1 before and after detected derailment

Level 2: ARGOS Q, wheel defects

With ARGOS Level 2 it is possible to detect irregularities in rolling stock by monitoring the vertical wheel forces (quasi-static and dynamic forces) and wheel defects. Vehicle control can be carried out selectively.

Figure 13: Argos Level 2 on wooden sleepers

Level 3: ARGOS Y/Q

In addition to Level 2, Level 3 also measures the horizontal forces. The forces are measured as continuous dynamic lateral wheel force and continuous wheel load. Derailments can be prevented through early detection of irregularities in rolling stock, and by measuring the wheel forces and the wheel geometry.

Level 3a: Y/Q in curves

ARGOS Level 3a is a comprehensive solution for curves. It provides reliable risk detection and cost factors of derailments on Y and Q force overload, derailment factors, load status, train composition, compliance with curves (positioning behaviour of wheels), running forces of the bogie and tilt resistance of the vehicle.

Figure 14: ARGOS Level 3a on slab track and Level 3b on concrete sleepers

Level 3b: Y/Q straight line

ARGOS Level 3b is mainly used for detection of instable running vehicles (e.g. hunting) in straight lines. The Y-force is continuously measured over a distance of around 45 m. This allows a classification of the running behaviour and noise emission.

Accuracy

ARGOS Level 2 and 3 are designed to supply a high level of measurement precision and reliability to provide legally valid proof of the measured values. The higher the accuracy of the measured value the easier it is to get practical acceptance from the vehicle operator and from homologation bodies.

ARGOS also detects wheel-shape irregularities with a high accuracy. All types of deviations are classified (flats, eccentricity, ovality, flattenings, polygons, etc.) and quantified.

3.6.7 ProRail Manual: hand-out RAMS/LCC

The RAMS / LCC hand-out is the means by which ProRail staff are instructed how to create effectively formulated assignments (calling for tenders) and how to evaluate the results of actions taken and tenders received.

The hand-out provides the necessary tools to be used with RAMS / LCC.

The hand-out provides a complete picture of RAMS / LCC analyses, including the relationship with MKBA (Social Cost – Benefit Analysis). Whether to apply (and to what degree and with what scope) RAMS / LCC analyses in the decision-making process is the responsibility of the project manager. The hand-out assumes that the RAMS / LCC specs are available. These specs will be further detailed throughout the new investment/renewal/O&M-project (ProRail, 2008 A).

3.6.8 Templates

ProRail has prepared templates for procurement documents (currently only available in Dutch) that can be translated and used as guidelines for other IMs, (ProRail 2008). As an example ProRail has provided a document for Functional Requirements. The template sets out from the description of the contract scope, describes the starting situation (origin state) and the expected situation (final state). Then specify a set of requirements including:

- Functional requirements
- Internal interfaces
- External interface
- Requirements for implementation
- Requirements contained in relevant documents
- RAMS, linked to functional requirements

It also contains templates for building specifications

In addition VAS has provided a spread sheet for conducting FMECA, see Annex 4.

Further ProRail has provided a spreadsheet for determining the costs of planned and unplanned unavailability, see Annex 4. It is a Excel sheet with an example that contains all formulas and a short description of all parameters.

The calculation for planned unavailability employs the following parameters:

- Duration of unavailability
- Number of passengers that have a delay
- Value of time for passengers (7 euro per passenger per hour)
- Value of time for freight trains (1000 euro per train per hour)
- Value of time other trains (500 euro per train per hour)
- Loss of revenue due to passengers that does not use the train during planned unavailability
- Cost for using busses to bring passengers to their destination
- Percentage of people that buy single or return tickets (everyone except cardholders)
- Average travel distance
- Number of freight trains
- Number of other trains

The calculation for the unplanned unavailability uses:

- Duration of unavailability
- Number of passengers that have a delay
- Value of time for passengers (7 x 2,4 euro per passenger per hour)
- Value of time for freight trains (1000 euro per train per hour)
- Value of time other trains (500 euro per train per hour)
- Number of freight trains
- Number of other trains

4. Discussion and Conclusion

The railway is very expensive to construct but has a long life and low operating costs. Therefore, the asset value is very high and leads to the statement that maintenance efforts might be of high value. By doing small changes in the maintenance strategy, the asset life length might be extended with for example 10% giving a large return on investment. Comparing railways with other civil engineering project with high investments in the initial phase, it is obvious that maintenance plays a crucial role in the long time cost effectiveness. (Larsson, 2004).

