Modeling an Optimal Track Maintenance Schedule in Consideration of Timing of Grinding and Tamping

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Today, tamping machines and rail grinding machines are used to maintain ballasted tracks and to remove rail surface irregularities, respectively. Even though maintenance cycles could be extended and the total cost of maintenance could be reduced by efficiently combining these two machines, they are usually operated independently. As such, in order to estimate the effect of combining both these machines (combined maintenance), a model has been designed along with a scheduling system, as a simple method for preparing maintenance schedules which combine tamping and grinding. Investigations were also carried out to establish how long this type of maintenance lasts, and determine the optimum level of combined maintenance.

Keywords: track maintenance, tamping, grinding, maintenance cycle, scheduling, optimization model

1. Introduction

Recently tamping machines have been used to maintain ballasted tracks with a view to minimizing longitudinal level irregularity, and rail grinding machines have been used to maintain rail surfaces by removing of rail surface irregularities. However, combining tamping and grinding, in a form of “Combined maintenance,” could extend the maintenance cycle and decrease the total cost of maintenance [1, 2]. It is considered that, decreasing not only longitudinal irregularity but also rail surface irregularity, decreases fluctuation of wheel loads and also the speed of growth in longitudinal irregularity. Figure 1 shows an example of the trend in standard deviation of the longitudinal level irregularity and that of the axle-box acceleration which was processed with a band-pass filter of wavelength 0.075-0.25 m (called Rail ABA) indicating rail surface roughness at the combined maintenance lot [3]. This figure reveals that the Rail ABA is decreased by rail grinding and the speed of growth of the longitudinal level irregularity is decreased after tamping. However, the two machines are operated independently in Japan, since scheduling combined operations is complex and there is no validated model to quantitatively estimate the effect of joint maintenance.

The purpose of this research was to build a model for estimating the effect and duration of combined maintenance through analysis of real data, and to develop a scheduling system to facilitate combined maintenance planning. In addition, investigations were made to determine the optimum level of combined maintenance.

2. Building the combined maintenance model

2.1 Outline of the combined maintenance model

This section discusses building a model for estimating the effect of combined maintenance. Figure 2 shows an outline of the combined maintenance model. This model is used for estimating longitudinal level irregularity at the year-end, by applying the combined maintenance effect to the lots where both tamping and grinding are executed as combined maintenance. To analyze the effect of combined maintenance, the maintenance record and statistical data of 25 m lots measured by a track inspection car over 3 years on the Sanyo Shinkansen Line, were used.

![Fig. 1 Trend in standard deviation of longitudinal level irregularity and of Rail ABA, after combined maintenance](image1)

![Fig. 2 Flow chart of combined maintenance model](image2)
2.2 The effective lot for combined maintenance

A combined maintenance effect is not always obtained even if the lot is tamped and ground at the same time. By analyzing actual data, it is assumed that the lots satisfying 4 conditions shown in Fig. 3 are the lots where combined maintenance would be effective. In Fig. 3, Ballast ABA means axle-box acceleration which was processed with a band-pass filter of wavelength 2-5m indicating ballast condition. 10m and 5m chords mean the length of chord of the chord measuring system which is generally used in Japan [4].

The meanings of the respective conditions are shown as follows.
Condition 1: There is no structural influence
Condition 2: Both the longitudinal level irregularity and speed at which it is progressing are high, therefore track conditions can be improved easily by tamping.
Condition 3: Rail surface irregularity is significant, therefore track conditions can be improved easily by grinding.
Condition 4: Condition of ballast is good.

