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Track degradation analysis in the scope of railway infrastructure maintenance management systems

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Subject review

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The condition of railway infrastructure elements is the key factor influencing the traffic safety, infrastructure availability, total maintenance and renewal costs, and revenues. The measurement and analysis of the condition of railway infrastructure elements is the only correct approach enabling an efficient monitoring of their behaviour and proper planning of maintenance activities. An optimum structure of the railway Maintenance Management System - RMMS is presented in the paper, with a special emphasis on the utilization of deterioration models, as one of the RMMS's key components.

Key words:
management, maintenance, railways infrastructure, modelling, track degradation modelling

Pregledni rad

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Analiza degradacije kolosijeka u sklopu sustava za upravljanje održavanjem željezničke infrastrukture

Stanje elemenata željezničke infrastrukture ključni je faktor koji utječe na sigurnost prometa, raspoloživost infrastrukture, ukupne troškove radova na održavanju i remontu, kao i prihode. Mjerenje i analiza stanja elemenata željezničke infrastrukture je jedini ispravan pristup kako bi se na učinkovit način pratilo njihovo ponašanje te planirali radovi na održavanju. U radu se opisuje optimalna struktura sustava za upravljanje održavanjem željezničke infrastrukture (Railway Maintenance Management System - RMMS) s posebnim osvrtom na primjenu modela degradacije kao jednog od ključnih dijelova RMMS-a.

Ključne riječi:
upravljanje, održavanje, željeznička infrastruktura, modeliranje degradacije kolosijeka

Übersichtsarbeit

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Analyse der Degradierung von Gleisen im Rahmen des Verwaltungssystems zur Erhaltung der Eisenbahninfrastruktur

Der Zustand einzelner Elemente der Eisenbahninfrastruktur beeinflusst wesentlich die Verkehrssicherheit, die Verfügbarkeit der Infrastruktur, die gesamten Kosten der Erhaltungs- und Überholungsarbeiten, sowie den Umsatz. Einzig durch Messungen und Analysen ist es möglich, das Verhalten dieser Elemente wirksam zu verfolgen und die Wartungsarbeiten zu planen. In dieser Arbeit wird die optimale Struktur des Verwaltungssystems zur Erhaltung von Eisenbahnen (Railway Maintenance Management System - RMMS) beschrieben, und insbesondere die Anwendung des Degradationsmodells, eines der wesentlichen Bestandteile des RMMS, erläutert.

Schlüsselwörter:
Verwaltung, Instandhaltung, Eisenbahnen Infrastruktur, Modellierung der Zustandsdegradation

1. Introduction

Significant investments are needed for the maintenance and renewal (M&R) of railway infrastructure networks. Average annual M&R expenditures per 1 km of tracks for West-European networks revolve around €50.000 [1]. To keep the Railway Infrastructure (RI) in a satisfactory condition, it is essential to properly understand the manner in which this condition of every single RI element changes. In fact, understanding this change in condition means understanding behaviour of RI facilities, which paves the way towards predicting such changes. The so called "Deterioration Models" (DM) are needed in order to relate the observed (captured) past behaviour with the predicted future behaviour. The incorporation of DMs in a suitable, powerful yet flexible Railway Maintenance Management System (RMMS) allows railways to perform true long-term simulations of the RI assets behaviour, balancing effectively the achieved quality with the costs of M&R works (as well as inspections and other consequences like traffic disruptions, availability, etc.), which enables significant cost-savings. In the present day conditions, a cost-effective railway infrastructure can be obtained only by regular monitoring of the RI assets' performance, and by using reliable prediction, planning, and optimization methods, all of which are the main goals of RMMS. The structure of RMMS will be explained using as an example (only for some specific aspects) the "TrackIT" & "AMA" (Automated Maintenance Advisor) systems of Ensco Inc., USA, the second of which was designed for Ensco by the first author of this paper.

1.1. Functional organization of RMMS

In order to satisfy the complex combination of requirements, RMMS must be created as a distinctly modular system, with all modules being completely independent and thus detachable, i.e. deployable individually or in any combination of the modules, yet working in complete unison when necessary. The list of key RMMS modules/functionalities is provided hereafter, while its modular structure can best be seen in Figure 1.

- Completely flexible database structure, providing full freedom in the incorporation or linking of data in (as many as possible) formats, thus considerably facilitating the connection to external systems (e.g. Enterprise Resource Planning (ERP) and Enterprise Asset Management (EAM) systems) and/or databases as well as condition-monitoring systems.
- Full Inventory of Assets, with their location, properties (e.g. types of rails, sleepers, ballast, fastenings, contact wire, third rail, etc.), their installation dates (providing age & accumulated tonnage), speeds, slopes, annual tonnage, condition (e.g. all kinds of measurements & inspections, performed by measuring vehicle(s) and/or by walking and visual inspections) and activities (e.g. M&R works, inspections).
- Ability to model the entire railway infrastructure, i.e. all assets, both the linear/spatial ones (using "Link" and "Node" objects), as well as all kinds of singular (point/discrete) objects (e.g. Switches & Crossings (S&C), Bridges, Culverts, Level-crossings, etc.) and their sub-components.
- Liner/Spatial referencing of all "distributed" properties (e.g. track geometry parameters, rail profile, rail corrugation, overhead line (OHL) geometry and wear parameters, etc.)
- Capability to handle both GPS and linear asset referencing (chainage), with the possibility of generating Geographic Information System (GIS)-based Thematic Maps.
- Superb Visualization of all relevant data (e.g. inventory, layout, condition, operation/exploitation, activity, history, economy, work plan, images, videos, etc.).
- Flexible Segmentation (user-defined, modifiable, unlimited number of criteria and dependencies), effectively performing a discretization or conversion of linear/spatial assets into track segments, i.e. singular assets.