The use of LCC and RAMS is in its infancy and furthermore very few use LCC and RAMS in their contracts. LCC and RAMS as a concept and method is not clearly defined or adapted for railway facilities which, unlike the industry have assets in geographic extent, affected by climate and the traffic that operates the track. One value e.g. the MTBF (Mean Time Between Failure), can vary with the seasons, the tonnage that operates over the asset, distance, etc. It is therefore too early to go out and recommend the values to be measured and how. Key values for RAMS and LCC needs to be developed and transformed to a railway user environment. Periodic reporting of key figures must be ensured even if maintenance is outsourced.

As being in an early state of use, this report aims on providing information of what has been done and by whom– in order to learn from best practice, and start the process of using LCC and RAMS in the railway administration/industry. The report summarize what kind of values we have to monitor and evaluate, gives some examples of monitoring methods, the need methods for monitoring changes in boundary conditions (and some example of equipment) that can be use today.

Models and tools in use are DeCoTrack, VTISM and TETrAs, so called low resolution models. Some equipment for monitoring traffic characteristics are Stratoforce, Argos and DafuR-system and there are also some templates and handbooks in use.

Similarly methods and tools needs to be developed for the exchange of key data between parties involved in the railway system, i.e. infrastructure managers, traffic companies, supplier, contractor, etc. Methods to measure and monitor changes that affect the operation of the assets, but which the supplier or the contractor can not influence, is another area of development. A common platform for exchanging data needs to be developed.

The development can be accelerated by the parties learning from best practice, e.g. enhanced cooperation between the infrastructure actors. It can also be enhanced by the use of predictive models to aid in maintenance planning.

Finally, when the objectives are developed for the future activities, they must be in harmony with the objectives of the ERRAC white paper.

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6. Annexes

1 Networks Characteristics, according to LICB

2 Light version “Template for key values for LCC and RAMS in contracts”

3 Key values for LCC and RAMS

4 Spreadsheet for FMECA

5 Spreadsheet for determining the costs of planned and unplanned unavailability

Annex 1. Network characteristics

Technical term	Description	Abbreviation [unit]	Source
lines	Total length of permanent way in (by the respective IM) maintained working order. Every kilometer of double or multiple track counts as one line kilometer.	**line km [km]**	
lines in double or multiple track	Total length of lines in double or multiple track.	**line km [km]**	
lines in single track	Total length of lines in single track.	**line km [km]**	
electrified lines	Lines equipped with an overhead trolley wire or with a third rail. Their length only includes entire line sections which allow the passage of electric traction units between two stations, or between a station and a traction unit depot. Line section segments which are electrified at station approaches exclusively for shunting purposes, and where electrification is not extended as far as the next station, count as non-electrified lines.	**line km [km]**	**[4], p 37**
track	Main track kilometre in maintained working order and side track kilometre.	**track km [km]**	
main track	Main running tracks providing end-to-end line continuity and used for working regular trains between stations or places indicated in the tariffs as independent points of departure or arrival for the conveyance of passengers or freight. All track kilometre branching off from main running tracks in stations (second track at stations on single track lines, passing tracks, etc.) used for working regular trains. The length is measured in the middle of the track, from centre to centre of the station buildings; if there is a junction in open track, the length is counted up to the end of the junction point (switch). Double track is counted twice, triple tracks are counted three times as much etc. Main track kilometre are only counted when in a (by the respective IM) maintained working order.	**track km [km]**	**[4], p 38**
side track	Other types of track include e.g. track kilometre at marshalling yards and at places which are not shown in the tariffs as independent points of departure or arrival for the carriage of passengers or freight,	**track km [km]**	
electrified main track	Main running tracks provided with an overhead catenary or with conductor rail (3^{rd} rail) to permit electric traction.	**track km [km]**	**[3], p 112**
tunnels	Total length of railway tunnels in maintained working order.	**[km]**	