2.3 Index showing effect of combined maintenance, (Rate at which longitudinal level irregularity progresses)

Equation (1) expresses the index showing the effect of combined maintenance, which is equal to the rate at which longitudinal level irregularity progresses after combined maintenance compared to the rate before combined maintenance. Figure 4 shows the order in which combined maintenance is carried out. Grinding followed by tamping, as shown in Fig. 4a is called “Grinding ahead.” Tamping followed by grinding however, as in Fig. 4b is called “Tamping ahead.” The maintenance interval ΔT means the number of days between tamping and grinding.

\[ \kappa = \Delta \sigma_a / \Delta \sigma_b \]  
\[ \Delta \sigma_a : \text{Speed of longitudinal level irregularity progression before the combined maintenance (mm/day)} \]  
\[ \Delta \sigma_b : \text{Speed of longitudinal level irregularity progression after the combined maintenance (mm/day)} \]

2.4 Factors influencing combined maintenance

(1) Maintenance interval ΔT and execution order (Fig. 5a)

The shorter the maintenance interval ΔT, the higher the effect of combined maintenance (the smaller κ). This is because it is considered that the track condition can be effectively improved through combined maintenance, if it is carried out before the track condition begins to gradually change again after having being improved by grinding or tamping.

In terms of order of combined maintenance, grinding ahead is more effective than tamping ahead. This is because once rail surface irregularity has been reduced by grinding, then wheel load variation also decreases, which means that tamping is more effective and longitudinal level irregularity progression is slowed down.

(2) Decreased amount of Rail ABA (Fig. 5b)

Decreased amount of Rail ABA by grinding is given by (2). For both grinding and tamping ahead, the larger the decreased amount of Rail ABA, the higher the effect of combined maintenance. This is because the smaller the rail surface irregularity, the lower the wheel load variation.

\[ \Delta \sigma = \Delta \sigma_{GB} - \Delta \sigma_{Ga} \text{ (m/s}^2) \]  
\[ \Delta \sigma_{GB} : \text{Rail ABA before grinding (m/s}^2) \]  
\[ \Delta \sigma_{Ga} : \text{Rail ABA after grinding (m/s}^2) \]
2.5 Estimation of index showing effect of combined maintenance, $\kappa$

From the above, the influence of maintenance intervals and decreased amount of Rail ABA on $\kappa$ are considered to be large, so that the index $\kappa$ is given by the equations shown in Table 1 below. These estimation equations have no maintenance interval parameter when the interval is shorter than a certain fixed number of days. In the case of tamping ahead, there was an insufficient number of samples for analysis; therefore the estimation equations were formulated by adding some values to the equations for grinding ahead. In future, when a sufficient number of samples have been collected, the estimation equations can be improved.

To check accuracy of these equations, the correlation between the estimated values and the actual measured values of the index showing effect of combined maintenance is shown in Fig. 6. Since the standard deviation of the errors between the estimated values and the actual measured values is 0.12, the equations are considered to have sufficient estimation accuracy.

### Table 1  Index showing effect of combined maintenance $\kappa$

<table>
<thead>
<tr>
<th>Order of maintenance</th>
<th>Maintenance interval (in days)</th>
<th>Effect of combined maintenance $\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding ahead</td>
<td>$0 \leq \Delta T &lt; 70$</td>
<td>$\kappa = -0.40 \times \Delta \alpha + 0.25$</td>
</tr>
<tr>
<td></td>
<td>$70 \leq \Delta T &lt; 300$</td>
<td>$\kappa = -0.31 \times \Delta \alpha + 0.0028 \times \Delta T + 0.25$</td>
</tr>
<tr>
<td></td>
<td>$300 \leq \Delta T$</td>
<td>$\kappa = 1.0$</td>
</tr>
<tr>
<td>Tamping ahead</td>
<td>$0 \leq \Delta T &lt; 20$</td>
<td>$\kappa = -0.40 \times \Delta \alpha + 0.46$</td>
</tr>
<tr>
<td></td>
<td>$20 \leq \Delta T &lt; 180$</td>
<td>$\kappa = -0.31 \times \Delta \alpha + 0.0028 \times \Delta T + 0.54$</td>
</tr>
<tr>
<td></td>
<td>$180 \leq \Delta T$</td>
<td>$\kappa = 1.0$</td>
</tr>
</tbody>
</table>