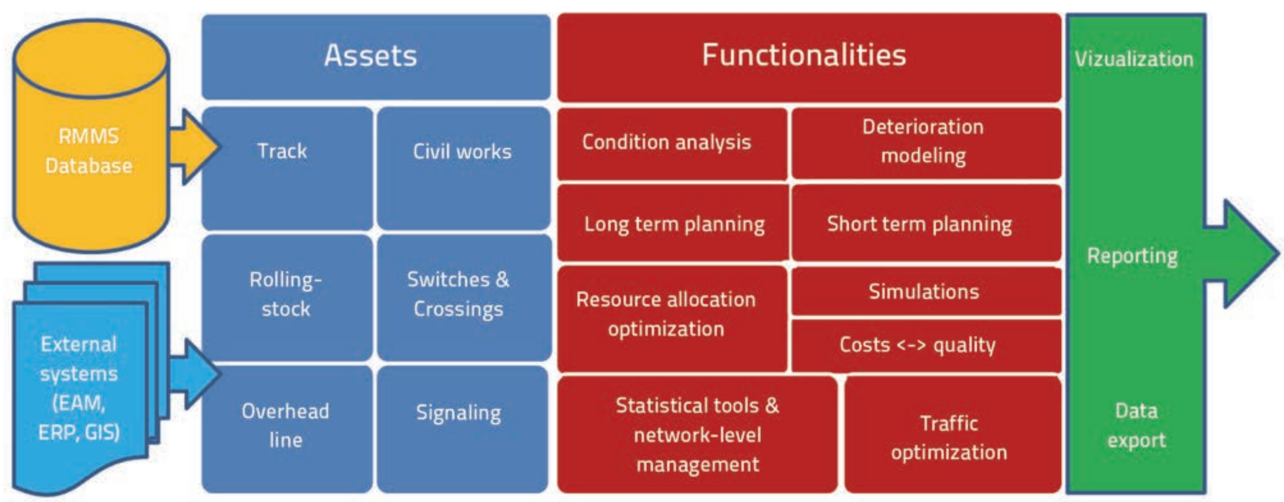

Figure 1. Modular architecture of RMMS (Railway Maintenance Management System)

- Sophisticated generic deterioration modelling & condition-forecasting (applicable to all assets and their condition parameters (e.g. rail wear, any of the track geometry parameters, OHL contact wire geometry, OHL contact wire wear, etc.), with utilization of linear and non-linear deterioration curves, short and long-term behaviour analysis, forecasting and consequential M&R works planning).
- Inference Engine with a completely flexible creation of Decision Rules and Thresholds (flexible, user-definable and modifiable Decision Rules making use of Deterioration Models, completely free and user-friendly Rule Editor; ability to plan any kind of activity (M&R Works, Inspections, etc.) or choose any of the already available Decision Rules in the standard/default Rule-base; ability to use official & unofficial rules for simulations, etc.).
- Automatic M&R Planning and Grouping and support for Maintenance Resources Budgeting.
- Extensive Network-level Management, Reporting, Exporting and Statistics functionalities, flexible, user-definable and modifiable.
- Simulations (allowing testing and checking of various M&R Policies, different standards and strategies, and evaluating their outcomes in terms of achieved quality and incurred costs, both in short and long term).

RMMS data-analysis functionalities are typically divided into two Levels, [2]:

- Low Level Analyses
- High Level Analyses.

Low level Analyses – represent manual deep/thorough analyses (usually for shorter track stretches and on a short-term basis) of any of the condition parameters, independently or in cross-examination with any number of other given parameters. They are performed typically by "Planner" & "Viewer" types of Users, simply by including the condition parameters, or assets and their characteristics, or work-history, or M&R Plans, or Segmentation, etc., into the Visualization area, and reaching conclusions by mere observation and/or by using additional visualization tools (cf. Figure 2).

The data analysis must be extremely easy and intuitive. Provisions must therefore be made so that the data can be arranged in a User-preferred way, overlaid and combined in any order, thus allowing for an excellent overview of the situation and observation of anomalies, e.g. threshold exceedances, local clustering of defects, etc.

