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Modelling railway track geometry deterioration

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Understanding track geometry deterioration decisively influences the planning and optimisation of track maintenance and renewal works and consequently the substantial related costs (savings) each year of every railway. To understand this deterioration it must be accurately modelled, paving the way towards its forecasting into the future. The main aim of the present study was to model railway track geometry deterioration using multivariate statistical analysis of the variables involved and to predict the future behaviour of the track geometry deterioration. For this purpose, a track section of about 180 km in length was selected as the base for the model and divided into analytical segments of as uniform characteristics as possible using a special segmentation algorithm. The lengths of the individual analytical segments were not identical, but were also kept as close to uniform as possible. For each analytical segment, the following general information was collected: track structure, traffic characteristics, track layout, environmental factors, track geometry measurements records and maintenance and renewal history data. Consequently, multivariate statistical analysis was performed on the main track geometry parameters: twist, level, alignment, gauge and cant. The coefficients of the independent variables involved in track geometry were found for each parameter in order to predict future behaviour for the purposes of efficient maintenance and renewal management.

Notation

D_i	deterioration (mm)
D_f	track damage factor
L	rail influence factor (= 1 for CWR; = 10 for jointed rail)
M	structure factor
N	number of axle passes
P	influence factor for subgrade (1 = good; 10 = bad)
p_b	ballast pressure (Pa)
p	significance
P_b	quasi-static ballast pressure
Q	axle load (tonnes)
R^2	coefficient of determination
S	average growth in irregularity (mm/100 days)
S_i	the impact coefficient (a function of the rail properties)
T	passed tonnage (million tonnes/year)
V	speed (km/h)
V_a	average running speed (km/h)
w	vehicle weight (tonne)
Y_i	accumulated (cumulative) traffic loads in tonnes
y_z	the rail acceleration (m/s^2)
ΔN	number of axle passes $\leqslant$ 10 000
α_i	coefficients of independent variables
τ_i	deterioration rate in mm/tonne

1. Introduction

The International Union of Railways (UIC, 2006) states that costs of permanent way and its maintenance and renewal (M&R) are substantial and form a large part of total infrastructure expenditure. Any reduction in these costs has a significant impact on the overall efficiency of the management of infrastructure. The process of determining whether, when, where and how to intervene and deciding on an optimum allocation of resources and minimisation of costs represents a very complex problem because: different track sections tend to behave differently under the effects of loading; decision processes for M&R works are closely interrelated technically and economically; and decision-making for M&R plans is based on a large quantity of technical and economic information, extensive knowledge and above all experience (Jovanovic, 2004; Jovanovic and Esveld, 2001). For the optimum use of the available information and control of the M&R processes the data should be condensed. Initially, the data are related only to the basic units of sections. Track recording car data, for example, mostly refer to sections 100 or 200 m long or are alternatively stored on a kilometre basis. Although these units are important for detailed planning of M&R works, there are far too many of them for general planning, namely for future M&R policy. The data extracted from these units, usually called analytical segments thus need to be further grouped into so-called maintenance sections (Mains) (Esveld, 2001) in order to provide a broader overview of a route as well as the suitable base for the utilisation of large machinery, and these would typically be 5 to 20 km long, the actual length normally being governed by the actual distance between adjacent stations or junctions. Finally, the information needs further aggregating into longer ‘route’ sections in order to obtain a network-scale assessment of the quality and consequential M&R needs. Therefore, obviously, Mains-based

M&R programmes depend on a reasonable deterioration model based on analytical segments (Esveld 2001).

Modelling of track geometry deterioration using analytical methods is a very complex problem because of the large number of influencing parameters. Therefore, empirical methods such as multivariate regression might prove to be more suitable for modelling track geometry deterioration since the relationships between the parameters are fairly well understood. Multivariate statistics represents a powerful tool for investigating the inherent structure in the indicators' set. A multivariate statistic is a statistic that involves two or more variables. Examples of multivariate statistics include correlation coefficients, Student's *t*-test, *F*-test and coefficient of determination. If all characteristic data for both qualitative and quantitative properties of the analytical segments are available, multivariate statistics can be designed to estimate the individual effect of each variable on track geometry deterioration with the coefficients (Draper and Smith, 1981; Montgomery and Peck, 1982; Washington *et al.*, 2003).

2. Hypothetical track geometry deterioration

Track design geometry is described in terms of vertical and horizontal geometry which are: superelevation (cant), gauge, twist, level and alignment as functions of distance along the track (BSI, 2003). The design geometry should be achieved within tight tolerances during track construction. Track geometry, however, tends to deteriorate away from the construction/design geometry with the passage of rolling stock. Defects in the geometry are caused, in general, by differential track support settlement and local spot irregularities associated with dipped joints, wetspots, wheel burns, corrugation and so on. Monitoring track geometry is thus very important primarily for maintaining safe train operation by identifying safety-critical geometric irregularities that need to be corrected (Weston *et al.*, 2007) (usually very quickly upon their observation), as well for preventing track geometry irregularities (which normally cause an, often significant, increase in dynamic forces) causing permanent damage to the track components, and thus reducing their service lives and, obviously, causing significant costs (Jovanovic, 2004).