2.6 Effective duration of combined maintenance

It is thought that the effects of combined maintenance decrease gradually as degradation of the track progresses. Figure 7 shows an example of the trend in longitudinal level irregularity and its rate of progression in the section where combined maintenance was carried out. In this paper, the effective duration of the combined maintenance is defined as the number of days until the rate of longitudinal level irregularity progression returns to the original level from before the combined maintenance. Figure 8 shows the correlation between the effective duration of the combined maintenance and the maintenance interval. This figure shows that the shorter the maintenance interval, the longer the effective duration, and that the maximum duration is almost one year. Accordingly, the effective duration $D$ can be expressed by (3).

$$D = -1.13 \Delta T + 320 \text{ (day)}$$  \hspace{1cm} (3)

This equation also needs to be improved once enough samples have been collected.
3. Development of combined maintenance system and its verification

In order to facilitate the planning of combined maintenance, a “Combined Maintenance System” was developed by linking three existing systems: the first was RCA (Railway Condition Analyzer) [5] to estimate track conditions, the second was MTS (Multiple Tie Tamper Scheduler) [6] to draw up tamping plans, and the third was RGS (Rail Grinding Scheduler) [7] to make grinding plans. The system, shown in Fig. 9, works as follows: The RCA estimates the track condition to select one of the proposed lots combined maintenance. Then, the MTS can plan the tamping machine schedule in one of two ways for the proposed lot. One way is to prepare a plan which always includes tamping (“strong consideration,” Fig. 9 [1]), the other is to prepare a plan without particular consideration for the proposed lot (“weak consideration,” Fig. 9 [2]). After fixing a date for tamping in the proposed lot for combined maintenance, the combined maintenance schedule is formulated by setting the date for grinding as close as possible to the tamping date.

From this chapter on, in order to simplify the model analysis, the duration of combined maintenance effect is assumed to last forever, regardless of the maintenance interval which was discussed in section 2.6.

For the computing test a one year combined maintenance plan was drawn up of a track line with 800 lots/100 m applying the combined maintenance system. Through the RCA, 107 lots out of 800 were chosen for combined maintenance. Figure 10 shows an example of the predicted transition in longitudinal level irregularity in the section selected for combined maintenance. It is estimated that longitudinal level irregularity at the end of the year would decrease by 40% as a result of the combined maintenance. It is estimated that longitudinal level irregularity at the end of the year would decrease by 40% as a result of the combined maintenance. Table 2 shows year-end longitudinal level irregularity and corresponding speeds of progression. Longitudinal level irregularity improves the most in cases where “weak consideration” was given. However, the speed of longitudinal lev-
el irregularity progression was slowest in the cases given “strong consideration.” Consequently, when maintenance is combined, and even if the length of maintained track is the same, the level of longitudinal irregularity or its speed of progression may be decreased.

4. Investigation into the optimum level of combined maintenance

Although combined maintenance lengthens the maintenance cycle, too much emphasis on combined maintenance could lead to sections with high longitudinal level irregularity which require more frequent attention, do not get sufficient maintenance. As such this paragraph describes a simple estimation model which was built to examine the optimum combined maintenance level which could facilitate preparation of the most suitable maintenance plan. Two indices are defined below, for this model.

(1) Tamping rate \( r \)

Tamping rate \( r \) is defined as the ratio of lots actually tamped to the total number of lots which could be tamped. Therefore, the number of lots for actual tamping can be obtained by multiplying \( r \) by the number of target tamping lots.

\[
r = \frac{L}{L_t} \quad (0 \leq r \leq 1)
\]

\( L \): Number of lots for actual tamping (lots/100 m)

\( L_t \): Total number of lots which could be for tamping (lots/100 m)

<table>
<thead>
<tr>
<th>Combined maintenance consideration</th>
<th>Longitudinal level irregularity (mm)</th>
<th>Speed of longitudinal level irregularity progression (mm/100 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No consideration</td>
<td>0.980</td>
<td>0.841</td>
</tr>
<tr>
<td>Strong consideration</td>
<td>0.980</td>
<td>0.855</td>
</tr>
<tr>
<td>Weak consideration</td>
<td>0.831</td>
<td>0.335</td>
</tr>
</tbody>
</table>

