Railway Track Degradation: Shape and Influencing Factors

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(Received on December 19, 2007)

Abstract: This paper presents the results of a study aiming at increase the knowledge of degradation phenomenon resulting in geometrical railway track irregularities. The paper show how data collected from ROGER 1000 together with variables affecting the degradation can be used to predict progression of railway track irregularities. The paper also describes a model which has been developed to show the relations between the irregularities and variables affecting it. The model has been developed using multivariable regression modeling.

Keywords: Railway track, degradation, regression analysis, influencing factors

1. Introduction

Maintenance actions like overall tamping and renewing of ballast and track are traditionally been scheduled for regular intervals, and spot maintenance is performed when results from measuring on track exceeds boundaries set in advance. However, the railway industry faces increased focus on cost, forcing the railway operators and infrastructure managers to optimize every stage of the process, including maintenance. In addition, railway operations today place greater demands on the track than ever before. It is not only faster trains with heavier payloads that create this extra pressure, but commercial aspects. There is less time to maintain track and the quality of ride has to meet increased customer expectations. This gives a need to improve our understanding of track degradation mechanisms.

This paper presents a study aiming to explore more about the railway track degradation. The paper presents how data collected from ROGER 1000 together with variables affecting the track degradation can be used to determine the degradation progression. The article also describes a model which has been developed to show the relations between the degradation and variables affecting this degradation. The model has been developed using multivariable regression analysis.

Notation

\( R^2 \) \hspace{1cm} \text{Goodness of a model, in this case retrieved from regression analysis}
\( s_y \) \hspace{1cm} \text{Standard error of the estimate}
\( T \) \hspace{1cm} \text{Load in tons}
\( T_0 \) \hspace{1cm} \text{The value of } T \text{ where the effect of the initial degradation takes place}
\( Q_{init} \) \hspace{1cm} \text{Initial degradation after a load size } T, \text{ Given as a MDZ value}
\( Q_{sec} \) \hspace{1cm} \text{Second phase of degradation}

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MDZ Quality number reflecting the riding comfort
\( \beta_i \) Regression coefficient
\( X_i \) Explaining variables
\( a \) Degradation coefficient, initial phase
\( b \) Degradation coefficient, second phase

2. Track degradation

Measurement of track geometry irregularities is the most used automated condition monitoring technique in railway infrastructure maintenance. Most problems with the track (at least the ones concerning the ballast and substructure) are unveiled as track geometry irregularities. According to Dahlberg [1] amongst others, the change in track geometry irregularities (of ballasted tracks) occurs in two major phases:

1. Directly after tamping the track geometry irregularities increases relatively fast until the gaps between the ballast particles have been reduced and the ballast is consolidated. Two ways of modeling this first phase, are with a lognormal \( (a \times \ln(b \times T)) \) and an exponential function \( (a \times (1 - e^{-b \cdot T})) \). An advantage with the exponential function is its ability to clearly separate the steepness of the function \( (b) \) and a resulting level \( (a) \). In this study we use the exponential function to model this first phase.

2. The second phase is slower and there is a more or less linear relationship between the degradation and load in the beginning. However the degradation rate seems to increase as the track degrades, leading to a suggestion that this second phase of degradation also can be modeled by an exponential function of the force added to the track.

Findings supporting these prepositions will be presented later in this paper.

DEGRADATION MEASUREMENT

Geometrical irregularities are in Norway measured by the measuring wagon Roger 1000. The Roger 1000 measures longitudinal level, lateral position, cant and twist. Furthermore, an optical laser measurement unit records gauge, profile, inclination, etc. of the rails. Having these data recorded; the question of which degradation measurement to use arises. Earlier models often use vertical and/or horizontal displacement of rail as degradation measurement. A model presented by Veit [2] however uses a quality number called MDZ. The MDZ number comprises both horizontal and vertical deviations in track together with speed and lack of super elevation [3]. This measurement is developed to capture the changes in acceleration over a certain distance from a passenger point of view by direct mathematical analysis of the real track geometry data, recorded by the measuring wagon. The variation of acceleration is by Veit [2] regarded as the main criteria for comfort. Therefore the sum of all changes in acceleration over a certain distance (charged with some corrective parameters) reflects the MDZ number for this section [3]. Being a supplement of the quality numbers reflecting track safety (twist and gauge) which contributes to derailment probability, the MDZ number is used in this article as the dependent variable in the regression analysis. Twist and gauge is handled in other works by same author [4].
The MDZ number is defined as:

$$MDZ = c \times \frac{1}{L} \times v^{0.65} \times \sum_{i=1}^{L} \sqrt{\Delta_{\text{vert level}}^2 + (\Delta_{\text{horiz level}} + \Delta_{\text{cant}})^2}$$  \hspace{1cm} (1)$$

where $\Delta_{\text{vert level}}$ and $\Delta_{\text{horiz level}}$ is the difference in track deviation from one measurement point to the next. Here, $\Delta_{\text{cant}}$ is the difference in cant level from one measurement point to the next.