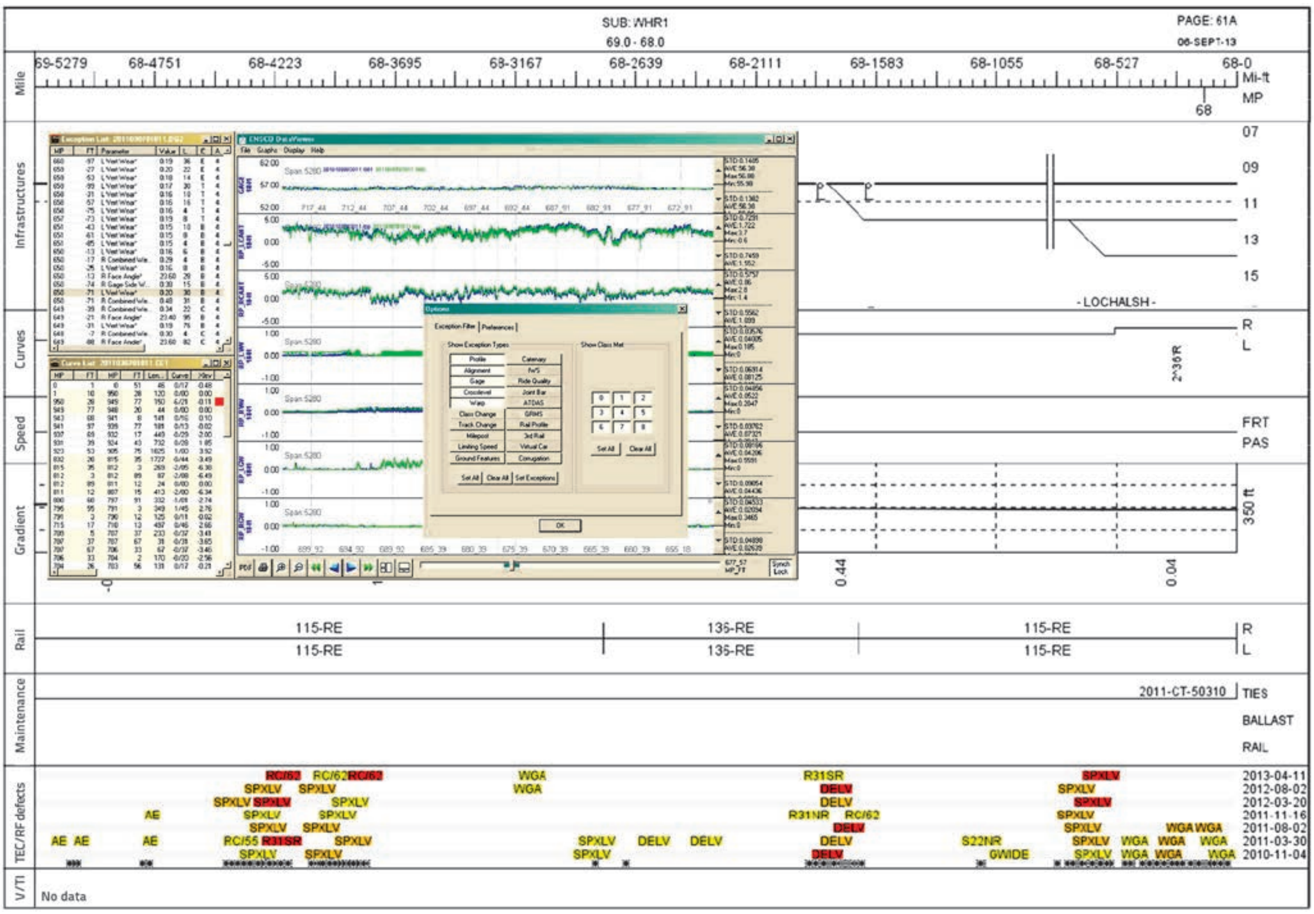

Figure 2. RMMS visualization

High Level Analyses – represent automatic analyses of any asset (or any group of assets), or any part of a network (usually larger scale assets, and even the entire network) on a short, middle and/or long term basis, based on the User-defined set of Decision Rules and Threshold, powered by the Deterioration Models (DM).

High Level Analyses are performed either on "singular" assets/objects (e.g. S&C units or their components, level-crossings, rolling-stock or their components, etc.) or, in case of linear/spatial assets/objects, the analyses are performed on (infrastructure/track) "Segments". Segments, in turn, are the product of the Segmentation process (Figure 3). The segmentation process represents a "discretization" process where the (linear) infrastructure (track, but also overhead-line (OHL), or any other linear structure that is freely definable in the system) is divided into Segments based on User (pre-defined, yet freely modifiable) criteria. This effectively brings any linear/spatial asset to the level of singular assets/objects allowing, from that moment on, their identical and joint treatment/analysis.

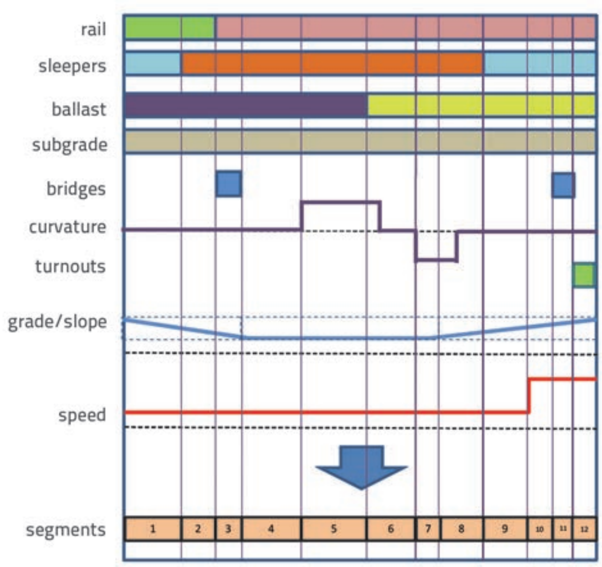

Figure 3. RMMS Segmentation process

The main idea of Segmentation is to create the greatest possible number of segments of uniform behaviour, as locations on the track with different behaviour should be (and are) treated differently. On the other hand, the uniformity of behaviour is expected due to uniformity of track characteristics and circumstances (e.g. component types, layout characteristics, traffic conditions, drainage conditions, etc.). Thus a new segment starts at every location where any of the user-defined "critical characteristics" changes. From that point on, each and every segment is allowed to behave (i.e. deteriorate, as well as improve in response to maintenance works) in a unique manner, as if every segment were a unique "organism". This allows a fully automatic analysis on a larger scale comprising even the entire network) [3], because it is analysed segment by segment.

Automatic analyses are performed on the basis of User-defined set(s) of Decision Rules (DR) and Thresholds, powered by DMs. Thus, the DRs (differentiated by their relative importance) are run within these analyses for each and every segment (or asset/object/component). Normally, the structure of a DR is such that it first checks if a segment/asset/object/component satisfies certain conditions (e.g. if it holds certain type of rail or sleeper or wheel or suspension; if it is on a main or secondary line; if the ballast age is within certain limits; etc.) and then it checks certain condition parameters against their respective thresholds and/or calculates when these thresholds would be reached. DMs are used in order to calculate when the thresholds would be reached. Thus, in short, a DM is assigned for every given condition parameter. Typically, this assigning would define the type of curve (linear, or non-linear, e.g. polynomial, exponential, logarithmic, etc.) and the "influencing works" (because not all M&R works influence all condition parameters, and even among those M&R works that influence a certain parameter, not all of them influence it in the same manner, etc.). Once this is described (pre-defined by the User, yet freely modifiable), the system calculates the "actual curves" that best fit the actual behaviour of this particular Segment, for every single segment/asset/object, based on the actual data (e.g. measurements and M&R Work History). Based on this "captured behaviour", the system calculates future behaviour (e.g. deterioration, response to various M&R works – i.e. their efficacy, etc.) and, based on this, the system forecasts and proposes when and which M&R works are to be performed, calculates their costs, balances them, etc., (cf. Figure 4).

1.2. Typical analytical process for RMMS

All measured condition-information (e.g. coming from various measuring vehicles or visual inspections) is subjected to DMs appropriate for each and every asset/object/component and their particular condition-parameter, for both singular assets/objects (and their components), and segmented linear/continuous assets/objects. The DMs first "capture" the behaviour of designated condition-parameters throughout the "known past" (for/during which the condition-measurements are available), after which this captured behaviour may be used for forecasting purposes (cf. Figure 4).

