Impact of preventive grinding on maintenance costs and determination of an optimal grinding cycle

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Abstract

For any railway infrastructure manager, rail maintenance is a very important task to accomplish as rail maintenance is directly related to traffic safety and also to availability and regularity. Consequently, it is essential that maintenance actions are carried out in an optimal way. The increase of rail traffic generates a decrease of the expected rail lifetime. The introduction of industrialized inspection and maintenance methods offer a possibility to increase the rail lifetime and thus to diminish the average cost of a track possession without reducing traffic safety. Based on very large infrastructure and rail maintenance databases, this study analyses whether it is beneficial to carry out preventive cyclic grinding and what cycles are the most adapted.

Introduction

Based on available data on rail defects and rail removals, the present study tries to provide an answer on the effectiveness of preventive grinding.

From a technical point of view preventive grinding allows
  • to eliminate surface defects before they degenerate and have to be removed;
  • and thus to extend the lifespan of the rail.

From an economic point of view it remains to determine to what extend preventive grinding:
  • reduces the maintenance costs of the rails;
  • delays the great investments related to rails replacement.

The introduction of cyclic grinding implies a change of the maintenance strategy, in particular the passage towards a predictive maintenance (preventive interventions fixed according to the propagation velocity of the defects) instead of a corrective or palliative maintenance (interventions when one detects the appearance and the propagation of defects). At the same time, preventive grinding contributes to the industrialization of the infrastructure maintenance.

In this study, the lifespan of a ground rail is compared to the lifespan of rail not experiencing interventions. This time depends on the propagation velocity of the defects. The associated maintenance costs are evaluated for various cycles and conditions of grinding. The proposals for this study should enable to define a maintenance policy including or excluding preventive grinding according to the results and to determine, if necessary, the optimal depth and cycles.

The study supposes that preventive grinding is applied from the construction of the line. We do not consider the introduction of cyclic grinding at the end of the rail lifetime in order to delay the replacement of the rail.

This analysis does not consider the effect of cyclic grinding on tamping interventions. A specific study showed already [1] that cyclic grinding of high-speed lines decreases the number of necessary tamping operations.
Data

We assume that the probability that one meter of rail must be removed can be approached by the percentage of removals carried out on the whole line. Calculations are carried out according to time and the results are given for every UIC group separately in order to reduce tonnage variations.

Several databases are used in this study

1. Description of the French railway network: This database contains information about the length of every line and the construction date. It includes also information that can be used to calculate the time of the last rail renewal. This database is used to build a reference population. We use information of selected French main lines which have been constructed or renewed after 1960. Lines that often changed the UIC group are not included in the analysis, as the tonnage variation can bias the estimation.

2. The rail removal database: We use all rail replacements carried out on the selected lines. The database specifies the type of defect resulting in the removal. The combination of the removal database and the reference population allows calculating the yearly removal rate.

3. The rail defect database: The defect database includes all detected defects and their follow-ups. This information is necessary for the estimation of the defect propagation velocity.

4. Maintenance costs: we use the costs of the following maintenance operations: rail renewal, ultrasonic inspections and the corresponding operators, follow-up of the defects, rail removal, rail rupture, stress relief and scrap. A stress relief is necessary when there are four rail removals on the same 100 m section. This relation can be used to calculate the stress relief costs with respect to the number of rail removals. In order to estimate the expected number of defects and ruptures, we are using defect/removal and rupture/removal ratios that were established earlier by our department based on feedback data. The grinding can be carried out applying various depths. The cost of preventive, primary and curative grinding is known. If these costs are fixed, it is possible to interpolate in order to obtain cost for all possible grinding depth.

Figure 1 shows how the different databases are combined to one global database. All lines concerned by the study are selected in the description database of the French network (CIV). It is verified if there are sections that are also in the removal database (red) and they are marked. The replaced rail sections are kept a second time in the database after changing the date of installation (fir-tree green).

Methods

This study uses the combination of several methods in order to obtain an economic evaluation of grinding strategies.

1. Lifetime estimation: The lifetime distribution of the rails is estimated using a Weibull survival model.

2. Velocity of rail defects: The propagation velocity of grindable defect is estimated using the defect database.

3. Impact of grinding: Every time grinding is carried out, the survival function is updated. As a matter of fact, grinding rejuvenates the rail.

4. Cost Model: In order to calculate the expected equivalent average cost of a specific grinding strategy, costs are attributed to every maintenance action.

5. The results are plotted in a 3D presentation. The costs are given with respect to the grinding cycle and the grinding depth.