Track condition is defined by the condition of its components and its geometry. These two groups of elements are closely interrelated within the complex process of track deterioration and restoration; if one is in poor condition this will contribute to the deterioration of the other, and if the components are in poor condition it will not be possible to correct the geometry efficiently. M&R activities must therefore be adjusted to match the age of the track. The model therefore distinguishes between 'young', 'old' and 'intermediate' track. The duration of each of these phases, and the lifetime of the track, will vary considerably depending on the characteristics of the track itself. Aside from the loads to which the track is subjected, the number and scale of maintenance operations will play an essential role (Guler and Jovanovic, 2003; Jovanovic, 2004).

The basic idea is that the behaviour of the track geometry of a certain segment, expressed by means of a certain geometry parameter, is monitored in time and, thus, captured (Figure 1). The solid black curve shows the hypothetical deterioration of the track geometry if the track had been left to deteriorate without any maintenance input. On this curve we can also distinguish three phases: the first phase, often referred to as 'youth', occurs immediately upon (re)construction or completion of a certain major renewal work and characterises rapid and substantial deterioration caused by the initial settlements of the track (Figure 1, marked with (a)). This period is also highly unpredictable and differs considerably from one track section to another and thus is very difficult to model. The duration of this period is fortunately quite short, which diminishes the consequences of omission (Guler and Jovanovic, 2003; Jovanovic, 2004; Jovanovic and Esveld, 2001).

The second phase, which occurs once the track has been sufficiently stabilised, shows a more-or-less linear deterioration pattern. This kind of behaviour occurs during the majority of the track's life-time (Figure 1, marked with (b)).

The third period occurs in the later part of the track's lifetime and is characterised by an increasingly rapid deterioration, which eventually exhibits a quasi-exponential form (Figure 1, marked with (c)). Normally, this is a situation which should never be allowed to happen under any circumstances, as it could affect the safety of traffic as well. This is avoided by applying certain appropriate M&R works at a much earlier stage; that is, there is always a maintenance threshold value present (horizontal black line), which, when reached, triggers certain M&R activity.

Based on this concept, measurement data within the linear part of the track behaviour are the data that are analysed most often. The track geometry behaviour is captured by calculating the trend line through the measured points and extrapolating it. Provided that the maintenance threshold has been set (black horizontal line), the moment (or the tonnage) when this extrapolated line will reach the threshold is calculated, marking the moment when certain M&R activity, such as tamping, should be performed.

After tamping has been performed, the parameter value drops abruptly; that is, the quality increases. In Figure 1 this is represented by the vertical distance marked with black (real parameter drops), or the black vertical distance and vertical drops marked by the thick black saw-tooth line (simulated parameter drops).

After the quality has been improved by tamping, the deterioration process will start again. However, several things will change over time as the track grows older. The first thing that changes is the efficiency of tamping, for example the intensity of the 'vertical drop'. This can be observed by looking at the line showing the 'real behaviour' of the track (black vertical dimensioning line) or by looking at the simulated linear line