Depending on the forecasting capability as well as the Decision-Rule-Base, all designated data are processed automatically to define M&R plans, according to given (modifiable) scenario-characteristics and constraints. Of course, these characteristics & constraints can (and should) be varied in order to reach optimal M&R plans, and this variation can be made both manually and automatically.

Finally, the resulting M&R works are checked against available resources and given (modifiable) constraints in order to run the Prioritization, yielding an optimum set of M&R works to be performed to achieve the desired quality, or moreover the

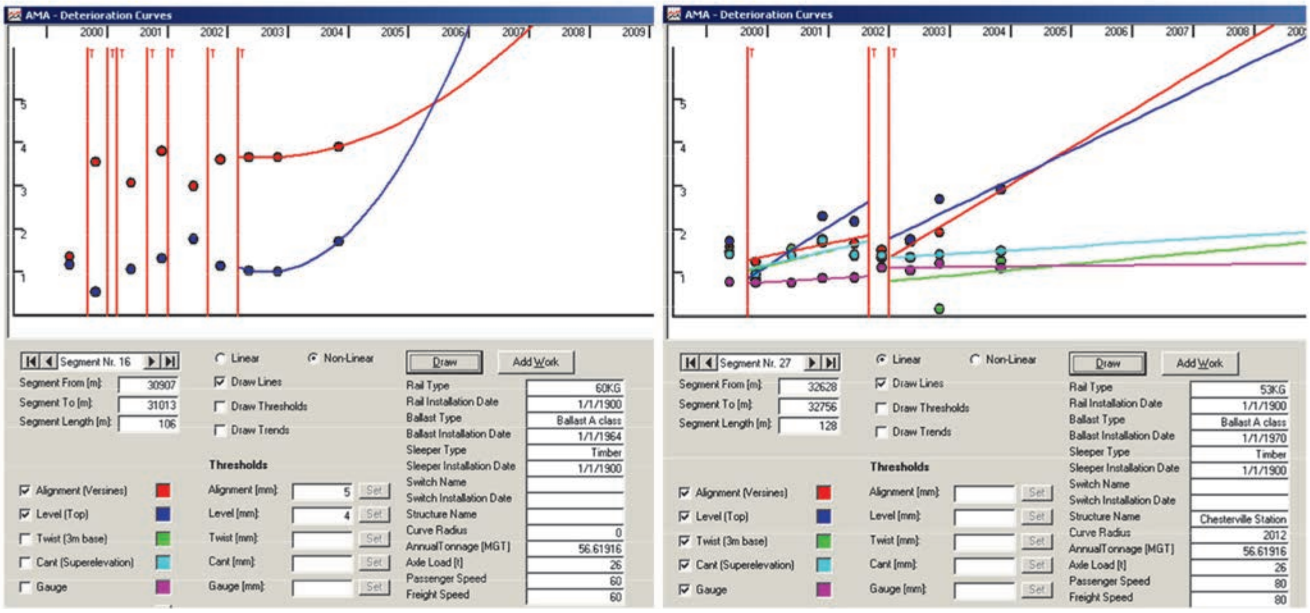

Figure 4. RMMS Deterioration Modelling View

(definable/modifiable) balance between costs and quality, as well as between maintenance an renewal volumes.

At the very end, the highest priority set of realistically feasible M&R works (within the given resource constraints) is gathered together to achieve the best economical effect/savings coming from performing works together within the same track possession periods (TPPs), respecting given (modifiable) capacity of available machinery, as well as durations of available TPPs.

2. Basic data needed for prediction and planning

A vast amount of data is needed for proper management of railway infrastructure (Jovanovic, Bozovic, Tomicic-Torlakovic 2014). For example, Italian railway infrastructure provider, Rete Ferroviaria Italiana (RFI), collects 1 TB of condition data every month from a single measuring vehicle "ARCHIMEDE" [4]. Some basic examples of the types of data to be collected for an optimum use of RMMS are listed below:

1. Superstructure and infrastructure inventory/register
   - Rails (type, jointed track or continuously welded, weld type, installation date, new/used when installed, accumulated tonnage on rails when installed if used)
   - Ballast (ballast type, date of installation, ballast thickness, grading information, etc.)
   - Sleepers (type, new/used when laid, accumulated tonnage if laid as used, spacing, fastening type, installation date)
   - Subgrade (geological condition, thickness, modulus, various monitored parameters, etc.)
   - Structures (type, start/end km, code, name)
   - Switches and Crossings (S&C) (type of S&C unit, code, name, start/end km)
   - Inspections and other measurements
   - General condition (e.g. from visual/walking inspections)
   - Ballast condition (% surface soiling, % pumping, % weedy ballast)
   - Fastening condition (% ineffective fastenings, % loose fastenings, % missing fastenings)
   - Sleeper condition (% bad sleepers, % medium sleepers, sleeper condition, clustering of bad sleepers)
   - Rail defects (internal & surface, no. of defects, no. of failures outside welding zones, % of defective rails)
   - Rail wear (vertical, lateral, combined wear, chamfered angle of rail-head)
   - Rail corrugation (corrugation amplitude in various wave-bands, accelerations, dynamic forces)

2. Layout and operating
   - Curves & transition-curves (start/end km, curve hand, radius, length, etc.)
   - Loads (annual load [MGT], maximum axle load [tons])
   - Speeds (speed of freight trains and passenger trains)
   - Gradients (start/end km, value)

3. Work history
   - Asset Renewals (start/end km, type, cost, etc.)
   - Asset Maintenance (e.g. rail grinding; track tamping & lining) (start/end km, type, cost, machine, crew, etc.)
   - Speed restriction history (start/end date of temporary speed restriction, reduced speed value, cost)
   - Spot maintenance history (start/end km, type, date, cost)
   - Inspection history (start/end km, type date, cost)

4. Condition Measurements
   - Track (alignment, vertical, twist, cross-level, gauge, quality indices, number of faults per fault-category;

