Modelling of the ballast maintenance expenses

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Abstract
In order to travel safely and comfortably on high speed lines, excellent conditions of the whole railway infrastructure in general and of the railway tracks geometry in particular, are required. The maintenance process required to achieve such excellent conditions is mostly complex and expensive, demanding an increased amount of both human and technical resources. In this framework, an optimal schedule of maintenance interventions is an issue of increased relevance. This work presents a method for estimating the ballast degradation. The purpose of this study is to formalize the existing economic link between the maintenance costs of a ballasted track, and the volume of infrastructure renewal.

Mathematical and data-processing tools dedicated to the optimization of renewal cycles are developed within several studies conducted by the Infrastructure head office of the SNCF. The objectives are, in addition to the optimization of the maintenance cycles, also for the budget planning for maintenance and renewal. We developed innovative statistical models to estimate the ballast’s lifetime and the track maintenance’s costs throughout the life cycle. These methods are applied to the tracks maintenance, on classical and high speed lines.

Keywords: ballasted track, ballast life time, levelling degradation, tamping and grinding operation, Veit model, Cochet-Maumy model

Introduction
Since the creation of RFF, the French infrastructure owner, SNCF Infrastructure ensures the maintenance of the whole French railway network. Its remuneration is contractual. At the moment there is a four year contract. The negotiation of the corresponding amount remains very global. In 2006, RFF and SNCF analyzed the consequences of a significant effort of renewal of the French network, and they were not able to agree on its possible consequences in terms of decreasing maintenance costs and of ageing of the network.

The present article treats the elaboration and use of technical and economic modeling of the maintenance expenses of the network. One of the purposes of this SNCF work is the improvement of the multi annual maintenance contract between RFF (Infrastructure manager) and SNCF (delegated infrastructure management). Such models can be developed in many different ways. They will be able to:

- help making decisions about the ballast’s renewal;
- estimate the future expenses of new or renewed track;
- determinate the long term, fixed and variable, expenses for any sub-networks…

These models are useful for the control of the economies in the railway system. They are difficult to manage and their reliability is often questioned. However, the statistic has an advantage that does not have the study case: the big numbers will allow to clear tendencies, which is not be visible on individual cases. For instance, if we want to know the augmentation of the expenses with the track’s age, it is not the study of a kilometer of track which will allow determining it, but the study of the whole railway system. Therefore, to know these tendencies it is necessary to every financial prediction.

This article illustrates the problems related to the prediction expenses evolution, taking as an example the expenses related to the maintenance of the track’s geometry (tamping, renewal). It shows particularly that it is not unusual to think that these expenses grow as a power function of the ballast age.
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Context

The track maintenance is an essential central task for the SNCF: it has to guaranty the respect of the track geometry norms for comfort and security. Under the crossing of trains, the ballast has tendency to settle, distorting the track. It is then necessary to intervene on the track, so that it finds its initial geometry. The effectiveness of these interventions turns out to be more or less competitive, according to the wear of the ballast.

We determine an increase of the intervention frequency with the age: therefore an increase of the maintenance expenses. As a result several questions are posed:

- What is the speed of increase?
- Can it be restricted by different maintenance choices?
- After how long the intervention frequency becomes unachievable in practice: the « technical life » of the ballast is attained?

The answer to these questions passes by a modelling of the levelling deterioration speed, and influence on this one of the maintenance operations. In order to answer to these questions it is necessary to model the levelling deterioration speed and the influence on this one of the maintenance operations.

This paper is subdivided into three parts:

- Preliminary for the study understanding, in regard with the realities and fields problems.
- Theoretical study phase, with the presentation of the already existent models, which allow the estimation of the technical life of the ballast as well as the available data and the necessary treatments.
- Identification of a new model and the comparison of different maintenance policies.

In order to estimate the technical ballast’s life time, in the first time we would have to analyze the SNCF’s return of experience and the databases full of data collected over more than 20 years. These data comes from regular measurements on the whole network. The access to these data allows the validation of the models and the estimation of the technical life time.

Two models were kept in particularly:

- Veit model: he proposes modelling the evolution of track’s geometry according to time, with the aid of a track deterioration indicator;
- Cochet and Maumy model: an evolution model taking into account the maintenance intervention.

This article summarizes the methods developed for this type of question, and gives several examples for their application in the field of tracks. The way of functioning of the model is explained on the basis of the track maintenance.

Data

Classical lines and UIC groups

To find similar line classes, the lines tracks are classified in different UIC groups, according to the nature and the traffics importance which they support. For this study, we have not taken into account the high speed lines because their behaviour is very particular in comparison with the classical lines. In fact, the speed is crucial factor, with a given tonnage, when we consider the tracks deterioration on these lines. On classical lines, the most important factor is the tonnage.