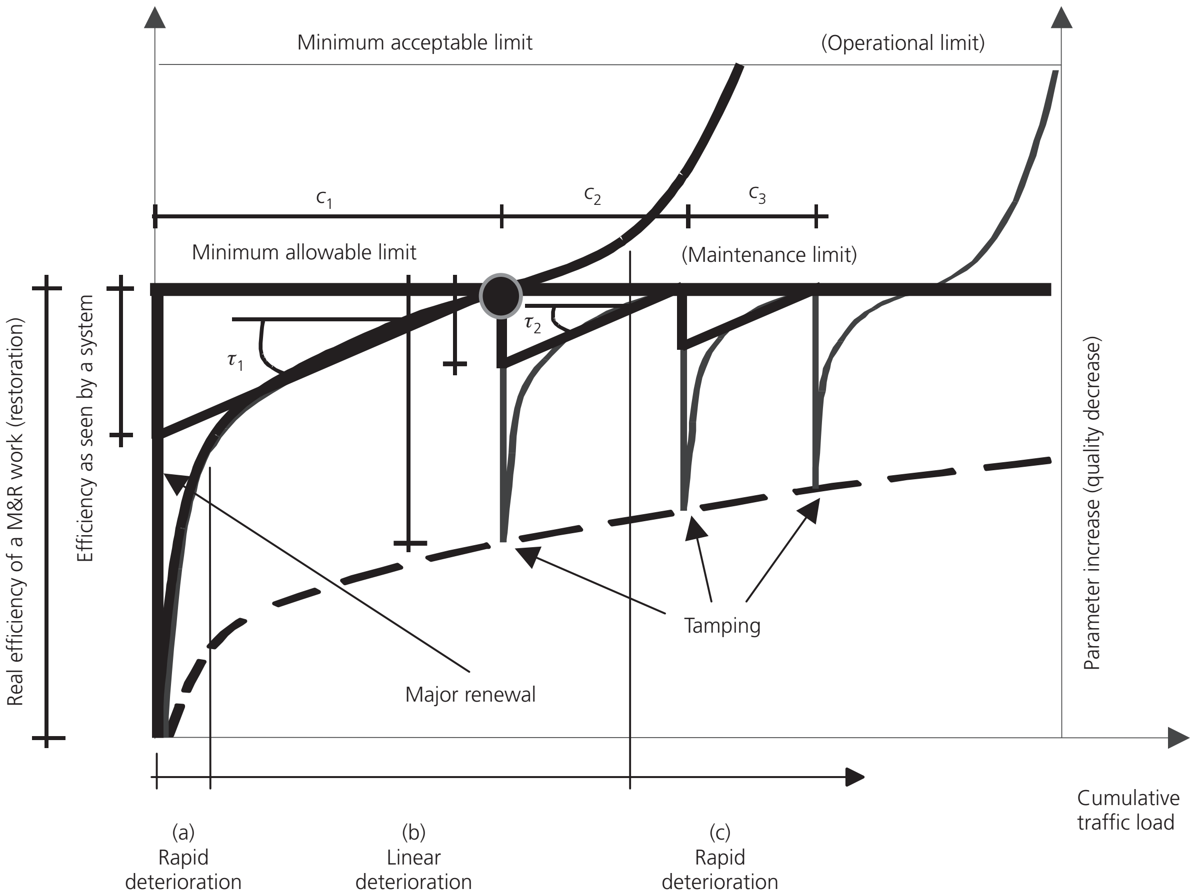

Figure 1. Analysis principle applied on hypothetical track geometry deterioration

(thick black saw-tooth-like one). It becomes even clearer, however, from the dashed black line which shows this change over time. Another thing that changes is the 'deterioration rate', which is the slope of the line defined by measured points (represented by τ_1 and τ_2).

Due to material fatigue, breakage or other ageing processes, the deterioration rate of the railway track increases in time. Both of these events have their impact on the required tamping frequency, which becomes higher and higher; that is, the time period between two tamping works (tamping cycle) becomes shorter and shorter. Eventually, the tamping frequency becomes so high that it no longer makes sense to tamp. However, action definitely needs to be taken, namely some other M&R activity such as ballast renewal (Guler *et al.*, 2004).

3. Overview of track deterioration models

Numerous deterioration models have been used to estimate track settlement and consequential track geometry deterioration. They include both statistical and empirical models, mostly based on various records (or measurements) made on track. A simple power law is used by a number of railway organisations, where ballast pressure is evaluated and raised to the second (optimistic) or fourth (pessimistic) power. The ORE (Office for Research and Experiments of the International Union of Railways, later called ERRI, European Rail Research Institute) deterioration model was developed as a statistical model with no track parameters but included traffic, dynamic axle load and speed raised to the power of empirically derived factors. Japanese experience has led to an empirical track-settlement model based on quasi-static ballast pressure and ballast acceleration, together with vehicle speed and tonnage and factors for track type (Iwnicki *et al.*, 2000; Sato 1995). Experiments at the Technical University of Munich led to a series of equations predicting settlement rate from ballast pressure (Iwnicki *et al.*, 2000).

3.1 The 'Sato' track damage model

Japanese records from track diagnostic vehicles over many years have led to an empirical track settlement model. Rail vibrations are used to predict ballast settlement and growth of irregularities using the following equation (Iwnicki *et al.*, 2000; Sato 1995)

1. $S = 2{\cdot}09^* 10^{-3*} T^{0{\cdot}31*} V_a{}^{0{\cdot}98*} M^{1{\cdot}1*} L^{0{\cdot}21*} P^{0{\cdot}26}$

The structure factor contains the influence of the forces on the track and is calculated as follows

2. $M = P_b{}^* y_z{}^* S_i$

For vehicles running on similar track, Equation 1 can be reduced to

3. $S \approx V^{0{\cdot}98*} T^{0{\cdot}31*} M^{1{\cdot}1}$

and therefore for an equal number of vehicle-passes a track damage factor can be defined

4. $D_f = V^{0{\cdot}98*} w^{0{\cdot}31*} \left(Q^* y_z\right)^{1{\cdot}1}$

3.2 British Rail Research track deterioration models

Ballast settlement has been studied in the laboratory and the results integrated into a system called Marpas (Maintenance and Renewal Planning Aid System) in British Rail Research (during the 1970s and 1980s it was a research office of British Rail). The track geometry deterioration model used in the Marpas system was extremely complex and was developed as a result of fundamental research over a period of about 30 years. This system did not include a model for the vehicle dynamics but used two coefficients to calculate the ride force. These coefficients were called the ride force constant and the ride force coefficient and they needed to be found for each vehicle being studied (European Rail Research Institute, 1993; Iwnicki *et al.*, 2000; Wiseman, 1989).

3.3 Technical University of Munich settlement model

Experiments under well-controlled laboratory conditions at the Technical University of Munich representative of vehicles passing a dipped joint have been used to establish equations to calculate rate of settlement. Ballast pressure was multiplied by the logarithm of the number of axle passes as follows (Iwnicki *et al.*, 2000)

5. $S_{opt} = 1{\cdot}57^* p_b{}^* \Delta N + 3{\cdot}04^* p_b{}^{1{\cdot}21*} \ln N$

6. $S_{pess} = 2{\cdot}33^* p_b{}^* \Delta N + 15{\cdot}20^* p_b{}^{1{\cdot}21*} \ln N$

7. $S_{med} = 1{\cdot}89^* p_b{}^* \Delta N + 5{\cdot}15^* p_b{}^{1{\cdot}21*} \ln N$

The first part of the equation relates to the initial settlement immediately after tamping and the second part relates to the longer term and more gradual settlement after about 10 000 axle passes. Ballast pressure is calculated using the Zimmermann method, which involves a theoretical 'equivalent longitudinal sleeper' (beam) placed under the track (Iwnicki *et al.*, 2000).