Rail Profile (Rail wear); Rail Corrugation (all wave-bands); Video inspection of track & wayside)
- Overhead Line [OHL] (OHL Geometry (static & dynamic); Contact Wire(s) Wear; Catenary/Pantograph Interaction; Electrical Parameters (Voltage and Tension) & Electrical Arcs; Video inspection)
- Ride Quality (Wheel-rail contact geometry; axle-box, bogie & car-body accelerations; Instrumented wheels for wheel/rail interaction forces)
- Telecommunication (GSM, GSM-R and ETACS signals)
- Signalling equipment (balises (position & signal correctness), coded currents)

3. Railway infrastructure degradation

3.1. Track geometry

Since track geometry is one of crucial track condition parameters, closely related to many other degradation phenomena, and as it is often used for triggering the whole range of track M&R activities, it will be used here as the basis for discussion. The whole track system is designed and maintained to provide satisfactory geometry. Renewal decisions are often governed by the geometry. Roughly speaking, too many rail failure repairs spoil the geometry and make renewal necessary, and ballast is renewed when it can no longer maintain good track geometry. Sleepers and fastenings are considered to have failed when the track gauge cannot be maintained. However, the process of determining whether, when, where and how best to intervene is far more complex.

3.2. Deterioration of track geometry

With the exception of drainage and substructure, the track geometry primarily deteriorates due to the influence of dynamic loads exerted by vehicles. The mechanism governing this phenomenon is rather complex. If a track is freshly tamped, it is well known that relatively large settlements will occur directly afterwards. If every point of the track were to settle equally, no irregularities would develop. However, these settlements are often far from uniform, due to non-homogeneities in support conditions, track structure, and load distribution. This results in differential settlements, which lead to the development of irregularities in the wavebands experienced by the rolling stock.
Many investigations have been carried out on the fundamentals of the deterioration mechanism and the possibilities of controlling this phenomenon via DMs and the existing or improved maintenance methods [5-13].
However, oftentimes these DMs, when approaching the modelling problem statistically, are oversimplified and are reduced a mere linear representation (Figure 5) [14], concentrating only on the "deterioration" part while completely neglecting the "restoration" part, i.e. the effectiveness of M&R works (in this case primarily Tamping). This effectively prevents any consideration of the increase of M&R works (Tamping) frequency in time, which makes them usable only for a very limited range of condition parameters, and for very short time-span forecasts (up to 2-3 years), while they are completely unsuitable for medium- and long-term simulations ranging from 5 to 30 years. Knowing that, due to a relatively long service lives of track components (typically 20-60 years, depending on their quality and exploitation), only long-term strategic optimizations could yield real benefits, it could be concluded that better, more flexible models are needed, especially taking into account today's enormous increase in the volume of available condition data (being perhaps 100-fold in comparison) and computer power.

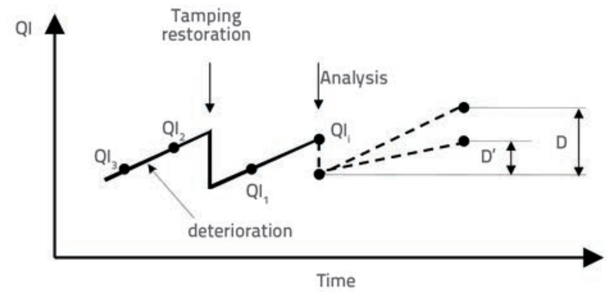

Figure 5. Track deterioration and restoration in terms of Track Quality Index (QI)

3.3. Basics for predicting track geometry deterioration

In order to know what the limiting quality is, and to decide when M&R is required, it is necessary to predict TG deterioration. Also, similar track sections may have very different rates of deterioration, as they may also have very different rates of improvement (restoration), as a consequence of M&R activities. Therefore, the TG data must be collected & processed in very short sections for the purpose of optimizing M&R and identifying the influencing factors.
Traditionally, the length of these sections is 200 m, or 1/8 of a mile. Nowadays, they represent the result of the Segmentation process, as indicated in Section 1.1 and, as the main idea of Segmentation is to create segments of uniform behaviour, they can actually assume any length, although they are usually restricted within the Segmentation process to the lengths of 100-500 m. In reality, a finer segmentation would be preferred, with segments of up to 200 m in length, for the short-term analyses (e.g. 3 months to 1 year) of local character (e.g. stretches of several kilometres), which primarily focus on maintenance activities. As opposed to that, coarser segmentation, with segment lengths of 500-1000 m, would be preferred for long-term analyses, typically for budgeting reasons, and here the primary focus is on renewal rather than on maintenance works. This coarser segmentation is of more global character (e.g. entire line/region, or indeed the entire network). Types of data required for the analysis are listed in Section 2 of this paper.
The vertical and lateral TG is usually measured by track recording vehicles. They enable calculation of standard

deviations, which has been shown to be useful for predictive purposes. In some cases, vehicle reactions calculated from recorded TG data are used to assess the track quality. When measurements have been made over two or more tamping and lining cycles, average values for both the "deterioration rate" and "restoration rate" (improvement through maintenance) can be found for each segment.

The deterioration rates are usually calculated either as a function of traffic in mm/MGT, or as a function of time in mm/year. Without including quick settlement and rapid deterioration of track immediately after tamping, the deterioration rate often (generally) displays a linear trend between two maintenance operations (if not allowed to deteriorate further without any interventions) [18].

Normally, the TG deterioration line exhibits the so-called "saw-tooth" pattern, where the quality deteriorates between two subsequent activities (in this case tamping), which is normally seen as an increase in measured values (or processed values like standard deviations), after which the tamping is performed causing a sudden increase in quality (i.e. drop/decrease in measured values). However, several other things change over time, as the track grows older. The first thing that changes is the efficiency of tamping, e.g. the intensity of the "vertical drop" on the graph. Another thing that changes is the "deterioration rate", i.e. the slope of the line defined by measured points. Finally, both of these two events have their impact on the required tamping frequency, which becomes higher and higher, i.e. the time period between two tamping operations (tamping cycle) becomes shorter and shorter. Eventually, the tamping frequency becomes so high that the tamping becomes inefficient, which is an indication that something else needs to be done, i.e. another M&R activity, such as ballast renewal.