Modification of the track’s geometry

The ballast has numerous roles, making it a necessary and critical element of the railway because:

- transmits and divides the static and dynamic charges led by circulation;
- assures a track fixation in the three directions of space;
- reduces the acoustical noises;
- amortizes vibrations;
- drains pluvial waters.

The ballast’s elements have to form a compact, but permeable mass. Sleepers are set in the ballast assuring the track’s stability. The track deterioration manifests itself by an evolution of the track’s geometry. The evolution’s speed depends on several factors, particularly on the tonnage and on the trains speed. The modification of the geometry can come from:

- the ballast packing under the traffic’s influence;
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- the effect of the tamping operations;
- transformations in the structure of the ballast, reduction of the ballast size;
- the rail alteration (for instance: distorted rails);
- the ageing of sleepers and clamps;
- the evolution of the under ballast protective layer or the subsoil;
- for the high speed, the solicitation of the bogies in the upper frequencies 30Hz (link of the distance between the axles with the train speed).

The first consequence of the modification of the track’s geometry is a comfort reduction for the passenger. Subsequently, beyond a certain safety threshold, speed limitations are systematically imposed on the considered track’s section of concerned ways, so that these defects are not the origin of incidents.

**Indicators of track geometry modification**

The track can degrade in a variety of ways. It is useful to define several indicators. The most useful are:

- Longitudinal leveling (NL): This indicator measures the track packing; rails on both sides follow the same curve, forming a hollow or a bump in comparison with the ideal shape of the way;
- Transversal leveling (NT): This indicator measures the deversexcess. Both rails follow different trajectories, so the one is higher than the other;
- Gauge variation: it is the distance between rails.

**Synthetic and classical indicators:** The classical indicators correspond to the temporal series which are directly given by the sensors. The synthetic indicators correspond to standard variation of the measurements accomplished on a 200 or 1000-metre windows. The synthetic indicators provide information about the global quality of the track. They will be used in this paper.

**Choice of a unique indicator:** The deterioration of the track’s geometry is defined by the indicators represented before. It would more useful for this study to sum it up in one single indicator. Following the works of Daniel Lévi (RFF), we chose to take the NL as indicator of the deterioration of the track’s geometry. The synthetic NL is one of the most important sources of deterioration of the track’s geometry himself.

**Different maintenance interventions**

When the measurements point out to an important modification of the track’s geometry (thresholds are defined according to the maintenance policy), it is necessary to perform a maintenance operation, in order to provide the track again with a good geometry quality and to ensure the safety.

**Tamping:** This intervention causes the ballast vibration to make it stickiness, allowing the repositioning of the rails and sleepers, and to compact the ballast under the sleepers. A tamping machine is used to perform this operation. This operation can correct the transversal and longitudinal leveling, by raising the level of every line of rail. They define a tamping cycle as the time between two successive tamping interventions.

**Grinding:** This intervention consists in taking of a fine metal coating in the surface of the rail. In general, they take away a coat between 0.1 and 0.8mm. This operation, preventive or corrective, introduces a double advantage. At first, it increases the technical life time of the rail: by eliminating the small fissures and defects of surface, while avoiding that they spread more profoundly and reducing the risks of a break of the rail. The savings in the economic field are notable, because of the augmentation of the technical life time of the rail and also of the ballast. The asperities of the rail lead to vertical dynamic pressures with every passage of a train; these dynamic pressures are directly reverberated of the rail towards the ballast. Grinding diminishes these dynamic pressures considerably. This study was lead with the intention of quantifying this reduction and therefore determining the benefits in term of the speed’s evolution reduction of the geometry defects. This study permeated to conclude that when a tamping is followed by a grinding operation, in a short period of time, then the effectiveness of the grinding is maxi. Grinding is a very interesting intervention; its price evaluated per kilometer is less than for tamping. However, this operation introduces three disadvantages: first of all, the park of specific rolling stock is comparatively weak in regard of the size of French network. Subsequently, the speed of these machines is under 10km/h, implicating a very weak output. At last, the passage of a grinding train can implicate a take down and up of any signalling installations.

**Renewal:** There are several types of renewals:
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- Rails: RR
- Ballast: RB
- Sleepers: RT
- All the track: RVB or regeneration

RB and RVB have a direct impact on the track’s geometry and particularly on the levelling. They define the technical life time of the ballast as bearable maximum length, between two RB, two RVB, successive RB or RVB.