4. Modelling track geometry deterioration

4.1 Data description

A model of about 180 km of track located between Arifiye and Eskisehir in Turkey, was divided into analytical segments to build a statistical deterioration model. The segmentation process enabled obtaining homogeneous analytical segments of uniform properties. The analytical segment choice was intended to enable a study of the effects of the following variables (European Rail Research Institute, 1987): gradient (‰); curvature ($1/R$) (1/m); cant (mm); speed (km/h); age (years); rail-type (kg/m); rail length (m); sleeper-type (Figure 2) (Jovanovic, 2004).

As a result of this segmentation operation, 820 uniform analytical segments were obtained, with an average length of 220 m, the minimum length was 12 m, the maximum length was 4916 m and the standard deviation was 224·646 m.

The following environmental effects were also determined for every analytical segment in order to detect the role of environmental effects on the track geometry deterioration: land-slide, flooding, falling rock and snow. These parameters were not included during the segmentation process.

Dedicated track recording vehicles accurately measure track geometry and provide the magnitude and locations of the exceedences according to the local line speed to inform track maintenance staff (Weston *et al.*, 2007). Track recording vehicles could be self-propelled or hauled, and with fixed, dedicated, measuring equipment and systems, used for the measurement, assessment and recording of the track geometry under loaded conditions, which measures and produces consistent results, to the requirements of the standards.

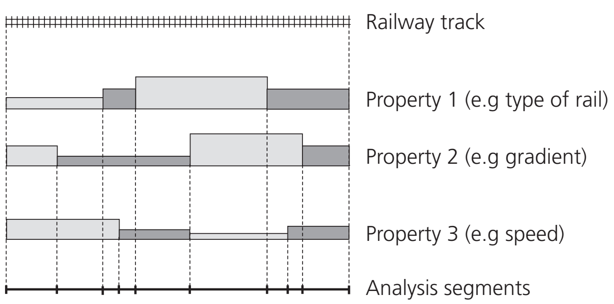

Figure 2. Track segmentation process

The track geometry irregularities and consequential deteriorations (*D*), regularly measured by the Turkish State Railways (TCDD) with the track diagnostic train every 6 months from 1995 to 2001 (7 years); namely corresponding to 14 periods, are presented in Figure 3.

Finally, the following $[D_i]_{820\times14}$ deterioration matrix was obtained. In this matrix, the D_i values represent the deteriorations in millimetres, (*i*) represents a specific track geometry parameter, 820 is the number of segments and 14 is the number of measurements.

$$[D_i]_{820\times14} = \begin{bmatrix} D_{i11} & D_{i12} & D_{i13} & \ldots & D_{i114} \\ D_{i21} & D_{i22} & D_{i23} & \ldots & D_{i214} \\ D_{i31} & D_{i32} & D_{i33} & \ldots & D_{i314} \\ . & . & . & \ldots & . \\ D_{i8201} & D_{i8202} & D_{i8203} & \ldots & D_{i82014} \end{bmatrix} \tag{8}$$

Information on the characteristics of railway track and turnouts is important to determine M&R needs over the short, medium and long term. This information must be periodically collected. Having only track geometry measurements does not tell track managers much. Only in case of having all data related to the track does the information become reliable and usable (Jovanovic, 2004).

M&R activities are regularly carried out, therefore they were also performed in the past on the analysed track segments and thus, inevitably some improvements were observed also on the analytical segments. Consequently, it was not possible to constitute a track geometry deterioration model using only the measurements provided by the diagnostic vehicle monitoring the track each 6 months without taking into account the influence of the performed M&R works. For that reason, the M&R activities in the investigated period were acquired on a monthly basis. Thus, 84 months (7 years) of M&R activities carried out between Arifiye and Eskisehir were documented. Table 1 represents the M&R activities carried out with the corresponding units of measure (TCDD, 2000).

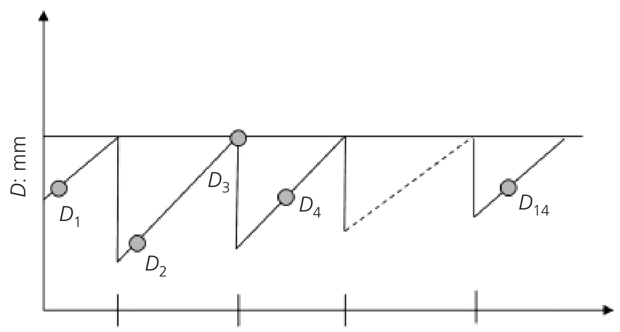

Figure 3. The measured track geometry deteriorations

Globally, railway track geometry consists of vertical and horizontal geometry. The vertical geometry includes twist, level and cant; horizontal geometry includes alignment and gauge. It is necessary to determine which M&R works are influencing (improving) which track geometry parameters in order to build a deterioration model for each geometry parameter separately. According to the manuals normally used by the railway maintenance departments, M&R works (1, 2, 11 and 12) influence the vertical geometry, namely twist, cant and level, whereas M&R works (3, 4, 5, 6, 9 and 10 influence the horizontal geometry, namely alignment and gauge. The track geometry deteriorations and corresponding/influencing M&R works are represented in Table 2 (TCDD, 2000).