The global idea is to analyse the track elements' condition from as many aspects as possible. The goal is to enable the track manager to see the "big picture", i.e. to simultaneously display all kinds of information that could influence track condition, to be able to search for the real cause of certain track problems, and reach decisions about the best possible remedial actions. This decision-making can be performed either manually, displaying and overlaying all sorts of information, or automatically using the pre-defined decision rules.

4. Generic/universal deterioration model

The research partially presented in this paper was undertaken following the above-explained shortcomings of currently available models, as well as the basic analysis principles, with an ultimate goal of developing a generic/universal DM that would be flexible enough to take into account any deterioration parameter, yet powerful and flexible enough to accurately represent/fit various condition-related behaviours as seen via measurement data.

Having defined the above as the final goal, the starting position can be formulated based on the following basic statements:

- There is a condition-parameter representing an aspect of a condition of an object of a system
- There is a certain number of activities that influence the behaviour of this parameter over time. By the "nature" of their influence on a given parameter, some activities are considered "essential", and some "temporary":
  - **Essential activities** influence essentially/profoundly the behaviour of a certain condition-parameter, by effectively "re-setting" the entire model (e.g. the effect of ballast renewal on the track geometry behaviour)
  - **Temporary activities,** e.g. maintenance activities that are performed several times between two (or more) essential activities, change (though only temporarily) the value of a condition parameter (e.g. by improving it); their efficiency (expected and allowed by the model) decreases over time, as the facility grows older.

Taking an imaginary condition-parameter and, for instance, 3 activities (A/B/C), the long-term behaviour can be depicted as shown in Figure 6.

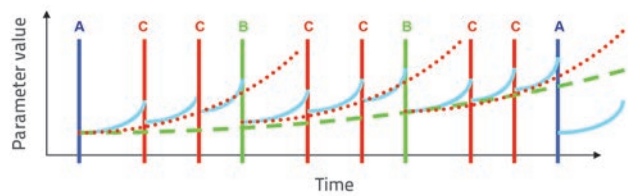

Figure 6. Schematic representation of a mono-parametric long-term generic deterioration model

The activity A represents an "essential" activity, while the activities B and C represent "temporary" activities. "C" is the temporary activity of the Level 1, and "B" of the Level 2 (with the number of "Levels" being unlimited in the model – although situations with more than 3 levels seldom occur in practice).

According to Figure 6, several "deterioration patterns" or sub-models can also be distinguished: the cyan curve (of any general form, e.g. linear, polynomial, exponential, etc.), representing the ("basic") deterioration between any two adjacent activities (Level 1 deterioration curve); the red-dotted curve (Level 2 deterioration curve) representing the change of "restoration points" from the Level 1 deterioration curve (points to which the temporary activities of the type C managed to improve the value of the parameter), as seen over several temporary activities of the type C (red) and, finally, the green-dashed curve representing the change of restoration points of the Level 2 deterioration curve (red-dotted), i.e. points to which the temporary activities of the Level 2 (green) managed to improve the value of the Level 2 deterioration curve (red-dotted), as seen over the period between two temporary activities of the type B (green), or in this case between the starting essential activity A (blue) and the first adjacent temporary activity of the Level 2 (type B - green). Also, a period between any two adjacent activities, regardless of their Level, is considered as an "Analysis

Period" of Level 1, whereas periods between Level 2 temporary activities are considered as "Analysis Periods" of Level 2, etc. If we now magnify this we obtain:

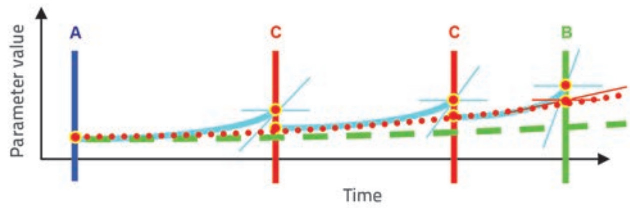

Figure 7. Mono-parametric long-term generic deterioration model (part between an essential "A" and a Level 2 temporary activity "B", over two Level 1 temporary activities "C", i.e. over 3 Level 1 "Analysis Periods")

The following can be observed from three analysis periods presented in Figure 7:

- The basic deterioration curve (cyan/continuous) is growing increasingly sharper over the three analysis periods, which can also be seen from the increased angle of the tangent to the basic curve (cyan) at its ends
- The starting point, representing the basic curve's "restoration value", is getting higher and higher, and that rise is in fact shown by the red-dotted line (the Level 2 deterioration curve).
- If we take a look at Figure 6 showing 9 analysis periods (in fact 10, as for the last one we just do not know the ending point), we can see that the red-dotted line is also becoming increasingly sharper, which can also be seen from the angle of the tangents to the red-dotted lines at their end points. We can additionally see that the starting point of the red-dotted line is also getting higher and higher, which is in fact shown by the green-dashed line that connects those starting points (restoration values) of the red-dotted line, i.e. of the temporary activity of the highest Importance Level (Level 2) (the green activity B).

We can explicitly model any condition-parameter, with any given number of activities and curves, if we know, for every condition-parameter, which are the influencing activities, i.e. which of them are the "essential ones", and which are the "temporary ones" (and at what Level of importance), which are the types of curves, which is the "law of change" of the angle of the tangent to each of the lines at their start and end points (marked as "α" and "β" curves, respectively). All this information can be obtained from the known past behaviour, via condition measurements.

If we now take a look at the very last analysis period, the 10th one in Figure 6, or the 4th one in Figure 7, i.e. the most right-hand ones, for which we do not know the end point, we obtain the situation as shown in Figure 8. This is precisely the core of the Deterioration Problem, and thus the very DM, where t_S and t_E represent the starting and ending points of the observed analysis period (with t_E being unknown and thus sought for).