The methods are derived from two studies concerning the optimal time of rail renewal. In our case, however, the date of rail renewal is fixed depending on the residual lifetime of the rails under a specific grinding strategy.
Estimation of the rail removal function

A two parameter Weibull survival model is used for modeling the rail removal function. The probability of a removal of a one meter section of rail is calculated. This model is known to be a good approximation of rail defects. The advantage of a parametric model is the possibility to extrapolate the number of rail sections removed and thus to obtain an estimate of the rail renewal date.

The cumulated distribution function of the Weibull distribution can be written as follows:

\[
F(t) = 1 - e^{\left(\frac{t}{\eta}\right)^{\beta}},
\]

where \( \beta > 0, \eta > 0 \) and \( t > 0 \). The variable \( t \) describes the age of the rail. The parameters \( \beta \) and \( \eta \) are estimated separately for every UIC group. To carry out the estimations, a global database is created as mentioned above. The removals are considered as events; the rail sections without removal are used as reference population and are right censored, i.e. there is no observed defect before the renewal of the line or before the end of the observation time (2007). So the date of their renewal or the date of the study is used as lower limit for the removal date. The treatment of censored data in parametric probability models is for example described in [3].

The parameters \( \beta \) and \( \eta \) are estimated by applying the least square method on the double logarithm of the empiric distribution function. The empiric distribution function is obtained by the Kaplan-Meier method which is adapted for censored data.

This method is used to estimate three distribution functions: the distribution of all defects, of grindable defects and of non-grindable defects. An example is given in Figure 2.
Propagation of rail defects

For each defect listed in the defect database, it is possible to find the visits that were carried out. Let \( P_i \) be the depth of a defect at the visit number \( i \) and \( t_i \) the corresponding date; the variable \( i \) then counts the number of visits carried out on the same defect. We can calculate the increase of the defect between two visits, \( \Delta P_i = P_i - P_{i-1} \).

Several possible methods for the propagation velocity estimation were tested. The choice of the estimator depends on the structure of the data (size of the available data, number of observations per defect, correlation between propagation velocity and the number of visits, …). The most intuitive estimator

\[
\hat{v} = \frac{1}{n_{\text{observation}}} \sum_{i} \frac{\Delta P_i}{\Delta t_i},
\]

where \( n \) is the number of observed defect growth and \( \Delta t_i = t_i - t_{i-1} \), is not used, as it depends highly on the number of visits per defect. It is also not very robust and quite sensitive to extreme values. The best results were obtained with the following estimator that is based on a linear regression for every defect:

\[
\hat{v} = \frac{1}{m} \sum_{\text{defect}} \frac{\text{COV}(P_i, t_i)}{\text{VAR}(t_i)} \mathbb{I}_{[\text{COV}(P_i, t_i) \geq 0]},
\]

where \( m \) is the number of observed defects, COV is the covariance function and VAR is the variance. The advantage of this estimator is the possibility of a graphical illustration of the estimation method and the fact that it allocates the same weight within the final estimate to each defect. Moreover, the estimator takes into account negative defect increases and in this way eliminates measurement errors; it assumes that there are no interventions on the defects. One thus keeps all available data for the slope. However, before calculating the average of the
estimated slopes, negative slopes are eliminated. That is justified because it is not possible to observe only improvements for a given defect. The results obtained on the defect propagation concerns defects deeper than 5 mm. Otherwise, the defects cannot be observed by ultrasonic inspections. The grinding interventions concern defects smaller than 1 mm. We thus have to transform the estimated speed in a speed valid for smaller defects. We use an approximation as shown in Figure 3.

![Figure 3: Diagram of defect propagation (squat).](image)

Squats are the most frequent defects among those treated by grinding operations. The observations in the defect database reveal that squats grow under an angle of 38° to the vertical. We estimate the velocity $v$ in the graph. We want to know the speed $\tilde{v}$. Supposed that the speed in the propagation direction remains constant, it is possible to calculate the propagation velocity $\tilde{v}$. We have:

$$\tilde{v} = v \frac{\sin \alpha}{\cos \beta} \approx v \cdot 0.2107.$$  \hspace{1cm} (4)

The estimates of the propagation velocity will thus be multiplied by the factor 0.2107.

A statistical analysis shows that the number of visits per defect does not depend on the importance of the line, i.e. it does not vary according to the UIC group. For this reason, it is not necessary to weight the observations. All grindable defects available in the defect database are used in the analysis. Thus we have an average of 15 visits per defect, which is a high number. At the end of this step we obtain estimates of the propagation velocity according to the vertical direction for defects smaller than 1 mm, separately for every UIC group.