Railway track is regularly monitored by maintenance gangs with portable diagnostic systems as well as visually, and if they detect any fault, the relevant M&R activities are carried out. Consequently, a track geometry parameter of an analytical segment was assumed to have deteriorated when an influencing M&R work was carried out on it. The M&R thresholds were taken into consideration during this process and the thresholds values were assigned to the deteriorated analytical segments. Table 3 shows M&R thresholds currently in use by TCDD (BSI, 2005; TCDD, 2000). Finally, $[B_i]_{820\times84}$ deterioration matrices were obtained for each track geometry parameter from the combination of the track recording measurements, and the assumed deteriorations based on the 84 months of M&R activities. In this matrix, D_i values represent the deteriorations in millimetres, *i* represents a track geometry parameter, 820 is the number of segments, and 84 is the number of measurements, combined measurements and M&R activities.

$$[D_i]_{820\times84} = \begin{bmatrix} D_{i11} & D_{i12} & D_{i13} & \ldots & D_{i184} \\ D_{i21} & D_{i22} & D_{i23} & \ldots & D_{i284} \\ D_{i31} & D_{i32} & D_{i33} & \ldots & D_{i384} \\ . & . & . & \ldots & . \\ D_{i8201} & D_{i8202} & D_{i8203} & \ldots & D_{i82084} \end{bmatrix} \tag{9}$$

ID	Type of M&R	Units
1	Manual tamping	m
2	Mechanical tamping	m
3	Small components maintenance	pcs
4	Small component renewal	pcs
5	Sleeper renewal	pcs
6	Rail renewal	pcs
7	Rail welding	pcs
8	Rail thermit welding	pcs
9	Plastic dowel renewal	pcs
10	Plastic insulator renewal	pcs
11	Ballast profiling and stabilisation	m
12	Mechanical ballast cleaning	m

Table 1. Maintenance and renewal (M&R) activities carried out in the 7-year period (1995–2001)

Number	Type of deterioration	Influencing M&R works
1	Twist	1,2,11,12
2	Gauge	3,4,5,6,9,10
3	Alignment	3,4,5,6,9,10
4	Cant	1,2,11,12
5	Level	1,2,11,12

Table 2. Track geometry deteriorations and influential maintenance and renewal (M&R) works

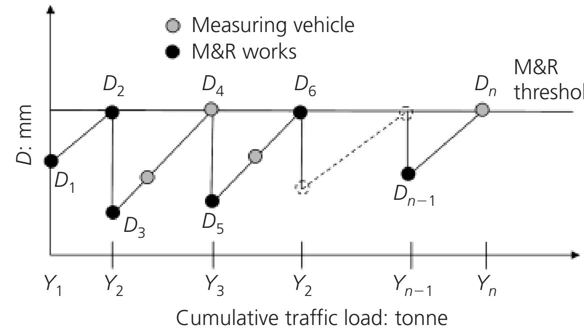

Figure 4. Determination of deterioration rates

Once deterioration values have been obtained, the next step is to determine the deterioration rate for each track geometry parameter. The accumulated traffic load for each segment is obtained and the deterioration rates is calculated by using the straight line between initial and final deterioration points, as represented in Figure 4.

The deterioration rate in mm/tonne was calculated by using the following equation

$$\tau_{ij} = \frac{D_j - D_i}{Y_j - Y_i} \tag{10}$$

where i and j stand for consequent deteriorations in Equation 10. After determination of the deterioration rates, the average deterioration rates were calculated for each analytical segment according to Equation 11. The equation of the average deterioration rate in mm/tonne is expressed as

$$\overline{\tau}_i = \frac{\sum_{ij} \tau_{ij}}{n} \tag{11}$$

Finally, the matrix of average deterioration rates $[\overline{\tau}_i]_{820\times1}$ was obtained for every analytical segment

$$[\overline{\tau}_i]_{n\times1} = \begin{bmatrix} \tau_{i1} \\ \tau_{i2} \\ \tau_{i3} \\ . \\ \tau_{in} \end{bmatrix}_{n\times1} \tag{12}$$

A crucial part in the modelling deterioration rate is taking account of uncertainties in deteriorations. In this study, the form of linear regression model that predicted the deterioration rate ($\overline{\tau}_i$) was expressed by the following equation

$$\begin{aligned} \overline{\tau}_i = {} & \alpha_{i1}x_1 + \alpha_{i2}x_2 + \alpha_{i3}x_3 + \alpha_{i4}x_4 + \alpha_{i5}x_5 \\ & + \alpha_{i6}x_6 + \alpha_{i7}x_7 + \alpha_{i8}x_8 + \alpha_{i9}x_9 \\ & + \alpha_{i10}x_{10} + \alpha_{i11}x_{11} + \alpha_{i12}x_{12} + \alpha_{i0} \end{aligned} \tag{13}$$

where: traffic loads (x_1); velocity (x_2); curvature ($1/R$) (x_3); gradient (x_4); cant (x_5); sleeper-type (x_6); rail-type (x_7); rail length (x_8); falling rock (x_9); land-slide (x_{10}); snow (x_{11}) and flood (x_{12}) also correspond to the independent variables. Multivariate statistical analysis was performed to find the regression coefficients of the equation. In the analyses, both qualitative and quantitative

Speed (V): km/h	Explanations	Level: mm	Twist: ‰	Gauge: mm	Cant: mm	Alignment: mm
$V > 140$	Maximum	10·5	2·0	8·5	6·5	10·5
	Maximum at joints	14·5	3·0	10·5	8·0	14·5
$80 < V \leqslant 140$	Maximum	12·5	2·0	10·5	7·0	12·5
	Maximum at joints	16·5	3·0	20·5	8·5	16·5
$V \leqslant 80$	Maximum	16·5	2·0	20·5	10·0	16·5
	Maximum at joints	22·5	3·5	30·0	13·0	22·5

Table 3. Maintenance and renewal thresholds in use by TCDD

variables were used. Dummy variables were used to express the qualitative variables x_6, x_7, x_8, x_9, x_{10}, x_{11} and x_{12}. The dummy variables are demonstrated in Table 4.