**Variables affecting the degradation**

The degradation process leading to irregularities in track geometry is a complicated process. The rate at which the degradation occurs is influenced by time and usage intensity. If all parts of railway track were identical, operated under exactly the same conditions and in exactly the same environment, then, every part would degrade in the same manner. However usage intensity or operating conditions together with environmental conditions, and material varies along the track.

A hypothesis forming the starting point of this article is that this degradation process, to a certain degree, can be explained through a set of variables. Regression analysis is used on the Norwegian track data to reveal those variables found to influence the degradation process. The task of finding possible variables is a task of looking both at and beyond what is captured in existing degradation models, meaning to include all variables suggested to influence the degradation in existing models together with searching for variables suggested in other research. Earlier research on track degradation indicate that variables affecting the degradation are numerous; load, climate, environment, water etc. These variables are organized into variables reflecting characteristics from the train, the track and the surroundings, and are further studied using statistical analysis.

### 3. Analyzing data

**Regression analysis**

In order to identify significant variables influencing the degradation and their impact, statistical regression analysis has been used. The R square ($R^2$) measure, represents the goodness of the model. It shows how closely the regression line (also referred to as the degradation coefficient) and observed values are related. $R^2$ is given by equation 2:

$$R^2 = \frac{\sum (\hat{y} - \bar{y})^2}{\sum (y - \bar{y})^2}$$  \hspace{1cm} (2)$$

where $\hat{y}$ is the regression line, $\bar{y}$ the mean of observed values and $y$ observed values. In this article observed values, $y$, represents MDZ values in the railway track. The $R^2$ value tells you how much your ability to predict is improved by using the regression line, compared with not using it. The least possible improvement is 0, i.e. the regression line does not help at all. The greatest possible improvement is 1, i.e. the regression line fits the data perfectly. The value of $R^2$ is then always between 0 and 1 and the adjusted $R^2$ takes into account the number of variables, such that an increasing number of variables not necessarily means higher adjusted $R^2$. Results have been obtained by using stepwise linear regression modeling with stepping criteria’s of entry, 0.10 and removal, 0.15. As another
measurement of the goodness of the model, the standard error of the estimate, $s_7$, is used. The standard error of estimate is the standard deviation of the error variable.

It tells us how much the observed $y$-values, $y'$, differ from the values on the regression line. It gives us an idea of the scatter of the points around the line of regression. The formula used to compute the estimated standard error of estimate is:

$$s_7 = \sqrt{\frac{\sum(y - y')^2}{n-2}}$$ (3)

where $y$ is the observed values and $y'$ is the predicted values ($y - y' = \text{error}$). For more information on the topic regression analysis, see for instance Gelman and Hill [5].

DIVIDING THE TRACK INTO SECTIONS

In order to cope with the information size regarding track data to analyze, the track is split into sections with similar variable characteristics. Each of the sections is homogeneous with respect of the variables used in the regression analysis representing the degradation in form of MDZ value given the composition of variables, as shown in Figure 1. The result of this dividing was a total of 871 sections including information of all variables taken into consideration. The sections are derived from four Norwegian lines using data from the Roger1000.

These tracks are located from Trondheim to Steinkjer (Nordlandsbanen), Trondheim to Storlien (Meråkerbanen), Støren to Trondheim (Dovrebanen) and Oslo to Stavanger (Sørlandsbanen). These tracks are quite different in term of rail and sleeper type. Dovrebanen and Sørlandsbanen are tracks with UIC 60 rail and concrete sleepers, while Nordlandsbanen and Meråkerbanen have light rail of type S49. Meråkerbanen also have wooden sleepers. As mentioned the degradation process can be divided into two phases. The first phase is modeled with an exponential function, and Figure 2 show the MDZ values in the first 1 000 000 tons passed. From the figure it looks like the effect of this first phase is apparent in the first 150 000 tons.