**Impact of grinding on the reliability**

In this section we would like to obtain from two reliability functions corresponding to grindable and non grindable defects, the hypothetical curve corresponding to the distribution of all defects under preventive grinding. In order to calculate this last curve, we use the following relation between the distribution functions:

$$R_{\text{global}}(t) = R_{\text{grindable}}(t) \cdot R_{\text{non grindable}}(t).$$  \hspace{1cm} (5)

This relation is valid if a defect is either grindable or non grindable, and if the random variables describing the occurrence of this two defects are independent.
It is supposed that grinding can lengthen the lifetime of the rail because it prevents the appearance of rail defects that can require preventive removals. Indeed, the total renewal of the rail is required if a given cumulated length has been removed.

If the end of life is defined by a number of removals carried out, we can state that grinding "rejuvenates" the rail. This effect is used for the modelling. We construct a function called \( \text{f}_{\text{virtual age}}(t) \) which transforms the age of a rail without grinding into the virtual age of a ground rail. This function allows the modelling of the effects of grinding interventions.

Figure 4 illustrates how we take into account the grinding operation. Let us suppose that a grinding was carried out at time \( t_0 \). A second grinding will be carried out at time \( t_1 \). The thick black dash gives the expected number of defects appeared between \( t_0 \) and \( t_1 \). The grinding operation has an impact on these defects. Under the competing effects of the propagation velocity and the couple frequency-grinding depth only a certain percentage of defects can be eliminated.

This percentage is calculated by the proportion of defects larger than the grinding depth at time \( t_i \) compared to all defects appeared on the same period \( (t_i - t_0) \). It should be noted that the result is identical for a selected grinding frequency and a fixed grinding depth and for a chosen grinding depth and a fixed grinding frequency.

Let \( p \) be the percentage of defects removed by the chosen type of grinding, \( F_{\text{grindable}}(t) = 1 - R_{\text{grindable}}(t) \) the distribution of grindible defects (Weibull distribution) and \( q_{\text{grindable}}(x) \) the \( x^{th} \) quantile of the grindable defects distribution. The formula for the virtual age function \( \text{f}_{\text{virtual age}}(t) \) is calculated in the following manner:

\[
\text{f}_{\text{virtual age}}(t_i) = q_{\text{grindable}}((1-p) \cdot [F_{\text{grindable}}(\text{f}_{\text{virtual age}}(t_i)) - F_{\text{grindable}}(\text{f}_{\text{virtual age}}(t_{i-1}))] + F_{\text{grindable}}(\text{f}_{\text{virtual age}}(t_{i-1}))).
\]

- The term \( F_{\text{grindable}}(\text{f}_{\text{virtual age}}(t_i)) - F_{\text{grindable}}(\text{f}_{\text{virtual age}}(t_{i-1})) \) is an approximation of the number of defects that appeared during \( \text{f}_{\text{virtual age}}(t_i) - \text{f}_{\text{virtual age}}(t_{i-1}) \) between two grinding operations;
- \((1-p)\) is the proportion of defects that remain after the grinding operation at time \( t_i \);
- \( F_{\text{grindable}}(\text{f}_{\text{virtual age}}(t_{i-1})) \) are defects longer than the grinding depth at time \( t_{i-1} \). These defects remain thus on the track;
- \( q_{\text{grindable}}(x) \) calculates the virtual age that corresponds to \( x \) defects.
Between the time $t_0$ and $t_1$, the virtual age function $f_{\text{virtual age}}(t)$ is equal to identity; in this interval the defects can appear on a ground rail as on a rail not ground. To obtain the total distribution of the defects on a ground rail, we insert the distribution of grindable defects under cyclic grinding into formula (5):

$$R_{\text{global}}(t) = R_{\text{grindable}}(f_{\text{virtual age}}(t)) \cdot R_{\text{non grindable}}(t).$$

(7)

Using the results of the preceding section, we obtain the velocity of defect propagation for every UIC group. For a given grinding frequency and a given grinding depth we calculate the percentage of eliminated defects. The results are inserted into formula (6) and subsequently into formula (7). Thus we obtain an approximation of the defect distribution for a ground rail even for combinations of grinding cycles and grinding depth that were never tested on real rails. An example of a $R_{\text{global}}(t)$ curve is given in Figure 5.