bridges	Total length of railway bridges in maintained working order. The minimum length of a bridge is 2 m.	**[km]**	
switches in main track	Points in main tracks in maintained working order managed, owned, maintained by the Infrastructure Manager. For a better comparability switch-units are calculated as follows: - ordinary point = 1 switch-unit - single diamond crossing = 2 switch-units - double diamond crossing = 4 switch-units	**number switch-units**	**[3], p 114** [5]
switches in side track	Points in side tracks following the definition of switches in main track.	**number switch-units**	
passenger station	Stations in maintained working order where passenger trains stop. All are counted even if they are not maintained or owned by the Infrastructure Manager.	**number**	
technically secured level crossing	Railway line and road crossing each other on the same level arranged for the passage of road vehicles, pedestrians, cyclists or animals. It is technically secured when using lights or barriers to warn road participants.	**number**	

Annex 2. Light version “Template for key values for LCC and RAMS in contracts”

<table>
<tr><th>Current situation</th><th>Specification</th><th>Additional aspects</th><th>Measurement</th><th>Possible future indicators</th></tr>
<tr><td>Scope</td><td>Description -</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Duration</td><td>20090701-</td><td></td><td></td><td></td></tr>
<tr><td>Network characteristics</td><td>Switch density LICB Definition</td><td></td><td>S&C/main track km</td><td></td></tr>
<tr><td></td><td>Track Density LICB Definition</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Track data (Ref Decotrack)
<table>
<tr><td></td><td colspan="9">Curve radius in m</td></tr>
<tr><td></td><td>o-300</td><td>301-450</td><td>451-600</td><td>601-800</td><td>801-1500</td><td>1501-10000</td><td>>10000</td><td>tangent</td><td>Total</td></tr>
<tr><td>Track length</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Vertical alignment</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cant</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Friction coefficient</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table></td><td></td><td></td><td></td></tr>
<tr><td></td><td>Substructure
<table>
<tr><td></td><td>In year</td><td>Numbers</td><td>Length</td><td></td></tr>
<tr><td>Slopes > 1 %</td><td>-</td><td></td><td></td><td></td></tr>
<tr><td>Embankment</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cuttings</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Tunnels</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Weet spots</td><td>-</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
</table></td><td></td><td></td><td></td></tr>
</table>

Permanent way/superstructure

Asset	Type/Model	In year	Age in tonnage	Length/ Amount	Note
Rail					
Fastenings					
Sleepers					c/c 65 cm
Under-sleepers pad					
Rail Lubrication					1:30

Switches and Crossings

Component	Type/model	In year	Age in tonnage		
Blade					
Frog					
Stock Rail					
Check Rail					
Point Rod					
Switch point machine					
Others					

	The system/subsystem/components standard		Type age in MGT	
	Maximal axle load		tonnage	
	Maximal speed		km/h	
	Capacity		Train / day	
	Current performance	Availability	Train Delay	See Annex 3
		Reliability	MTBF	
		Maintainability	MTTR	
		Safety	No accidents	
	Track Quality			
Traffic characteristics	Passenger train High speed	Vehicle data	Train/day	Y/Q and maintenance condition
	Passenger train type X		Train/day	
	Passenger train type std		Train/day	
	Passenger train …		Train/day	
	Freight train ore/bulk train, 25 tonnes axle load speed		Train/day	
	Freight train – Closed transport system, axle load X, Speed X		Train/day	
	Freight train – container/trailer, axle load X, Speed X		Train/day	
	Freight train – mixed freight, axle load X, Speed X		Train/day	
	Freight …		Train/day	