Different types of strategies: In general, an intervention which acts to correct the already present defects is called curative maintenance. The rest of time, the adopted strategy of maintenance aims at restricting the appearance of new defects, this time we speak about preventive maintenance. This type of maintenance requires an optimization, in time and number, of the resources used for this purpose. This preventive maintenance can prove to be predictive when the appearance of defects is anticipated. It is this prediction which allows the optimization of expenses. In fact, the curative maintenance is expensive, because it is necessary to act fast and if needed, to introduce restrictions in speed. The preventive maintenance is planned and it answers to a long term service’s policy and for a large scale of the railway. The preventive maintenance of the railway remains still complex to determine and to plan. Nowadays the SNCF prefers to use preventive and predictive maintenance.

Ballast’s degradation

Absence of direct indicators

It is necessary to differentiate the ballast’s degradation from the degradation of the track’s geometry: although these observations are very different, they are tied by the fact that the ballast’s wear which degrades irreversibly the track’s geometry. The measure of the ballast’s degradation, which is essential for the estimation of its technical life time, does not exist. There are not direct indicators. Only a detailed observation of the existing data will allow to determinate the most significant indicators, which result from the measures made on the evolution of the track’s geometry. These indicators provide important information about the ballast’s wear and also about the parameters they depend on.

Causes

There are three principal factors which influence directly the ballast’s wear:
- The railway traffic: the vibrations and the dynamic impacts, which are a direct consequence of the railway traffic, produce a modification of the track’s geometry and at the same time they wear the ballast. The railway traffic is responsible for approximately 30% of the ballast’s wear.
- The tamping interventions: if the tamping interventions have a very positive impact on the track’s geometry, they are not destructive for the ballast. This is one of the main causes for the ballast’s wear with the pollution of the ballast.

Consequences

These two phenomenon produce the same mechanism of deterioration: the ballast’s abrasion, which is the reduction of the ballast in “small coals” (dust). When these dusts become a lot, they forbid rainwater’s drainage. The last prevents the “fluidization” of the ballast when the train passes by, and as a direct consequence the ballast cannot achieve one of its principal roles. The ballast’s degradation is principally observable because of its ovalization, and as a consequence it does not support in a good way the track. Therefore the track’s geometry degrades rapidly. The principal consequence of the ballast’s degradation is the augmentation of the frequency of the interventions for the leveling. With time (the same called technical life of ballast), the frequency of the necessary interventions for keeping up with the comfort and the security norms, are almost as important as the alternative of replacing all of the ballast.

The Data

The “Timon” base

The base named TIMON has two different aspects. First, it stocks the measures (which come from MAUZIN or IRIS 320), and also the information concerning the maintenance’s interventions.
- Measures of the synthetic geometry: the base describes, for each kilometer (i.e. for each KP), the kilometric synthetic indicators. These measures are not well shared in time for the whole railway system. The last is a result of the important differences between the tracks,
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and to the changes in the referential used in order to define the time interval between two measures.

- Geometry interventions: TIMON describes a number of interventions which could impact the track’s geometry. For each operation, we dispose of its date as well as its arrival and departure point.

- Timon’s interface: this interface allows, between other things, to display the evolution of the synthetic indicators as a function of the time for a given KP, and also for the interventions made in this KP. The figure 1 presents the evolution of NL (the down window) and the interventions (the top window) for a given kilometer.

![Figure 1: Extract from Timon’s interface](image)

The vertical bars represent the interventions (the length of the bar is proportional to the length of the intervention). The tamping operations are represented in red, the grinding operations in green, the replacement operations in black, and the partial ballast renewal by a dotted red-line.

**The DL base (Lines load)**

This base provides for each segment and year the average tonnage per day.

**The ARMEN-CIV base**

The variables concerning the track’s infrastructure are listed in the base Installations Consistency (in French, Consistance des Installations Voie) CIV. This base has a tremendous amount of data (more than 145,000 segments). It is a description of the railway system per geographic regional part. It is completed by agents who are in-site and it is updated every time there are visible changes on the tracks, the rails and the ballast. This base possesses the precise elements concerning the equipment (constituent elements of the track: rail, sleeper, ballast).

**Modelisation**

**COCHET and MAUMY’S Model**

**Initial Model**

The statistical studies on the whole SNCF’s railway network have shown that between two successive replacements of the ballast, the average annual cost of the maintenance works are not constant, and it varies with time in a monotone and increasing way. This variation is a consequence of the ballast’s degradation, as it was explained before.