4.2 Methodology

Multivariate statistical analysis is a kind of statistics concerned with analysing, interpreting, displaying and making decisions based on multivariate data. In fact, one of the most important things for planning/targeting of M&R activities, is to understand the main drivers of assets' deterioration, namely the hidden/salient 'root causes', and the correlations that these statistical techniques can reveal, can exactly indicate some of the most important 'drivers' of deterioration. Multivariate statistical analysis can help to prove (or disprove) the existence of correlation between such variables present on the track, which is very important for optimal planning of M&R.

Before the multivariate statistical analysis, variance–covariance and scattered analyses were performed to find the best relationship between the variables and what kind of relationship (linear or non-linear) they have. Pearson's product moment correlation coefficient was used to calculate bivariate associations. The condition $p < 0{\cdot}05$ was regarded as statistically significant. The statistical analyses performed in this study are listed below (Draper and Smith, 1981; Montgomery *et al.*, 2001).

(*a*) Correlations between the variables.
(*b*) First multivariate statistic analyses; calculating determination coefficients, variance analysis (ANOVA), significance analyses of independent variables.
(*c*) Scatter plots between variables.
(*d*) Stepwise regression analysis; calculating determination coefficients, ANOVA, significance analyses of independent variables.
(*e*) Case statistics and case analyses for outlier and influential points; residuals, standardised residuals, Studentised residuals, Mahalanobis distance, DFBETA (change in the regression coefficient that results from the deletion of the *i*th case) values, Cook distance, DFFIT (change in predicted value when the *i*th case is deleted) values, covariance ratios.
(*f*) Multi-collinearity analyses; variance inflation factors, variance decompositions ratios.
(*g*) Final stepwise multivariate statistic analyses; calculating determination coefficients, ANOVA, significance analyses of independent variables.

Variables	Type	Dummy variables
x_6	Wooden sleeper	1
	Concrete sleeper	0
x_7	49·430 kg/m	1
	49·050 kg/m	0
x_8	Continuously welded rail	1
	Joined rail	0
x_9	Falling rock	1
	No falling rock	0
x_{10}	Land-slide	1
	No land-slide	0
x_{11}	Snow	1
	No snow	0
x_{12}	Flood	1
	No flood	0

Table 4. Dummy variables

5. Analysis results

All analyses listed above were performed using SPSS for Windows 12·0 (Chicago, Illinois, USA). Before multivariate statistical analysis, correlation matrices were obtained for each track geometry parameter to better evaluate the relationship between the variables. Table 5 shows the correlations matrix of the 'twist' parameter. If the values represented in the table are close to 1·00, this means that there is a high correlation between the parameters. The negative sign means that there is an inverse relation between the parameters. Similarly, the other correlation matrices were obtained and approximately close correlations were found with the correlation matrix of twist. The correlation matrices indicated that there was a high correlation between curvature ($x_{1,3}$) and cant ($x_{1,5}$) of about 0·879. This means that it is not significant to include both variables in the analyses. Scatter plot graphics were obtained as in matrix format. According to this scatter plot matrix, it was accepted that there was a linear relationship between dependent and independent variables.

First multivariate statistic analyses were performed. The regression model obtained was tested by using some hypothesis tests. Variance analysis was performed to determine whether there was a linear relationship between dependent and independent variables. *F*-test was used for this purpose and the result was found to be lower than the significance level. Significances of the parameters in the analysis were tested with Student's test (*t*-test) and most of the significances were found to be lower than the significance level (0·05). The coefficients of determinations were found to be 0·539, 0·650, 0·624, 0·716 and 0·608, respectively, for twist, gauge, alignment, cant and level.

First stepwise analyses were performed. Uninformative variables could be removed by continual inspection of the results or they could be removed by a semi-automated stepwise procedure. Stepwise analysis includes a wide variety of techniques that have proved useful in exploratory multiple regression (Draper and Smith, 1981; Montgomery *et al.*, 2001). *F*-test results were found to be lower than the significance level. Significances of the parameters in the analysis were tested with Student's test (*t*-test) and all significances were found to be lower than the significance level ($p < 0{\cdot}05$). According to the significances, land-slide and snow were excluded from all regression models. It was also decided to exclude the cant variable from gauge and alignment