LCC	Maintenance		Annual maintenance cost, traffic nondependent [M€]	
			Annual maint. cost, rail+sleepers+ turnout+tampi ng[M€]	
			Annual maint. cost, track replacement+ others [M€]	
		Amount of corrective maintenance		
			Corrective maintenance cost	
			Preventive maintenance cost	

Annex 3. Key values for LCC and RAMS

	Example	Railway system	Sub system	Component level
Reliability	Failure rate, MTBF, MTTF, MDBF, MTBM MTBSAF		Critical item list Critical function list	Number of remarks leading to short - range planned action Number of train delaying failures MWT Mean Waiting Time
Availability	Total train delay Train delay caused by infrastructure Down time required for maintenance (both preventive and corrective)	Deliverance of train time slots according to plan Number of errors affecting train schedule Number of errors not affecting train schedule Number of trains with less then 3 minutes of delay KPI availability; number of errors * recovery time * area * weighting factor Deliverance of train time slots according to plan		
Maintainability	MTTR, MTTM, MDT	Qualification, /competence requirements for maintenance personnel	Mean logistic time Mean time to restore Special tools and test equipment Mean time to restore	Possible – but not always done Spare part supply
Safety	Number of derailments, number of external accidents, number of internal accidents Safety Planning Hazard analysis acc. to type of defect	Safety planning done according to regulations	Accident and incidents due to maintenance activities Accident and incident due to maintenance activities	

	Example	Railway system	Sub system	Component level
LCC		Cost of maintenance, Cost of preventive maintenance. Cost of corrective maintenance, Capital Costs, Cost Drivers Analysis of cost drivers, both on system level but also on line level and contract level	Cost of corrective maintenance Cost of preventive maintenance Analysis of cost drivers Asset cost of control centre technology and their additional expenses (eg. Changes ot the building, energy supply, wiring etc.). Technical lifetime of the complete system. Definition of parts which will not reach lifetime of the system and their changing time. Energy demand,	

Annex 4. Template for FMECA

PROBABILITY of Failure	Failure Probability	Ranking
Very High: failure is almost inevitable	> 1 in 2	10
	1 in 3	9
High: repeated failures	1 in 8	8
	1 in 20	7
Moderate: occasional failures	1 in 80	6
	1 in 400	5
	1 in 2,000	4
Low: relatively few failures	1 in 15,000	3
	1 in 150,000	2
Remote: failure is unlikely	< 1 in 1,500,000	1

Effect	SEVERITY of effect	Ranking
hazardous without warning	very high severity ranking when a potential failure mode affects safe system operation without warning	10
hazardous with warning	very high severity ranking when a potential failure mode affects safe system operation with warning	9
very high	system inoperable with destructive failure without compromising safety	8
high	system inoperable with equipment damage	7
moderate	system inoperable with minor damage	6
low	system inoperable without damage	5
very low	system operable with significant degradation of performance	4
minor	system operable with some degradation of performance	3
very minor	system operable with minimal interference	2
none	no effect	1

Detection	Likelihood of DETECTION by design control	Ranking
absolute uncertainty	control cannot detect potential cause/mechanism and subsequent failure mode	10
very remote	very remote chance control will detect potential cause/mechanism and subsequent failure mode	9
remote	remote chance control will detect potential cause/mechanism and subsequent failure mode	8
very low	very low chance control will detect potential cause/mechanism and subsequent failure mode	7
low	low chance control will detect potential cause/mechanism and subsequent failure mode	6
moderate	moderate control will detect potential cause/mechanism and subsequent failure mode	5
moderately high	moderate high chance control will detect potential cause/mechanism and subsequent failure mode	4
high	high chance control will detect potential cause/mechanism and subsequent failure mode	3
very high	very high chance control will detect potential cause/mechanism and subsequent failure mode	2
almost certain	control will detect potential cause/mechanism and subsequent failure mode	1