For a given group UIC, it is possible to evaluate statistically the average number of $I_m$ operations per year on the leveling (tamping interventions) in function of the age $N$ of the track, since the last replacement of the ballast. In this study, which was conducted by the interns Mister Cochet and Maumy, from the National School of Bridges and Pavements (École Nationale des Ponts et Chaussées), it was demonstrated that this average evolution curve can be represented by next expression:
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\[ I_m(N) = 0.8 \cdot \delta \cdot \left[ a + b \cdot \left( 2^{\frac{N}{\log(2)}} - 1 \right) \right] \]

The values of \( a \), \( b \) and \( \delta \) were determinate, allowing therefore to trace the curves for the UIC groups 1 to 3 and 4 to 6, as shown in Figure 2.

By integrating the last formula, we obtain the total of the tamping interventions that were carried out:

\[ C(N) = \int_0^N I_m(t)\,dt = 0.8 \cdot \delta \cdot \left[ aN - bN + \frac{5b}{\log(2)} \cdot \left( 2^{\frac{N}{\log(2)}} - 1 \right) \right] \]

Using the parameters that were defined before, we can trace the curves represented in Figure 3. It is this variant that we will use in order to estimate the ballast’s technical life.

How to determine the life’s technical duration of the ballast from this model?

According to the Cochet and Maumy model, the evolution of the number of tamping interventions as a function of time is exponential. We would have a limited number of tamping interventions from where it will be really hard to continue with the maintenance. Under reserve that the Cochet and Maumy model is valid for the actual lines, and fixing a limit number of tamping interventions, we could be able to determine the technical life of the ballast (the function \( C \), which models the number of interventions as a function of time, is bijective). We count generally between 10 and 15 for classical lines and 30 to 40.
for HSL tamping operations between two ballast’s replacements. Using these values, we obtain a good prediction of the ballast’s technical life. It is a simple method to use and it is also very intuitive: when a track has to be maintained frequently, we can indicate that ballast’s replacement is necessary. However, this empiric method was developed when there were not high speed lines, and when the informations were also limited. With the TIMON base, we can dispose of a big number of informations which turned out to be useful for the validation of this method on the high speed lines, and as a result we would reevaluate the parameters that were indicated for the classic lines.

**Veit Model**

**Initial Model**

Veit Model, named after the Austrian scientist who developed it, is based on track geometry defects. If we consider an indicator of the track geometry state (the higher it is, the more the track is degraded), the Veit model, for a given KP, calls the evolution’s law as illustrated in Figure 4.

![Veit Model](image)

**Figure 4: Veit Model**

We consider the NL as an indicator of the track geometry state. \( NL(t) \) represents the track geometry state at time \( t \) (thin black curve in Figure 4). Each instantaneous drop in \( NL \) corresponds to an intervention on the leveling (vertical red lines in Figure 4). Initially we have:

\[
NL(t) = Q_0 \cdot e^{b_0 t}
\]

\( Q_0 \) represents the initial state and \( b_0 \) is the speed of evolution of the track geometry. This relationship was validated using real measurements of the track condition in Austria. For a track’s section, the measurement history is observed and the degradation rate \( b_0 \) is estimated. To determine whether a maintenance operation is necessary, we define a threshold \( E \). If this threshold \( E \) is exceeded, the track geometry state is such that it impacts on passenger comfort: it is imperative to schedule a maintenance operation. The operation \( i \) can achieve a level of quality \( Q_i \) (such as \( Q_i > Q_{i-1} \)) with a speed of evolution of the track geometry \( b_i \) (such as \( b_i > b_{i-1} \)): the quality of the ballast decreases related to the previous tamping and the track becomes less sustained:

\[
NL(t) = Q_i \cdot e^{b_i t}
\]

The points \( Q_i \) form a curve, which is called the curve of overall degradation of the ballast and it’s the image of the function called \( DgB \), such as:

\[
\begin{align*}
\{ & \mathbb{R} \rightarrow \mathbb{R} \\
& t \mapsto DgB(t) \}
\end{align*}
\]

\[
\begin{align*}
\{ & \mathbb{R} \rightarrow \mathbb{R} \\
& t \mapsto Q \cdot e^{b t} \}
\end{align*}
\]

This represents the minimum attainable level of degradation over time (blue curve in Figure 4). Veit considers that this function depends only on time. All points \( b_i \) (degradation rate after the tamping \( i \)) also form a curve that depends, according to Veit, on the number of interventions: the behavior of the curve is nonlinear - constant from 0 to 10 interventions, the parameter \( b \) increases critically beyond this limit. So we will verify this hypothesis on the French network.