POSSIBLE SOURCES OF ERROR

Measuring system

A possible source of error regarding the analysis of trends is the use of different measurement systems. Analysis performed by Hummitzsch [6], indicated difference in results given the same track measured with an accelerometer and with three point laser. He suggest a constant calibration factor (of 1.6) in order to transform the measurement from
the accelerometer to result comparable to the measurement from the three point laser. However, in this analysis, all measurement are done by the Roger 1000, giving measurement that are comparable from one measurement to the next.

**Positioning of measuring points**

Another source of error is the exact position of measurement points measured. A small displacement in the positioning system of the measuring wagon reduces the accuracy of the tracking of degradation. These displacements can result from inaccuracy in the manual plotting of starting point, or the manual calibration when passing positioning points along the track. Another source of error is wear of the wheel, making the measuring wagon believe that the wagon is traveling faster than it is as the radius of the wheel is smaller. These problems in the positioning of measuring points are attempted overcome by calibrating the positioning by the measured radius of the track. The effect of this inaccuracy is also reduced by the action of taking the average value over a section with similar variable characteristics. The regression analysis is also weighted with respect to the length of the section.

**OUTCOME OF ANALYSIS**

As mentioned an initial degradation occurs directly after tamping, and Figure 2 shows the measured values of MDZ with number of tons after last tamping action as the values of the x-axis and measured MDZ value on the y-axis.

The best approximation for a trend line was found given by an exponential fit in this first phase, giving the general equation:

$$Q_{\text{init}} = Q_0 \times \left(1 - e^{-a \cdot T}\right)$$

where $Q_{\text{init}}$ denotes the initial degradation after a load size $T$ has passed, and $Q_0$ the resulting quality of the initial phase, which is the goal of the regression analysis. This equation gives the freedom of defining both the resulting quality of this stage, and the steepness of the development (how fast it reaches this quality). Let’s say that $T_0$ is the value of $T$ where the effect of the initial degradation is considered fulfilled. According to Demharter [7], $T_0$ is approximately 100 000 to 200 000 tons. The empirical data set used in this analysis can neither confirm nor reject this; however it seems to be a realistic assumption looking at figure 2. Adapting this fact into equation (4) above, we can retrieve a value of the pavement $a$. An approximate value of around 0.00004 seems to fit in this case. From equation (4), we can easy retrieve the initial quality:

$$Q_0 = \frac{Q_{\text{init}}}{1 - e^{-a \cdot T}}$$

By running the regression analysis with the initial degradation coefficient as the dependent variable and suggested variables as independent variables we retrieve the following expression for $Q_0$:

$$Q_0 = -7.02 - 0.214 \times \text{Speed} \ [\text{km/h}]$$

Calculating the $Q_{\text{init}}$ using equation (4) with $a = 0.00004$ and $Q_0 = -7.02 - 0.214 \times \text{Speed} \ [\text{km/h}]$, we get the following correlation between the calculated values and the real values (adjusted $R^2$ value of 0.621 and std. error 0.821) with a total of 129 sections included in the analysis.
The second phase of degradation, $Q_{Sec}$, is also described by an exponential function:

$$Q_{Sec} = Q_0 \times e^{b_0 T}$$

(7)

The change in degradation in the second phase can also be retrieved from regression analysis. The target for the regression analysis is the degradation coefficient, $b$, obtained from equation (7) as follows:

$$Q_{Sec,1} = Q_0 \times e^{b_0 T} \text{ and } Q_{Sec,2} = Q_0 \times e^{b_0(T+\Delta T)}$$

(8)

$$Q_0 = \frac{Q_{Sec,2}}{e^{b_0(T+\Delta T)}}$$

(9)

$$Q_{Sec,1} = \frac{Q_{Sec,2}}{e^{b_0(T+\Delta T)}} \times e^{b_0 T}$$

(10)

$$b = \frac{\ln \left( \frac{Q_{Sec,2}}{Q_{Sec,1}} \right)}{\Delta T}$$

(11)

$$b = \beta_0 + \sum_{i=1}^{9} (\beta_i \times X_i)$$

(12)

Figure 4 shows the result of comparing the predicted MDZ value, using the values presented in Table 1, with the measurements from the inspection wagon.