Table 2 Year-end longitudinal level irregularity and speed of progression

![Graph showing irregularity at each year-end and combined maintenance ratio]

Fig. 11 Irregularity at each year-end and combined maintenance ratio
(2) Combined maintenance rate $f$

The combined maintenance rate $f$ is defined as the ratio of the total number of combined maintenance lots to the number of total lots for tamping. Therefore, number of combined maintenance lots (or amount of combined maintenance) can be obtained by multiplying $f$ by the number of lots for actual tamping.

$$f = \frac{L_f}{L_c}$$  \hspace{1cm} (5)

$L_f$: Number of lots of combined maintenance (lots/100m)

(Amount of combined maintenance)

The correlation between year-end longitudinal level irregularity, the number of combined maintenance lots, and the combined maintenance ratio $f$ for each tamping ratio $r$ and for each year, calculated in this simple model, is shown in Fig. 11. This correlation shows that the lower the tamping ratio, the worse the irregularity, especially when the combined maintenance ratio $f$ or $r$ is large. This is because when the tamping ratio is small, priority is given to the lots which have high irregularity, i.e. for lots where the decrease in irregularity after tamping is significant, the combined maintenance ratio $f$ has to be kept low. Moreover, for each tamping ratio $r$, there is the best rate of combined maintenance $f^*$ where year-end irregularity is at a minimum. This ratio increases as the tamping ratio $r$ rises. As for $f^*$, even if the tamping ratio remains the same, year-end irregularity decreases year after year due to the effect of combined maintenance.

From what is described above, it can be said that year-end longitudinal level irregularity fluctuates depending on combination of tamping ratio $r$ and combined maintenance ratio $f$. Therefore, given a tamping ratio $r$, the best ratio of combined maintenance $f^*$ can be estimated using the simple model and it is also possible to devise the most efficient tamping and grinding plan.

In order to verify the optimum level of combined maintenance $f^*$, estimated through the simple estimation model, an analysis was made of the correlation between year-end longitudinal level irregularities and the combined maintenance ratio $f$ obtained with the combined maintenance system and the simple estimation model. The results of this analysis are shown in Fig. 12.

When the system generates a tamping and grinding schedule, a maintenance block made up of several consecutive lots, is considered. The simple model however, only considers each lot individually and tamping and grinding are always carried out in the middle of the year. This means that the longitudinal level irregularity estimated in the model is lower or almost the same as the irregularity estimated in the system.

Consequently, year-end longitudinal level irregularity is at a minimum when the combined maintenance ratio $f$ is about 0.25 in either the model or the system. Thus, the best rate of combined maintenance $f^*$ calculated with the simple estimation model, which offers sufficient accuracy, can be input (Fig. 9) to the combined maintenance system. The system can then easily build a plan for a year which will not only decrease longitudinal level irregularity but also lengthen the maintenance cycle.

In this simple model, the combined maintenance effect is assumed to last forever; therefore, if the model is improved, results in the 2nd and 3rd will change.

5. Conclusions

The following insight was gained through this research:

(1) The effect of combined maintenance is influenced by the maintenance interval and the order in which tamping and grinding are carried out, and decreased amount of Rail ABA after grinding. A model was built for estimating the effect of combined maintenance based on this relationship.

(2) The effective duration of combined maintenance was influenced by the length of interval between tamping and grinding. A model was designed to estimate the duration based on this relationship.

(3) Development of a combined maintenance system facilitates the drafting of tamping and grinding schedules while considering the effect of combined maintenance.

(4) Building a model to estimate the appropriate amount of combined maintenance makes medium term planning with the system more effective.

In sum, the development of a combined maintenance system can facilitate the preparation of tamping and grinding schedules while considering the effect of combined maintenance. In addition to verifying the validity of this system, future work will investigate a maintenance model covering several years, based on items (1) and (2) above.

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