**Linearity assumption**

The curves analysis shows that the assumption of a linear evolution of the track geometry between two consecutive tamping can be made. This simplifies the Veit model:
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\[ NL(t) = Q_0 + b_0 \cdot t \]
\[ NL(t) = Q_i + b_i \cdot t \]

The speed of evolution of the track geometry is then directly the slope of the evolution of the track geometry between two consecutive tamping: \( b_i \). The curve of overall degradation of the ballast, \( DgB \), remains almost the same as defined in the preceding paragraph. We obtain the curve as in Figure 5.

![Figure 5: Linear Veit Model](image)

**How to determine the technical lifetime of the ballast from this model?**

The technical lifetime is determined by the intersection between the curve of overall degradation \( DgB \) and the threshold \( E \) of maximum degradation. However, in practice, the duration between two consecutive tamping has a minimum \( N_c \). We note \( (N_i)_{i>0} \) as the successive durations between two consecutive tamping. \( N_0 \) is equal to the period between the opening of the track and the first tamping. We call \( N_{i_{\text{max}}} \) the first value that is inferior than \( N_c \). The technical real lifetime is:

\[ \sum_{i=0}^{i_{\text{max}}} N_i \]

This method is less simple than the Cochet Maumy method. It models the evolution of the track geometry, and also the ballast degradation, through the function of overall degradation of the ballast \( DgB \) and the slope of the evolution of the track geometry, given by the function \( b(i) \). This model is closer to the aging phenomenon than the Cochet Maumy method, but the overall degradation takes only the time into account.

**Data Processing**

In order to estimate the technical lifetime of the ballast, either from existing models or by creating a new model, we need a high amount of data: some are directly accessible, others require various treatments. We discussed the traffic effect on the life of the ballast, which requires a distinction of the results in homogeneous groups of tonnage. All treatments are performed for high-speed lines (HSL) or classical lines (CL) with UIC group.

We also tested a method that transforms all time variables in accumulated tonnage. Although this approach is justified at a theoretical level, it does not improve the quality of statistical estimates. Thereafter we present the results over time, those easier to interpret. Now we specify relevant data to our study. With the available data we can already quantify the ballast degradation. In fact, we have three indicators:

- The number of interventions on the track geometry: the more the ballast is degraded the more the frequency of interventions is high (Cochet Maumy model).
- The value of the NL initial (which is called \( Q \) in the Veit model): The value of the NL just after a tamping operation tends to increase when the ballast wears: it is an indicator of Ballast's wear (Veit model).
- The value of the degradation parameter \( b \): the slope of the evolution of the track geometry increases as the ballast wears. The ballast loses its good geometry (Veit model).

The ballast wears after several phenomena that we must take into account: the number of tamping made since the last regeneration, with or without grinding after tamping: the time, the accumulated...
tonnage, the train speed, the $N L_{\text{max}}$ (the value of the NL just before a tamping operation)... With the available data, we were able to identify and isolate the factors affecting the ballast degradation and then work on homogeneous sections based on these parameters. Timon summarizes the data by displaying the history of each Kilometric Point (KP). So for every KP, the life of ballast succeeds (Figure 6).

![Figure 6: Schematic of a life cycle of the ballast.](image)

The objective is to isolate each life cycle of the ballast, whatever the KP, and average them to obtain a typical life cycle. The data are sufficiently numerous to allow to correctly estimation of the parameters from Veit and Cochet and Maumy models. Each life cycle of the ballast is composed of a number of tamping cycles. Tamping cycles are delimited by two consecutive leveling interventions as shown in Figure 7.

![Figure 7: Available information about a tamping intervention](image)

For each tamping cycle, we find the intervention that produced it. By definition, the regeneration operation of the track which is the responsible for the life cycle of the ballast is the intervention of rank 0 and corresponds to the first tamping round. The intervention of rank $(i-1)$ corresponds to the tamping cycle number $i$ (Figure 7). The rank of the intervention shows the number of tappings before each tamping cycle. The gain of an intervention is the difference $N L_{\text{min}} - N L_{\text{max}}$.

$$\text{Gain} = N L_{\text{min}} - N L_{\text{max}}.$$  

This value is in most cases negative: an intervention on leveling corrects the NL and therefore improves the track geometry.