The adjusted $R^2$ value was calculated to 0.752 with a total of 801 section included in the calculation. Standard error of the estimate was 1.99. As can be seen from Figure 4, there is uncertainty in the result, both positive and negative. Values being far better than the model can be caused by maintenance work on the track not appearing in the data’s. In the case where the real Q values are far worse than the calculated values of Q, it may be explained by an unforeseen escalated development of the Q, an escalation which the model is unable to predict. These will most certainty be the case as we will never be able to make a perfect model taking all possible variables into account.
Table 1 Variables affecting the second phase of degradation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Notation</th>
<th>$\beta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Constant</td>
<td>$X_0$</td>
<td>-2.10E-006</td>
</tr>
<tr>
<td>1</td>
<td># tampings</td>
<td>$X_1$</td>
<td>1.11E-008</td>
</tr>
<tr>
<td></td>
<td>since renewal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Rail type</td>
<td>$X_2$</td>
<td>3.95E-007</td>
</tr>
<tr>
<td>3</td>
<td>Rainfall</td>
<td>$X_3$</td>
<td>1.07E-008</td>
</tr>
<tr>
<td>4</td>
<td>Curvature</td>
<td>$X_4$</td>
<td>2.57E-010</td>
</tr>
<tr>
<td>5</td>
<td>Switches</td>
<td>$X_5$</td>
<td>3.75E-008</td>
</tr>
<tr>
<td>6</td>
<td>Sleeper type</td>
<td>$X_6$</td>
<td>-2.20E-007</td>
</tr>
<tr>
<td>7</td>
<td>Axle load</td>
<td>$X_7$</td>
<td>8.45E-008</td>
</tr>
<tr>
<td>8</td>
<td>Soil type</td>
<td>$X_8$</td>
<td>5.07E-008</td>
</tr>
<tr>
<td>9</td>
<td>Soil type</td>
<td>$X_9$</td>
<td>2.78E-008</td>
</tr>
</tbody>
</table>

By taking both initial and second phase of degradation into consideration, a resulting degradation model can be formulated:

$$Q(T) = Q_{Init}(T) + (Q_{Sec}(T) - Q_0(T))$$

$$Q(T) = Q_0(T)\times(1-e^{-\alpha T}) + (Q_{Sec}(T) - Q_0(T)) = Q_0(T)\times(e^{\alpha T} - e^{-\alpha T})$$

The above equations relates to the situation where we do not have any inspection data, but just a date of last inspection. If we have some inspection data at time $T$, we can adjust the equation:

$$Q_1(T) = Q_0(T)\times(e^{\alpha T} - e^{-\alpha T}) \quad \text{and} \quad Q_2(T) = Q_0(T)\times(e^{\alpha(T+\Delta T)} - e^{-\alpha(T+\Delta T)})$$

Figure 4 shows the result of comparing the predicted MDZ value with the measurements from the inspection wagon.

By connecting the above equations we get:

$$Q_2(T) = Q_1(T)\times\frac{e^{\alpha(T+\Delta T)} - e^{-\alpha T}}{e^{\alpha T} - e^{-\alpha T}} \quad \text{for} \quad T > 0 \quad \text{and} \quad Q_1 > 0$$

In order to simplify the above equation, we may for values of $T$ larger than $T_0$ use:

$$Q_2(T) = Q_1(T)\times e^{\alpha T} \quad \text{for} \quad T \geq T_0$$
Figure 5 shows the result of comparing predicted values of MDZ with the data from the measuring wagon with a total of 871 sections included in the calculation. The goodness of the model is represented by the $R^2$ number with a value of 0.649 and std. error of the estimate of 2.54. By dividing the standard error of the estimate ($s_\tilde{y}$) by the average value of the MDZ value, we get a percentage deviation of the predicted value compared to the measured value ($s_\tilde{y}/\text{MDZ}_{\text{mean}} = 2.54/-27.08 = 9.4\%$).

In order to validate the model, we conduct a test:
1. Dividing the data’s in two at the beginning.
2. One part is used to create the model.
3. Predict the data’s of the second part by the model and compare with the observed data’s.

The result of this test is given in Figure 6:

(a) Q measured (second phase) | (b) Q measured (initial phase)

Figure 6: Test of model with new set of data

The result given the new set of data was a $R^2$ of 0.917 (Figure 6 (a)), calculating from a known Q0 and a $R^2$ of 0.378 (Figure 6 (b)) with no knowledge of existing condition.

VARIABLES AFFECTING THE DEGRADATION

The results from the regression analysis indicate that the axle load influence the degradation rate. This is in line with other studies [1], which show that a heavy axle load causes higher rate of degradation per ton than a light load; i.e., there is a non-linear relationship between the axle load and the degradation.