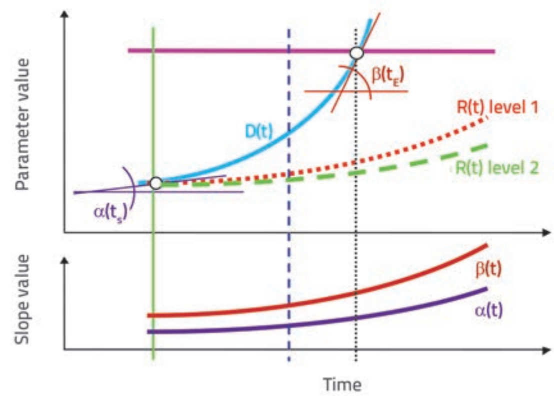

Figure 8. Generic starting shape of Deterioration Curve

4.1. Particular solutions for curve types and mathematical formulations

Obviously, the modelling approach and the solution will differ depending on the actual type of curves *D(t)*, *R(t)*, $\alpha(t)$ and $\beta(t)$ (for all levels). More particularly, a number of known points will differ depending on the parametric shape of the curve (i.e. the actual number of unknown coefficients). For the sake of comparison with older models, only the case based on the following assumptions will be presented in this paper:

- *D(t)* curve is linear,
- *R(t)* and $\alpha(t)$ are square (polynomial, 2nd order)
- There are only two "Levels of diagnosis", i.e. there are only two types of works – "temporary" (Tamping) and "essential" (Ballast renewal).

Obviously, the complexity of the model builds up rapidly with the number of levels, and the number of "governing curves" increases by the factor of 3 with every additional Level. The full model is of course generic and can handle any number of Levels of diagnosis, and any types of curves at each of the Levels.

According to the above assumptions, the basic structure of the model looks as shown in Figure 9. With $D(t) = b*t + c$, we effectively get the following three conditions for the model to satisfy in order to unequivocally define the *D(t)* curve:

$$b = \alpha\,(t_S), \tag{1}$$

knowing that:

$$D(t_S) = R(t_S),\ \text{tj. } R(t_S) = \alpha(t_S)*t_S + c \quad \text{gives: } c = R(t_S) - \alpha(t_S)*t_S \tag{2}$$

Finally, we also know that:

$$t_E = t_S + [L - R(t_S)] \,/\, \alpha(t_S) \tag{3}$$

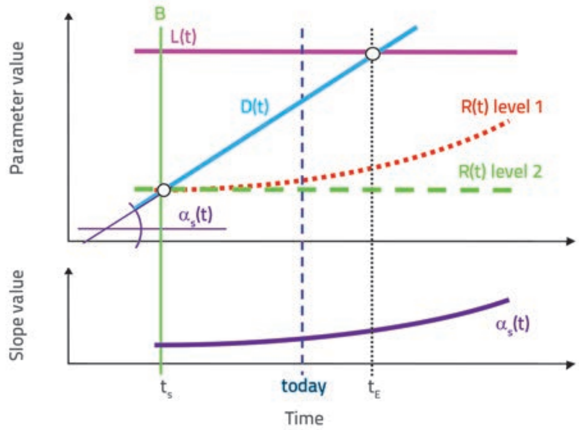

Figure 9. Generic starting shape of the deterioration curve

The known parameters are obviously tt_S, $\alpha(t_S)$, $R(t_S)$, $L(t)$ = *const.* = L, , while the unknown ones are the *D(t)* curve coefficients "*a*" & "*b*", and t_E. After solving the above-described system of equations (1-3), the *D(t)* curve takes up the following form:

$$D(t) = R + (t - t_s) * \alpha(t_S) \quad (4)$$

Various curve types can be found in practice. In RMMS, all major curves (linear, quadratic, exponential, logarithmic and power) must be mathematically resolved and made available for the generic DM. However, in the railway practice the most suitable, and thus also most often used combination of curve types (especially for TG) is Linear or Quadratic for the Level 1 curves, and Quadratic for the upper level curves (Level 2 in particular).

4.2. The case study

For the purposes of this paper, a Case Study for Linear *D(t)* curve will be presented. The following data are used: TG Measurements (Alignment Standard Deviation (SD), values for 200m track segments), as measured by a Track Geometry Recording Vehicle on the Category I Line, Rome–Naples in Italy (Table 1) (*Dates are rounded to a month, due to the work & inspections recording system in Italy, at RFI, that records only months and not the days; within a month, actual dates are taken arbitrarily, with the date being equal to the month, for mere simplicity, e.g. 3/3 or 6/6 or 9/9*).

Since Activities (Tamping works) interfere with the values of the condition parameter, we can distinguish three periods (Table 2):

Table 1. Track geometry measurements (Standard Deviations - SD) and work history (Tamping)

Track geometry measurements (SDs)				Work history (Tamping)	
Date	**Measured value**	**Date**	**Measured value**	**Date**	**Activity**
3/3/98	1,2	3/3/01	1,5	1/1/98	podbijanje
9/9/98	1,4	9/9/01	1,9	6/6/00	podbijanje
3/3/99	1,6	3/3/02	2,3	6/6/02	podbijanje
9/9/99	1,8	9/9/02	1,8		
3/3/00	2,3	3/3/03	2,1		
9/9/00	1,4				

Table 2. Activities (Tamping works) defining the (starts and ends of) analysis periods

Analysis period	Starting moment	Ending moment
1	**Start of the model** - The date of first activity (Tamping)(**1/1/98**)	The date of **second activity** (Tamping) (**6/6/00**)
2	The date of **second activity** (Tamping) (**6/6/00**)	The date of **third activity** (Tamping) (**6/6/02**)
3	The date of **third activity** (Tamping) (**6/6/02**)	**Today (planning period start, i.e. the "Reference date")**

Table 3. Track Geometry Measurements (Standard Deviations) grouped into analysis periods

Date	Value	Date	Value	Date	Value
1st Analysis period		2nd Analysis period		3rd Analysis period	
3/3/98	1,2	9/9/00	1,4	9/9/02	1,8
9/9/98	1,4	3/3/01	1,5	3/3/03	2,2
3/3/99	1,6	9/9/01	1,9		
9/9/99	1,8	3/3/02	2,3		
3/3/00	2,3				

Therefore, we can write our measurements grouped into **analysis periods** as follows:

By applying the Model, we obtain the following resulting situation in terms of the past behaviour modelling (Figure 10).