We considered the assumption that the evolution of the track geometry is linear between two consecutive operations. By using the regression of the NL function over time we get a line of linear fit. The data processing program will use this method to determine the pieces of lines corresponding to the degradation of the track geometry between two interventions. The coefficient of determination $R^2$ of the regression is capable to validate or not the linearity assumption made above.
The estimation assisted by models of the technical life lasting:

**Cochet et Maumy Model**

In order to estimate the parameters, we calculate the average date of each intervention level. We sort out the data, & keep only the $i^{th}$ tamping operation of each life cycle, then calculate the average of the time separating it from the start of ballast life cycle. This operation is executed at the same time for all the levels (from level 0, which is the first cycle, so at time 0, to the highest level, matching with the last tamping operation in the most grinded ballast life cycle). These points allow calculating the parameters $a$, $b$ and $\delta$ of the Cochet Maumy distribution and that minimize the error with the least squares method. We obtain a frame of the technical lifetime, corresponding to 20 and 25 tampings. In the case of the UIC group chosen for Figure 8, there is a technical lifetime of between 24 and 26 years. The coefficients were determined. The magnitudes $T_{\text{min}} \text{[years]}$, $T_{\text{max}} \text{[years]}$, $a \text{[10^{-2}]}$, $b \text{[10^{-2}]}$, $\delta$ were determined for each HSL and for each group of UIC classical lines. For UIC groups 2 to 4, the results match with the results of Cochet and Maumy.

![Figure 8: Life time estimation with the Cochet and Maumy method.](image)

**Veit Model**

At a first time, we estimate $g$ value. That’s why, the exponential curve $Db(t)=Q_0 e^{gt}$ is determined, passing by the clouds of points:

$$\{(t, NL_{\text{initial}}(t)); t = 1, ..., n\}$$

And minimizing the error using the least squares method. This allows estimating the $Q_0$ value. In our case, we find that:

$$Q_0 = 0, 410 , \ g = 5, 80 \cdot 10^{-5}.$$  

In order to estimate the $b(i)$ function, it’s necessary to find the exponential curve:

$$\left\{\begin{array}{c} 
\mathbb{N} \rightarrow \mathbb{R} \\
 i \mapsto b(i) 
\end{array} \right\} \left\{\begin{array}{c} 
\mathbb{N} \rightarrow \mathbb{R} \\
 i \mapsto P_0 \cdot e^{a \cdot i} 
\end{array} \right\},$$

that minimize the error with the least squares method. We distinguish between cycles with and without grinding in estimating and taking into account the operating speed lines. Taking into account or not grinding can refine the estimate of the technical lifetime compared to the Cochet Maumy model. We need to define a break-even point $E$, corresponding to the maximum tolerated of the mean value of the NL. This break-even point depends on the standing line. We must then define a break-even point Nc corresponding to the minimum duration of a cycle of tamping. We believe that $Nc = 180$ days is a minimum corresponding to reality. Once the two curves $Db$ and $b$ determined, and defined constants $E$ and $Nc$, we can determine the lifetime of an iterative technique, determining the characteristics of each cycle of tamping.

This gives the hole technical lifetime estimated, the number of tamping made, and the graph of $NL$ function of time; as shown in Figure 9 having the technical lifetime respectively with and without grinding all year. Table 1 some results on HSL and classical lines.
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Figure 9: Life time estimation with the Veit method, with and without grinding.

<table>
<thead>
<tr>
<th>Name</th>
<th>Life time [year]</th>
<th>Tamping</th>
<th>Life time [year]</th>
<th>Tamping</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN A</td>
<td>27.0</td>
<td>15</td>
<td>34.4</td>
<td>15</td>
<td>0.9</td>
</tr>
<tr>
<td>LN B</td>
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<td>22</td>
<td>29.2</td>
<td>21</td>
<td>0.9</td>
</tr>
<tr>
<td>LN C</td>
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<td>13</td>
<td>23.5</td>
<td>11</td>
<td>0.9</td>
</tr>
<tr>
<td>LN D</td>
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<td>13</td>
<td>17.2</td>
<td>10</td>
<td>0.9</td>
</tr>
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<td>UIC c</td>
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<td>11</td>
<td>1.2</td>
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</table>

Table 1: Veit Method - summary table

Model limitations

Cochet and Maumy model limitations

Regarding the HSL, we find that the method of Cochet and Maumy indicates a technical lifetime much less than that given by the method of Veit (even without grinding). This reflects the fact that no HSL counts the complete ballast life cycle. Thus, when calculating the average date of the interventions, the population is very low from a certain break-even point and counts only the KP with problems, where lot of tamping was needed. The influence of these KP is disproportionated with this method, and significantly reduces the technical lifetime. In sum, the method of Cochet and Maumy is currently not suitable for HSL.

Veit model limitations

Veit model provides good estimations while considering tamping cycles without grinding. They are consistent with field observations and reveal a hierarchy in terms of proven quality lines. However, the Veit model has a major drawback: the $DgB$ function depends on time, which is not the most influential variable on the degradation of ballast. Moreover, even if time is strongly correlated with the number of jams and accumulated tonnage, it calls into question the foundations of the model. On the one hand, it is physically incorrect to consider that the degradation of ballast depends directly on time, on the other
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hand, it "freezes" the model and prevents it from being applied to various maintenance policies, as shown in 10, or to further simulations of new maintenance strategies.