![Figure 5: Distribution of rail removals for a fixed grinding cycle depending on the grinding depth. Using this type of graphic, the lifetime of the rail under cyclic grinding can be obtained. As the condition for renewal is based on a fixed percentage of rail removals, one only has to follow the vertical red line and to note the age at the crossing with the black curves.](image)

**Global cost model**

In this section we will present the calculation of the global costs for all possible grinding strategies. In order to do this, all results of the partial modelling are combined. The overall costs are calculated according to the following formula:

$$C_{\text{global}} = \frac{\sum C_i}{\sum (1 + \alpha)^i},$$

(8)

where $\alpha$ is the discount rate and the variable $\text{horizon}$ is the lifetime of the rail, i.e. the date of the replacement. $C_i$ are the costs corresponding to the year $i$ after construction. This formula makes
it possible to compare investments on various life-spans. This is important in our case, as preventive grinding also influences the lifespan of the rail. The costs $C_i$ are calculated as shown in Figure 6.

![Figure 6: Calculation of the global maintenance costs.](image)

The global costs $C_{global}$ depend on the values chosen for the variables marked in green. We fix the UIC group and the discount rate. The method developed in our study allows us then to calculate the global costs depending on two parameters belonging to the grinding strategy: the grinding cycle and the grinding depth.

**Results**

For every chosen UIC group, we obtain a cost function depending on the predefined grinding cycles. Therefore it is possible to judge whether a systematic grinding strategy is efficient for the given UIC group and which cycle has to be chosen.

The results are presented in two different ways. The first chart is a 3D plot that displays the global costs depending on the grinding cycle and the grinding depth. An example is given in Figure 7. A second plot gives the expected number of rail ruptures in a contour plot. The optimal maintenance strategy in terms of costs is marked by a red point. All other almost equivalent strategies (< 1% difference to the optimal strategy) in terms of costs are marked with blue points. An example is given in Figure 8. This plot enables the decision maker to use a grinding strategy similar to the optimal strategy but more adapted in terms of rail ruptures or other organisational topics.

The optima determined by the cost minimizing algorithm are located between 2 and 4 year cycles and use a grinding depth of about 0.3 mm depending on the UIC group. These results are only valid on the conventional lines of the French railway network. The mathematical optima seem to reduce the rail maintenance costs up to 15%. The number of rail ruptures can also be reduced.

In order to analyze the impact of uncertainty related to the velocity estimation of grindable defects, the preceding results are recalculated for a propagation velocity reduced by 10% and increased by 10%. The results change only slightly.
Figure 7: Global costs of different grinding strategies.

Figure 8: Comparison of the optimal maintenance strategy in terms of costs and the expected rail ruptures.
Conclusion

This study enables the SNCF to optimise economically different preventive grinding strategies that allow extending the lifetime without experiencing increased deterioration of the rails. This first approach will be validated based on several test zones. After this step, systematic preventive grinding can help to extend rail lifetime and thus to make rail maintenance and removal more efficient.

The method presented in this article is derived from two studies ([2], [4]) concerning the optimal time for rail renewal. In our case, however, the date of rail renewal is fixed depending on the residual lifetime of the rails under a specific grinding strategy. This is the first time that the economic model afore developed is used for optimising grinding cycles.

Impact on tamping
As evoked in the introduction, this study does not consider the effect of cyclic grinding on tamping interventions. The results of another study [1], which expresses the benefit of grinding as a reduction of the track geometry deterioration and not as a cost reduction, show that a grinding after tamping is advantageous.

Impact on train movements
Another factor, which is taken into account only indirectly by calculating the number of expected ruptures, is the effect of rail incidents on the safety and the regularity of train movements. It is possible that a grinding strategy, even if it reduces only slightly the number of ruptures, can become a preferable strategy, especially on heavy charged lines. As it is difficult to quantify the costs of safety and lost minutes, we preferred to calculate only the number of expected ruptures as a help for decision making. The fact of taking into account the cost of lost minutes could even reduce the grinding cycle.

Perspectives

Even if a very big part of the French network consists of conventional lines, it is important to work on high-speed lines as these lines have very high maintenance costs. Hence, the next step will be the extension to these lines. According to the age of these lines, it is more difficult to gather a significant database, as well for the rail removals as for the rail defect propagation.

Another perspective is the adjustment of the model for lines already existing. In most cases, there was only corrective grinding carried out until now. It would be, for example, interesting to know if a reinforced cyclic grinding strategy only several years before the usual renewal time could also extend the rail lifetime.

Latency period
Grinding removes the surface layer of steel containing the majority of the rail defects. At the same time, new defects develop in priority in this layer. The effect of grinding is thus double. The present study did not take into account this effect of latency of the new defects. It is thus possible that we underestimate the benefit related to grinding.

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References


