Optimizing Policies of Railway Ballast Tamping and Renewal

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This paper discusses optimizing ballast tamping and renewal (T&R) jointly to reduce the life-cycle cost of ballast. A life-cycle cost model is developed to incorporate a track deterioration model and a tamping model. Based on the models, three optimal policies of ballast T&R are investigated, which include fixed intervention level, constant interval of tamping, and optimal nonconstant intervals of tamping. Three algorithms are presented to obtain the optimal solutions for the three policies. An example is presented to illustrate model performance. From a whole life point of view, eight options based on the three policies are compared for a better understanding of the effectiveness of the policies. The results show that considerable benefit could be achieved by considering ballast tamping and renewal together and implementing the optimal policy.

Currently, most railways in the world are running on ballasted track, and each year great expense is incurred in ballast maintenance and renewal (M&R). For example, in the United Kingdom the cost of only material in ballast M&R is about \$80 million (approximately £45 million with an exchange rate of 1.77) annually (*1*). Traditionally, ballast M&R is scheduled in terms of its performance, and no economical analysis is significantly involved. Therefore, much potential saving in ballast M&R could exist.

So far, considerable effort has been made to reduce the expenditure by optimizing ballast maintenance. Higgins (*2*) proposed a model to determine the best allocation of tamping activities and screws within the cost budget, so as to minimize the disruption to train traffic and to reduce the amount of delay. Miwa et al. (*3*) described ballast deterioration as a stochastic process and developed a mathematical programming model to obtain the optimal decision of tamping based on both tamping costs and level of track quality. Lake and Ferreira (*4*) optimized maintenance activities by minimizing a weighted combination of the cost of conducting the track maintenance and a measure of the interference delays. To solve the problem characterized by the nonlinearity and large number of variables, Simulated Annealing, Local Search, and Tabu Search were incorporated in the implementation. However, not much work has been done to optimize the intervention level of tamping and work out the optimal intervals of tamping from an economical point of view. Besides, the above works basically focused on the short-term plan of ballast maintenance, and no effect of ballast renewal was considered.

Life-cycle costing has been used in planning railway M&R since the 1980s and much benefit has been obtained in several railway networks. Markow (*5*) reported a study at RENFE (Spanish National Railroad) to evaluate different maintenance policies by application of the life-cycle costing method. At BR Research (*6, 7*), a software system (MARPAS) was developed to determine an optimal tamping period by minimizing total cost. Chrismer and Selig (*8*) presented a number of mechanistic and economic models for comparing economics of different ballast and subballast maintenance polices. According to Jovanovic and Esveld (*9*), a decision support system, named ECOTRACK, provided a function to minimize the cost of track M&R through a combination of ballast renewal and other components (rail and sleeper), but no major application has been reported.

It is well known that the efficiency of ballast tamping is reduced by an increase of ballast service life, and, consequently, the durability of track quality is reduced. This means that tamping must be applied more and more frequently in order to keep the track quality at a specific level. Correspondingly, the annual tamping cost increases considerably with this frequent intervention. Therefore, one reasonable way to make track maintenance cost-effective is to employ a ballast renewal before tamping becomes too frequent. Although some efforts have been made to develop tamping and ballast renewal plans separately, little work has incorporated ballast renewal into a tamping plan to provide reduction of the whole life cost of ballast.

This paper discusses optimizing ballast tamping and renewal (T&R) together from a life-cycle cost point of view. A life-cycle cost model is developed that incorporates a track deterioration model and a tamping model. Renewal cost, tamping cost, and penalty cost are addressed in the analysis of ballast life-cycle cost. Based on the models, three optimal policies of ballast T&R are investigated, which include fixed intervention level, constant interval of tamping, and optimal nonconstant intervals of tamping. The objective of the optimization is to minimize life-cycle cost per unit traffic load. Three algorithms are presented to obtain the optimal intervention level, optimal period of tamping, and optimal intervals of tamping. The optimal service life to renewal for each policy is also obtained, which represents the ballast economic life and could be used in the decision making for ballast renewal. An example is given to show the performance of the approach. From a whole life point of view, eight options based on the three policies are compared for a better understanding of the effectiveness of the policies. The results show that significant benefit could be achieved by considering ballast tamping and renewal together.

In this paper, the focus is on the analysis of ballast T&R policies using life-cycle costing, and conclusions are drawn from the results of an example focusing on one type of ballasted track with high-speed light-axle loads. However, the methodology allows incorporating different track quality deterioration and tamping models, which may give different tamping costs in a ballast life-cycle and may yield different results. In this sense, it could be applied both for the cases of high-speed light-axle loads and heavy haul line, which

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have different parameters of track deterioration and costs. Instead of using physical time as the time variable, the paper uses tonnage as the time variable. Therefore, the assumption of steady-state traffic (no variations) is not required. Although the authors agree that if the traffic pattern is hugely different over time, the deterioration rate may be affected.

LIFE-CYCLE MODEL OF BALLAST

In this section, the key behavior involving track quality deterioration and tamping is analyzed. Based on this analysis, a life-cycle cost (LCC) model of ballast is developed. It is assumed that little or no new ballast is added during ballast tamping. Because the analysis is done for a general case in a railway network but not for a specific site, the conditions of subgrade and rail are assumed to be the same over the considered section of track. It is also assumed that tamping is employed to maintain the ride quality limit. In the development of the LCC model, it is supposed that a model for track deterioration has been formulated, which could be linear or nonlinear.