![Graph](image)

**Figure 10**: Limit of the Veit model

We should have $Q_i \approx Q_i'$ since the number of tamping, $i$, is the parameter that most affects the degradation of the ballast. But this is not the case here since $DgB$ is estimated based on time, whatever the grinding policy: the technical life time with grinding is widely underestimated.

**Proposition of a new model**

The number of tamping has a significant influence on the degradation of ballast. The idea is to get the curves $DgB$ and $b$ depending on the number of interventions. It is already the case for $b$, it remains to determine $DgB$. To do this, simply draw the $NL_{initial}$ means according to the rank $i$ of the procedure: we obtain the sequence of points

$$\{(i, Q_i); i = 1, ..., n\}$$

where $Q_i$ is the average of rank $i$ $NL_{initial}$

![Graph](image)

**Figure 11**: $NL_{initial}$ moyen en fonction du nombre d’interventions de bourrage.

There are two distinct trends: from 0 to 5 tamping (blue Part of Figure 11), degradation of the track is very fast: the transitional regime. Then from 6 tamping and above (orange part of Figure 11), degradation stabilizes and grows in a less pronounced: the steady state. The blue area right of the degraded blue vertical bar indicates the points which are not material, that is to say whose population is strictly less than 10. This reflects that the substructure and new ballast are stabilized in the first place: it’s what we see on the ground. We have seen this type of curves on all groups and UIC HSL lines. From the provision of these points, we determine an analytical formula common to all lines.

$$\left\{ \begin{array}{lcl}
\mathbb{N} & \longrightarrow & \mathbb{R} \\
 i & \longmapsto & DgB(i) = A + (B \cdot i)^{\frac{1}{2}}
\end{array} \right.$$
with $A$, $B$, and $\theta$ three parameters to be determined for each group UIC of CL or HSL. The coefficient $A$ determines the first value of $NL_{\text{initial}}$ early in the cycle. $\theta$ The coefficients $B$ and determine the evolution of $NL_{\text{initial}}$ based on the number of interventions. Figure 12 shows the true values of $NL_{\text{initial}}$ averaged and approximated by an analytic function.

Figure 12: Approximation du $NL_{\text{initial}}$ en fonction du nombre d'interventions de bourrage.

<table>
<thead>
<tr>
<th>Name</th>
<th>$A$</th>
<th>$B$</th>
<th>$\theta$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN A</td>
<td>4.164.10^{-3}</td>
<td>8.182.10^{-3}</td>
<td>1.1</td>
<td>0.915</td>
</tr>
<tr>
<td>LN B</td>
<td>4.253.10^{-3}</td>
<td>1.156.10^{-4}</td>
<td>1</td>
<td>0.968</td>
</tr>
<tr>
<td>LN C</td>
<td>3.953.10^{-3}</td>
<td>6.033.10^{-3}</td>
<td>1.5</td>
<td>0.940</td>
</tr>
<tr>
<td>LN D</td>
<td>2.684.10^{-3}</td>
<td>2.616.10^{-4}</td>
<td>3.1</td>
<td>0.958</td>
</tr>
<tr>
<td>UIC a</td>
<td>6.278.10^{-3}</td>
<td>2.688.10^{-3}</td>
<td>2.2</td>
<td>0.862</td>
</tr>
<tr>
<td>UIC b</td>
<td>5.888.10^{-3}</td>
<td>3.380.10^{-3}</td>
<td>2.6</td>
<td>0.671</td>
</tr>
</tbody>
</table>

Table 2: Coefficients $i \rightarrow DgB(i)$

Table 2 shows the estimation results. The coefficient of determination is greater than 0.9 on all HSL which validates the law on these lines. Regarding the classic lines, the law is also validated.