Prel. HAZ

No.	description of hazard	possible results	possible causes	possible mitigation	risk category	comments for mitigation strategy
1.1	derailment	death, injury	rail breakage	Inspection	Highest	production control, material choice, wear limit, fatigue limit, maintenance
1.2						
1.3						
2.1	injury at installation					
3.2	injury at maintenance					

FMECA

failure identification				failure effects		failure management					
item (e.g. component)	**Function(s)**	**Potential failure mode(s)**	**potential cause(s)/ Mechanism(s) of failure**	**Potential consequences of failure**	**location(s)**	**current detection/ diagnostics**	**(design) Mitigation**	**PROB**	**SEV**	**DET**	**RPN**
rail	carries load guides vehicle	200 brittle fracture	cold environment	vertical fracture, crack located in rail cap	Head Surface, cap	US, visual	watch over				
rail	carries load guides vehicle	211 detail fracture									
rail	carries load guides vehicle	2201 Corrugations									
rail	carries load guides vehicle	2202 waves									
rail	carries load guides vehicle	2203 gauge corner wear									
rail	carries load guides vehicle	2204 abnormal vertical wear									
rail	carries load guides vehicle	221 surface defects									
rail	carries load guides vehicle	2221 surface flaking									
rail	carries load guides vehicle	2222 Shelling									
rail	carries load guides vehicle	2223 head checking and spalling									
rail	carries load guides vehicle	223 head crushing									
rail	carries load guides vehicle	2251 single wheel									

		burn									
rail	carries load guides vehicle	2252 repeated wheel burn									
rail	carries load guides vehicle	227 Squat									
rail	carries load guides vehicle	301 damage									

MTBF + MTTR

failure identification	**failure management**		**radius**	**MTBF [years]**		**MTBF [h]**		**MTBF [Mio to]**		**MTTM**		**prev/corr**
Potential failure mode(s)	**current detection/ diagnostics**	**(design) Mitigation**	**[m]**	**grade R260**	**grade R350HT**	**grade R260**	**grade R350HT**	**grade R260**	**grade R350HT**	**measure**	**unit**	
200 brittle fracure	US, visual	correct neutralisation	all	event dependent		event dependent		event dependent		intermediate fishplating install plug rail	1h 3h	corrective
211 detail fracture	US, visual	manufacturing practice	all									
Fatigue foot breakage	visual	replacement	all									
2201 Corrugations	track inspection car, visual, noise	grinding higher hardness	> 7500									
2202 waves	track inspection car, visual, noise	grinding higher hardness	< 7500									
2203 gauge corner wear	track inspection car, visual; 10 mm wear limit	lubrication replacement	< 700									
			700 - 2500									
			2500 - 5000									
			5000 - 7500									
			> 7500									
221 surface defects	track inspection car, visual	improve QA of manufacturer grinding repair welding	all									

2221 surface flaking	track inspection car, visual	replacement	all									
2222 Shelling	US, visual	manufacturing practice	all									
2223 head checking and spalling	US, visual	preventive grinding corrective grinding replacement	< 700							preventive grinding condition based grinding		preventive
			700 - 2500									
			2500 - 5000									
			5000 - 7500									
			> 7500 [1)]									
223 head crushing	visual	grinding replacement	all	event dependent		event dependent		event dependent				
2251 single wheel burn	visual	repair welding, replacement	all	event dependent		event dependent		event dependent				
2252 repeated wheel burn	visual	grinding repair welding, replacement	all	event dependent		event dependent		event dependent				
227 Squat	US, visual	replacement	all									
301 damage	US, visual	grinding, repair welding, replacement	all	event dependent		event dependent		event dependent				

Annex 5. Spreadsheet for determining the costs of planned and unplanned unavailability