Objects in track such as switches represent point on the track with abrupt change in vertical track stiffness. The approach area is usually characterized by having soils softer than the foundation of the objects, and thereby creating a transition from low stiffness in approach area and high stiffness on object.

Soil is the ground where rail track structure is constructed. It may be naturally deposited soils or specially placed fill material. The sub-grade must be stiff and have sufficient bearing capacity to resist traffic induced stresses at the sub-ballast/sub-grade interface. Instability or failure of sub grade will result in an unacceptable distortion of track geometry and alignment, even with excellent ballast and sub ballast layers. The soil is in
this article divided into different soil types, and it was found that soils consisting of a clay material (marine and ocean sediments) settled faster than other soil types.

There is also an indication of imperfect maintenance regarding the tamping action. Taking the number of tampings since last renewal of the track into account, a relationship between this number and the initial degradation coefficient as well as the degradation coefficient was revealed. This indicates that the degradation after a tamping action is dependent on how many times this part of the track is tamped since it was renewed. Veit [2] has analyzed tamping cycles within the project “permanent way strategy” of Austrian Federal Railways, finding a relatively strict relation between tamping cycles and service life of track super-structure considering sections with good subsoil quality. The service life is assumed as the point where tamping actions are not capable of increasing the quality of the track above a threshold value. It must, however, be noted that the study of Veit regards track on good subsoil.

Tracks with light rails settled faster than tracks with heavy rails. This can be explained by the rails capability to absorb forces from the train.

There was also an indication that tracks with wooden sleepers had lower rate of degradation than those with concrete sleepers. Theory supporting this outcome is that wooden sleepers are slightly elastic in contradiction to the concrete sleepers. This allows the wooden sleeper to absorb some of the dynamic forces from the train. The concrete sleepers are dependent on a good ballast due to its lack of elasticity, which is not obvious on the northern tracks analyzed (Nordlandsbanen and Meråkerbanen).

Heavy rainfall seems to increase the degradation rate. This could be connected to the moisture in track as result of lack of drainage. A hypothesis is that moisture in the track affects the degradation by altering the characteristics of the ballast and sub grade. Li and Selig [8] suggest that, if the water table is within approximately 6 m of the surface, it is the major factor affecting in-situ moisture content and a likely influence on subsequent sub grade problems.

The effect of curvature on degradation rate could be seen from the regression results. Curved tracks result in higher quasi static forces on the track. The quasi static force is calculated using the variables axle load, speed, curvature and super elevation. As we experience a variation in speed in some parts of track (different traffic etc) we will get a higher force on the inner or outer rail dependent of the train going faster or slower than what the super elevation is designed for.

4. Conclusions

The resulting model gives a $R^2$ value slightly above 0.6. However, there is no absolute standard for what is a "good" $R^2$ value. Furthermore, instead of talking about a good model, a reduction in uncertainty dealing with predicted development of the degradation can be stated as a result of the modeling.

Figures 3 and 4 indicate that there is some problem of predicting a number of cases with fast degradation rate. Following the initial hypothesis saying that the degradation to a certain degree can be described by a number of variables, one problem could be lack of descriptive variables. However, a deterministic model of this kind will hardly be able to take every possible phenomenon into consideration, whereas the term; to a certain degree, but will be a good contribution to reduce the uncertainty predicting the degradation process. However, an idea for further work is to use the knowledge gained in this deterministic modeling together with stochastic modeling such as Markov modeling.
Another question is the adequacy of the approach vis-à-vis other approaches. Finite element modeling (FEM) and dynamic modeling are examples of other approaches to degradation modeling. FEM models and dynamic models are not limited to static analyses and may be utilized to model discrete track components and determine the interaction between them, as well as the stresses; however, they are computationally expensive. Further; they cannot be changed quickly to represent different track layouts or different loading conditions and can only present results for the specific vehicle and track under consideration. The choice of approach should therefore be taken in light of what the results of the models are to be used for. For use within maintenance decisions on a daily basis, the deterministic model might be a good supplement to reduce uncertainty.

Acknowledgements: The Author would like to thank the anonymous referees and the Editor, for the help in improving the paper.

References


Narve Lyngby was born on January 12, 1976 in Oslo, Norway. He received his M. Sc. in HSE (Health, safety and environmental studies) from the University of Science and Technology (NTNU), Trondheim, Norway in 2002. He is working with degradation models for railway tracks, maintenance planning and optimizing towards a Ph. D. degree at the same time he is having an employment with Safetec Nordic, where he is a senior project manager. The main application areas are offshore oil and gas industry and transportation.