**Comparison of the maintenance policies**

We have seen that the political grinding affects a lot the technical lifetime of the ballast. It is therefore interesting to see what impact the policy was grinding on maintenance costs. We study three policies in this part of different grinding: no grinding, grinding once in a year with maximum one grinding per tamping cycle, of one per cycle, and tamping every five years, with at most one grinding per tamping cycle. We will compare the cumulative annual costs of several strategies to isolate those costing the least. The results of the new method provide the estimated date of each tamping and grinding, and the technical lifetime. We can this way, knowing the price of grinding and stuffing kilometer, calculate the cumulative annual cost for a given KP. We can visualize the results as a graphic (Figure 13) and graphically compare the three different maintenance strategies.
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We notice that in terms of cumulative cost, it is more interesting to do a grinding per year, plus the tamping. We obtained similar results on the entire network. Let’s introduce the calculation of overall costs, meaning the costs on the comprehensive review of the investment. This issue will be further studied in our next article. Let’s present without further explanation the total costs:

\[ C_{\text{global}} = \frac{\sum_{i \leq \text{horizon}} C_i}{\sum_{i \leq \text{horizon}} (1+\alpha)^i} \]

where \( C_i \) is the maintenance cost of the year \( i \) (\( C_0 \) is the cost of initial investment, that is to say the cost of the RVB\(^1\)), \( \alpha \) is the discount rate and the variable is the time horizon technical life of the ballast (in years). This formula allows you to compare investments on different horizons, which is important in our case, since grinding affects the technical lifetime of the ballast.

The total cost here represents an average annual cost per equivalent KP. We can compare the gain in terms of cost, rather than in terms of technical life, following the policy of grinding. Table 3 summarizes the results of this economic study by taking the cost per kilometer of the tamping \( X \).

<table>
<thead>
<tr>
<th></th>
<th>Without grinding</th>
<th>With a grinding pro 5 years</th>
<th>With a grinding pro year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value for HSL</td>
<td>9,6( \times )</td>
<td>8,5( \times )</td>
<td>7,0( \times )</td>
</tr>
<tr>
<td>Mean value for</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classical Lines (LC)</td>
<td>6,7( \times )</td>
<td>6,1( \times )</td>
<td>5,8( \times )</td>
</tr>
</tbody>
</table>

Table 3: Simulations économiques : tableau récapitulatif

Grinding is much more efficient on HSL than on CL and impact of grinding on CL is lower as the group UIC is high. However, for all channels analyzed, a strategy of preventive grinding is reasonable. We want therefore to synchronize grinding and tamping at the operational level, although it remains an organizational difficulty. The grinding is a procedure periodically carried out regularly over long distances. The tamping is a conditional intervention on track segments more targeted. It is necessary to optimize the organization of maintenance, taking into account the inherent constraints to the operations of grinding (low gear park, cumbersome, inefficient).

Conclusion

The function defined in the Cochet and Maumy method and provided a good approximation of the number of tampings with time. Nevertheless, a policy that includes a mix of grinding and tamping operations, cyclical for them, the costs are added at different rates. However, depending on the

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\(^1\) The cost of a RVB is around 1M\( \text{€} \)/km for classical line and around 2M\( \text{€} \)/km for HSL then it doesn’t exist any alternative line
chosen strategy (the break-even point $E$), the cost of tamping is fixed and the cost of grinding is added directly to the tamping one as the operations should be very close. That why, the curve of the cumulative cost of maintenance over time looks like the function describing the combination of maintenance over time. Thus, to estimate the function of the cumulative costs of maintenance of ballast versus time, the parameters $a$, $b$ and $\delta$ can be estimated. By derivating the function, we obtain the annual maintenance cost over time (Figure 14).

![Figure 14: Annual costs in function of the age $N$ and his approximation in blue](image)

On the technical lifetime of the ballast, it is possible to approach the curves reflecting the need for intervention by a power function of time. We’ll see in our next article that this type of approach could be usefully used in the context of economic studies with discounting. We saw that we could model the track geometry, derive a technical lifetime of the ballast and compare different maintenance policies considered. A gap may appear between a lifetime of technical and economic life, then it may be more interesting, in some cases, to replace the ballast before the technical lifetime. This knowledge allows the Maintenance Engineering Department of the SNCF to confirm in an objective way its new maintenance strategies.

For HSL, it is important to take into account the train type circulating on it. The ballast deterioration laws are sensitive to several mailmen of whom the most important are:

- the axles load (17t en France);
- the distance between axles of a bogie (2,5 or 3m en general);
- the number of axles...

and of course the speed of circulation.

So we could demonstrate that; by respecting a 17 tonnes axles load, a train including bogies with a wheelbase of 2,5m at 260km/h generates identical solicitations, at 30Hz (Figure 15) that is the limit of the viscosity of the ballast, that a train with 3,0m wheelbase bogies at 320km/h. The first train type generates at 320km/h solicitation à 35Hz, that is the work frequency of the tamping machine, increase the speed of the leveling deterioration and the annual tamping costs (around 22%). In this case, the parameters of the model have to be reestimated.
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Figure 15: Spectral power density of sleeper and ballast solicitation with high speed trains

Bibliography