	Calculation of costs for planned train free periods and unplanned disruption					
			input			
I	Number of passenger train per day (working day)		495	trains per day		
II	average number of passengers per train (working day)		128	passengers		
III	Number of passenger train per day (weekend day)		232	trains per day		
IV	average number of passengers per train (weekend day)		128	passengers		
V	Number of freight train per day		35	trains per day		
VI	number of other trains per day		26	trains per day		
	Result					
VII	average cost delay per hour (working day)	€	6 899	per hour		formula: XXXI/24
VIII	average costs for using busses per hour (working day)	€	4 066	per hour		formula: XXXII/24
IX	average revenue loss per hour (working day)	€	1 619	per hour		formula: XXXIII/24
X	cost for <u>planned train free period</u> per hour (working day)	€	12 584	per hour		formula: VII+VIII+IX
XI	average cost delay per hour (weekend day)	€	3 234	per hour		formula: XXXVI/24
XII	average costs for using busses per hour (weekend day)	€	1 905	per hour		formula: XXXVII/24
XIII	average revenue loss per hour (weekend day)	€	952	per hour		formula: XXXVIII/24
XIV	cost for <u>planned trainfree period</u> per hour (weekend day)	€	6 091	per hour		formula: XI+XII+XIII
XV	average costs freight trains per hour	€	1 823	per hour		formula: XXXX/24
XVI	average cost other trains per hour	€	677	per hour		formula: XXXXI/24
XVII	cost for <u>unplanned disruption</u> per hour	€	31 079	per hour		formula: ((VII*5+Xi*2)/(XXX1*7) + XV+XV1)*2,4
	fixed parameters					Used for calculation of:
XVIII	duration delay per preventive maintenance activity		40	min	estimation	cost delay passenger
XIX	Value of Time passengers (2007)	€	7,00	per hour		cost delay passenger
XX	additional costs using for busses	€	2,75	per passenger		costs using busses
XXI	Percentage of passengers that keeps travelling and uses the offerd alternative		56%			costs delay passenger and costs using busses
XXII	Percentage of passengers that does not travel due to preventive maintenance activi		20%			revenue loss
XXIII	Percentage single / return ticket sales		60%		estimation	revenue loss
XXIV	revenue trainticket	€	0,12	per km		revenue loss
XXV	average travel distance (working day)		42,6	kilometer		revenue loss
XXVI	average travel distance (weekend day)		53,4	kilometer		revenue loss
XXVII	duration redirection freight train + 1 extra stop		75	min	estimation	cost delay freight trains
XXVIII	Value of Time freight train	€	1 000	per hour		cost delay freight trains
XXIX	Value of Time other trains	€	500	per hour	estimation	cost delay other trains
	intermediate result workingday					
XXX	number of passengers per day		63 360	passengers per day		
XXXI	value delay passenger	€	165 581	euro per day		formula: nbr of passengers x % that keeps travelling using trainfree period x train delay minutes x Value of Time
XXXII	cost of using busses for passengers	€	97 574	euro per day		formula: number of passengers x % that uses the busses x cost for busses per passenger
XXXIII	revenue loss	€	38 868	euro per day		formula: number of passengers that does not travel due to trainfree period x % with single or return ticket x
XXXIV	Total cost for passengers per working day	€	302 023	euro per day		revenue loss per km x average travel distance
	intermediate result weekend					
XXXV	number of passengers per day		29 696	passengers per day		
XXXVI	value delay passenger	€	77 606	euro per day		formula: nbr of passengers x % that keeps travelling using trainfree period x train delay minutes x Value of Time
XXXVII	cost of using busses for passengers	€	45 732	euro per day		formula: number of passengers x % that uses the busses x cost for busses per passenger
XXXVIII	revenue loss	€	22 848	euro per day		formula: number of passengers that does not travel due to trainfree period x % with single or return ticket x
XXXIX	Total cost for passengers per weekend day	€	146 186	euro per day		revenu loss per km x average travel distance
	intermediate result freight trains per day					
XXXX	value freight trains per day	€	43 750	euro per day		formula: number of freight trains x delay minutes x Value of Times freight trains
	intermediate result other trains per day					
XXXXI	value other trains per day	€	16 250	euro per day		formula: number of other trains x delay minutes x Value of Time other trains