	τ_1	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$	$x_{1,4}$	$x_{1,5}$	$x_{1,6}$	$x_{1,7}$	$x_{1,8}$	$x_{1,9}$	$x_{1,10}$	$x_{1,11}$	$x_{1,12}$
τ_1	1												
$x_{1,1}$	−0·211	1											
$x_{1,2}$	−0·363	−0·400	1										
$x_{1,3}$	0·273	0·109	−0·354	1									
$x_{1,4}$	0·444	0·063	−0·257	0·184	1								
$x_{1,5}$	0·124	0·091	−0·202	0·879	0·040	1							
$x_{1,6}$	0·542	0·131	−0·484	0·275	0·604	0·087	1						
$x_{1,7}$	0·067	−0·692	0·404	−0·154	−0·193	−0·111	−0·315	1					
$x_{1,8}$	−0·455	0·158	−0·071	−0·067	−0·462	0·027	−0·696	−0·118	1				
$x_{1,9}$	0·317	0·114	−0·311	0·203	0·234	0·101	0·480	−0·208	−0·297	1			
$x_{1,10}$	−0·022	−0·211	0·278	−0·093	−0·107	−0·096	−0·112	0·374	−0·225	−0·075	1		
$x_{1,11}$	0·031	−0·089	0·129	−0·049	−0·039	−0·035	−0·053	0·133	−0·097	−0·035	0·217	1	
$x_{1,12}$	0·265	−0·061	−0·075	0·086	0·115	0·088	0·185	−0·019	−0·051	0·043	−0·152	−0·062	1

Table 5. Correlation matrix of the 'twist' parameter

parameters. Rail-type was excluded from twist, cant and level parameters. Sleeper-type was excluded from level parameter. Gradient was excluded from cant parameter. The coefficients of determinations were found to be 0·537, 0·649, 0·622, 0·712 and 0·606, respectively, for twist, gauge, alignment, cant and level.

After first stepwise regression analysis, case statistics and case analyses were performed to determine outlier and influential points. The analyses expressed in step (e) were performed for this purpose. Standardised values, Studentised values and Mahalanobis distance were used to determine outliers at first. Mostly, observations were accepted to scatter between −2 and +2 for standardised and Studentised values. The observations above +2 and below −2 were accepted as high leverage points (Montgomery *et al.*, 2001). Studentised values were plotted with estimation values. After high leverage points were determined, these points were tested whether they were influential on some variables. The DFBETAs, Cook distance, DFFITs and covariance ratios tests showed that there were no influential points on the parameters. Consequently, 42, 35, 36, 18 and 45 observations were found to be outliers from twist, gauge, alignment, cant and level, respectively. The outlier points were excluded from the analyses as suggested and supported by Montgomery *et al.* (2001) and Draper and Smith (1981).

Correlation coefficients, variance inflation factors and condition indices were used to determine collinearity between the variables. Collinearity (or multicollinearity) is the undesirable situation in which the correlations among the independent variables are strong (Montgomery and Peck, 1982). Correlation coefficients were examined first for collinearity investigation. A high correlation was found between cant and curvature in all parameters. It was decided to exclude cant variable from the analyses because it had lower correlation with the dependent variable in comparison with curvature. Second, the variance inflation factors (VIF_i) were examined and it was found that all VIF values were below 5, meaning that they were reasonable. Third, the condition indices for each variable were examined and it was found that there were no values which exceeded 30. The variance decompositions ratios were then examined and found by the researchers to be below 0·9.

Finally, the final stepwise analyses were performed for all track geometry parameters. F-test results were found to be lower than the p-value. Significances of the parameters in the analysis were tested with Student's test (t-test) and the confidence level was found to be high because the 'p-value' was lower than 0·05. The results are summarised in Tables 6, 7 and 8.

Finally, the linear regression equations for each track geometry parameter are given below. The equation for the twist deterioration model is presented here; the other equations could be written in the same form, considering Table 7

$$\begin{aligned}\bar{\tau}_1 = &-0{\cdot}049x_1 - 0{\cdot}078x_2 + 0{\cdot}25x_3 + 0{\cdot}096x_4\\ &+ 0x_5 - 1{\cdot}704x_6 + 0x_7 - 3{\cdot}456x_8 + 1{\cdot}284x_9\\ &+ 0x_{10} + 0x_{11} + 1{\cdot}534x_{12} + 22{\cdot}866\end{aligned} \quad (14)$$

6. Evaluation of the model

In this study, multivariate statistical analyses were performed by using the steps mentioned above. It was determined that landslide and snow had no effect on the track geometry deterioration. On the other hand, it was observed that flooding and falling rock had an effect. These two environmental effects tended to increase the deterioration rate as they had positive signs. It was also proved that these two effects had a positive correlation with the deterioration rate.

Curvature and gradient had an effect on the deterioration rate

Parameters	Coefficients	SS	df	MS	F	p	R^2
Twist	Regression	6348·5	8	793·6	159·8	0·00	
	Residuals	3819·3	769	5·0			0·624
	Total	10167·8	777				
Gauge	Regression	84829·2	9	9425·5	219·6	0·00	
	Residuals	33259·4	775	42·9			0·718
	Total	118088·6	784				
Alignment	Regression	43131·1	9	4792·3	195·0	0·00	
	Residuals	19023·9	774	24·6			0·694
	Total	62154·9	783				
Cant	Regression	7519·7	8	940·0	139·3	0·00	
	Residuals	2179·3	323	6·8			0·775
	Total	9699·0	331				
Level	Regression	35058·1	8	4382·3	207·1	0·00	
	Residuals	16210·7	766	21·2			0·684

df, degrees of freedom; MS, mean squares; SS, sum of squares.