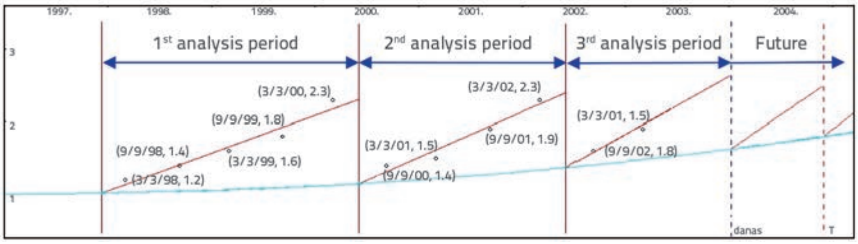

Figure 10. Past behaviour modelling

Or, if we apply the Model to get the future progression of the forecast behaviour, we get the situation as shown in Figure 11 (a). This again allows us to count both the Level 1 and Level 2 activities during the pre-specified Planning Period, which would have to be long enough (e.g. 50 years) and, knowing the unit costs of these works, to calculate the total costs of the Work Plan, perhaps also including the costs of the track possessions, traffic disruptions, etc. With this being fully definable, and thus automated, we can start testing different scenarios/strategies, e.g. by applying different Decision Rules, different (assumed) Deterioration curves of the Level 1 & 2, and by calculating consequential costs, as well as the quality (the value of the condition parameter in question) at any given time in the future. One of the approaches to defining various Decision-making strategies would be to determine when the Level 2 Work (in this case ballast renewal) should be applied, as opposed to the Level 1 (maintenance) Work (in this case tamping). Our strategy could for example be directed towards limiting the minimum time between two consecutive Maintenance (tamping) works, following the situation in practice where traffic closures are necessary for the performance of these works, causing unpleasant and costly traffic disturbances, thus clearly calling for minimization. In Figure 11 (a), the minimum time between two consecutive maintenance (tamping) works was set to 6 months (182 days), and the resulting annual costs were 2590 units, while the resulting quality was 1.68 (mm standard deviation). The situation becomes quite different (as shown in Figure 11 (b) if we for example set it to 30 days, which is extreme, but still sometimes applied at some railways and often metros in some specific conditions characterized typically by old and contaminated ballast, often with poor substructure conditions, yet with inability to perform major remedial works (e.g. ballast cleaning/renewal), either due to the lack of available track possessions or simply finances. Here the resulting annual costs are 3364 units (more expensive), and the quality is 1.71 mm (thus worse – i.e. higher value in case of this particular condition parameter, i.e. TG SD, signifies worse condition).

As the final exercise, we could set the minimal tamping cycle to a high value, e.g. 2 years, 730 days, in which case we obtain the situation shown in Figure 11 (c), with the resulting costs of 2368 units (lowest!) and the quality of 1.61 mm (best!).

Another prudent strategy (fully supported by this model) could be to specify the minimum quality improvement expected to be achieved by a maintenance activity (tamping), i.e. should the quality improvement (value drop on the graph) after a certain maintenance activity become too small, it should call for performance of a renewal activity instead of the maintenance activity, which has clearly become ineffective. However, due to space restrictions, we did not utilize and describe this inherent capability of the model to govern and use the efficiency of the works in question (e.g. Level 1 - tamping) to decide on the moment when the Level 2 works (ballast renewal) are needed, although it is in fact one of its most significant features, extremely useful for determining an optimum balance between the costs of the M&R plan and the resulting quality.

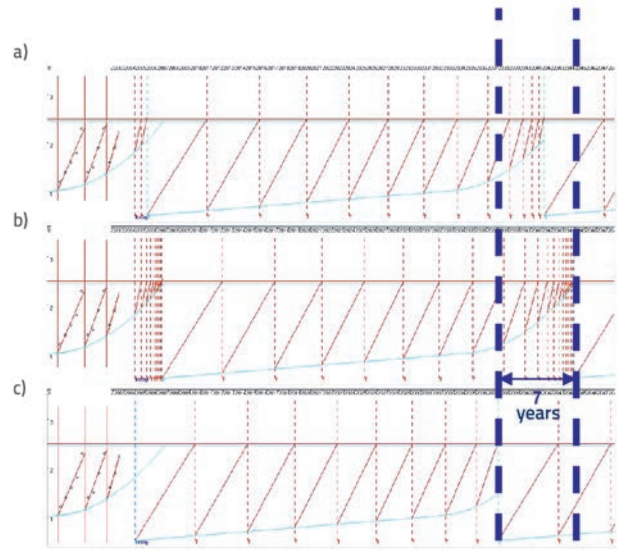

Figure 11. Modelled future behaviour with a) 6 moths; b) 30 days; c) 2 years minimum time between consecutive tamping works

5. Conclusions

The use of generic DMs allows railways to perform long-term simulations of track behaviour, balancing effectively maintenance with renewal, and the achieved quality with the costs of M&R works, inspections and other consequences like traffic disruptions, unavailability, etc. A truly optimum long-term balance, resulting in significant cost savings for railway organisations, can be achieved by empowering this model with the Life Cycle Costing and numerical optimization techniques (with proper and flexible formulation of global objectives) within a well-structured RMMS. At the same time, such a tool would be of invaluable assistance to infrastructure managers.

The RMMS structure and the functionalities described in this paper strongly support the claim that RMMS is a completely unique system in railway industry. It fully supports the condition-based M&R management approach, linking all necessary data from asset inventory and exploitation, via condition monitoring/measurements, to the M&R work history and resource allocation, through a unique and sophisticated automatic process of deterioration-modelling and powerful rule-(engine)-based work-planning.

By providing all this, RMMS allows true targeting of M&R works, i.e. ensuring that the right works are always conducted at the right places, at the right time and for the right reasons. This in turn enables considerable cost-savings, while keeping full and constant control over the traffic safety and quality of infrastructure assets. Finally, the RMMS allows railways to simulate, test and explore various M&R policies and their consequences.

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