Table 6. Final stepwise regression model summary and variance analyses

Variables	Twist			Gauge		
	α_j	t	p	α_j	t	p
x_1	−0·049	−15·969	0	−0·076	−6·528	0·000
x_2	−0·078	−14·612	0	−0·258	−16·054	0·000
x_3	0·25	3·889	0	0·958	5·094	0·000
x_4	0·096	7·073	0	0·305	7·572	0·000
x_5	–	–	–	–	–	–
x_6	−1·704	−4·098	0	3·454	2·520	0·012
x_7	–	–	–	5·478	5·775	0·000
x_8	−3·456	−11·445	0	−6·029	−6·081	0·000
x_9	1·284	4·85	0	3·161	4·097	0·000
x_{10}	–	–	–	–	–	–
x_{11}	–	–	–	–	–	–
x_{12}	1·534	8·788	0	4·624	9·042	0·000
Constant	22·866	31·494	0	53·565	20·404	0·000

Table 7. Analyses results of twist and gauge

with positive signs. These two independent variables increased the deterioration rate. The correlation matrices and scatter graphs showed that there was a positive relationship between them and the deterioration rate.

Cant had an effect on the deterioration rate in the first multivariate analyses, but it was observed that there was a high correlation between cant and curvature of about 0·879. Thus, it was decided to exclude cant from the analyses to prevent multicollinearity, because it had a weak effect (correlation) on the deterioration rate in comparison with curvature.

Sleeper-type had an effect on the deterioration rate, but it was found that it had both positive and negative signs on some variables. It was observed that the vertical geometry parameters, namely twist, cant and level had a negative sign with cant, meaning that sleeper-type had a decreasing effect on the deterioration rate. In contrast to that, horizontal geometry parameters, namely gauge and alignment, had a positive sign with cant, meaning that they had an increasing effect on the deterioration rate. It could be interpreted that the wooden sleepers had a lower rigidity under vertical loads, but had a low resistance to horizontal forces.

Variables	Alignment			Cant			Level		
	α_j	t	p	α_i	t	p	α_j	t	p
x_1	−0·043	−4·836	0·000	−0·056	−9·734	0·000	−0·105	−16·47	0·000
x_2	−0·17	−14	0·000	−0·153	−13·34	0·000	−0·22	−19·91	0·000
x_3	0·901	6·318	0·000	1·298	6·763	0·000	0·507	3·806	0·000
x_4	0·226	7·417	0·000	0·084	3·651	0·000	0·201	7·135	0·000
x_5	–	–	–	–	–	–	–	–	–
x_6	2·335	2·269	0·02	−3·772	−4·828	0·000	−2·734	−3·163	0·002
x_7	4·751	6·646	0·000	–	–	–	–	–	–
x_8	−4·914	−6·585	0·000	−5·879	−9·406	0·000	−6·196	−9·926	0·000
x_9	2·019	3·476	0·000	1·67	4·001	0·000	2·856	5·214	0·000
x_{10}	–	–	–	–	–	–	–	–	–
x_{11}	–	–	–	–	–	–	–	–	–
x_{12}	3·208	8·353	0·000	1·91	6·2	0·000	3·238	8·947	0·000
Constant	37·92	19·136	0·000	31·67	19·222	0·000	51·55	34·302	0·000

Table 8. Analyses results of alignment, cant and level

It was also observed that rail-type had an effect on the deterioration rate. There were two different rail types (49·430 and 49·050 kg/m) within the investigated track stretch. The first one had an increasing effect on the deterioration rate.

It was determined that rail length had an effect on the deterioration rate with a negative sign. In the case of using continuously welded rail (CWR), the deterioration rate tended to decrease. Numerous other studies in the past also showed that CWR was better than joined rails with respect to retaining track geometry.

Cumulative load and speed had an effect on the deterioration rate, but it was found that they had negative signs, which was unexpected. The cumulative load with the negative sign meant that the deterioration rate was decreasing with the increase in load, which certainly did not make sense. In this study, the M&R works history over time was determined for the investigated track section. The plotted graph showed that while the maintenance activities were decreasing, the renewal activities were increasing. Consequently, the deterioration rate decreased as an effect of renewals. This finding also represents the M&R policy of TCDD. In the case of efficient life cycle management, the renewal policy gets replaced by a policy representing an optimal balance between maintenance and renewal.

In the present study, it was also found that speed had a negative effect on the deterioration rate. The speeds regarded in the analyses were the maximum speeds on the investigated track section. There were no speed-changes (ΔV) within the analytical segments. The speed is high at straight and higher radius sections. On the other hand, the speed is low at lower radius segments as well as over some structures such as switches, crossings and bridges. One can consider that it is not meaningful to include the speed variable in the analyses but the speed variable represents some structures and the points on the track where the speed is restricted. Consequently, the negative signs are thus logical in these analyses and therefore the speed variable must be taken into consideration in the analyses.

7. Conclusion

The intrinsic behaviour of the track geometry deterioration and its individual components remain mostly unknown. It has been long suspected, but never scientifically proven nor even quantified, that the states of individual track components detrimentally influence each other, sometimes even forming a vicious circle. In order to decide when, where and which M&R activities are required, it is necessary to be able to predict track geometry deterioration. In the present study, railway track geometry deterioration was modelled with multivariate statistical analysis considering the variables involved in the track geometry deterioration and, based on the analysis results, the future behaviour of the track geometry deterioration was predicted for the purpose of efficient track M&R management. In the case of having more reliable data related to railway track, multivariate statistical analysis is one of the best ways of modelling track geometry deterioration. In this study, significant relationships were found between the deterioration rate and the independent variables by using multivariate statistical analysis. The model can further be enhanced with more accurate data properly recorded over time.

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