Models of Track Quality Deterioration and Maintenance

Track quality is commonly quantified by standard deviations of track geometry parameters, σ_i, such as vertical geometry, alignment, and cross-level, which can be given by

$$Q = \sum_i \sigma_i \tag{1}$$

where Q is referred to as the track quality index (TQI). In principle, all the geometry parameters are equally significant and should be involved in the calculation of TQI (*10*). However, railway companies may use some of the track geometry parameters for the evaluation of TQI, which may be different from one company to another. Therefore, the parametric values in track deterioration models in different railway networks may be different. Because TQI is represented by the standard deviations of track geometry parameters, the higher the TQI is, the poorer the track quality.

In general, there are three stages in the evolution of track quality deterioration: initial deterioration, linear period, and nonlinear accelerated deterioration (*11*). For simplicity, a linear function is widely used to model the track quality deterioration, such as ECOTRACK (*9*). Chrismer and Selig (*12*) presented a logarithmic equation for track settlement, and later modified it to a power equation for better representing ballast behavior (*8*). Recently, a nonlinear model was reported by Riessberger (*13*) with a combination of both initial and linear deterioration. In the following analysis, Riessberger's model is used to describe the deterioration of track quality. For the ith tamping cycle, the model is given by

$$Q_i(T_i) = h_i + q_a\left(1 - e^{-\theta_i T_i}\right) + \alpha_i T_i \tag{2}$$

where

$Q_i(T_i)$ = TQI,
h_i = initial TQI after the i-1th tamping,
q_a = initial deterioration,
T_i = traffic load from the i-1th tamping activity to the ith one, and
α_i, and θ_i = track quality deterioration rate and deterioration constant, respectively.

According to Riessberger (*13*), α_i usually varies from 0.05 to 0.3 mm/MGT and θ_i varies from 2.0 to 5.0 MGT. Graphically, α_i is the slope of the asymptote of $Q_i(T_i)$ (the linear part of the curve), $q_a + h_i$ is the intercept of the asymptote where h_i can be determined using Equation 4, and $\theta_I \approx 1.6/t$ where t is the tonnage corresponding to the intersection of curve $Q_i(T_i)$ with the asymptote of $0.8Q_i(T_i)$. Therefore, if the curve of track quality deterioration in a ballast life-cycle is known, the parameters can then be determined.

Although Riessberger's model can capture the nonlinear characteristics of track quality deterioration in a ballast life-cycle, determination of the parameters will be a problem. Nevertheless, the methodology allows using other models (e.g., a linear model), although the nonlinear model is employed in the following analysis of ballast LCC.

After tamping, although ballast geometry condition is improved, the ballast performance is consistently degrading with increase of traffic load, and the restoration ability of tamping decreases. According to the results of previous studies (*3, 14*), it could be assumed that the restoration value by tamping decreases proportionally at a certain ratio:

$$\Delta Q_i / \Delta Q_{i-1} = \beta \tag{3}$$

where $\Delta Q_i = Q_i(T_i) - h_i$, which represents the restoration value by the ith tamping action, and β is the restoration ratio. From Equation 3, it follows that the initial track quality after the ith tamping is

$$h_{i+1} = (1-\beta)Q_i(T_i) + \beta h_i \tag{4}$$

The effects of the subballast and subgrade are not analyzed separately in this study. According to Chrismer and Selig (*8*), the track settlements caused by subballast and subgrade vary linearly with load cycles after a small initial tonnage, and the rates of settlements are constant for specific track conditions. This means that although subballast and subgrade contributed significantly to track total settlement, their effects on the rate of irregular settlements do not vary with an increase of tonnage for a specific track condition, and these are assumed to be already addressed in the TQI deterioration model. In addition, as a result of an increase of fouling degree, track quality will degrade faster when ballast becomes older. This behavior could be considered in the track quality deterioration model (Equation 2) with an increasing deterioration rate, and in the maintenance model (Equation 4), the decreasing maintenance efficiency addresses this property as well.

Life-Cycle Cost Model

This paper focuses on a segment (unit track) of ballast. The life-cycle of ballast is defined as the period between two consecutive activities of ballast renewal. The related costs in a ballast life cycle include tamping cost, renewal cost, and penalty cost.

Tamping Cost

It is assumed that in a ballast life cycle, tamping is conducted for n times, where n could be a decision variable. If c_m denotes the tamping cost per unit track, then tamping cost in a ballast life cycle is nc_m.

Renewal Cost

The definition of ballast life cycle implies that there is only one renewal of ballast in a ballast life cycle. If c_r denotes the ballast renewal cost per unit track, then ballast renewal cost in a ballast life cycle is c_r.

Penalty Cost

Penalty cost is the loss caused by poor track quality. It derives mainly from three sources. First, it may result from a penalty through contract of asset management on track quality requirement (e.g., from the operator of the track to the train operating companies). Second, penalty cost may result from the loss of customers and the competence of train service when ride quality becomes poor and is considered unsatisfactory by the passengers. Third, this cost arises from the damage to track components and vehicles as a result of poor track quality. Hope (*6*) studied the effect of the track quality on revenue and the results suggested that the penalty cost could be considered to be proportional to TQI. Hence in this paper, it is assumed that penalty cost is proportional to the amount that track quality exceeds the initial penalty level (L_p), and also it is proportional to the accumulative traffic load during which ride quality is beyond the threshold. Therefore, for the *i*th tamping interval, penalty cost can be given by

$$\int_{t_{\mathrm{pi}}}^{T_i} c_p \left[Q_i(t_i) - L_p \right] dt_i \tag{5}$$

where c_p is the coefficient of penalty cost, and t_{pi} is the amount of traffic during which the track quality just exceeds penalty level, which can be calculated by

$$Q_i(t_{\mathrm{pi}}) = L_p \tag{6}$$

Total Cost per Unit Traffic Load

By summing up the above cost elements and dividing by the traffic load in a ballast life cycle, the total cost per unit traffic load per unit track (LCC*p*) can be determined:

$$C(n, \mathbf{T}) = \frac{c_r + nc_m + \sum_{i=1}^{n+1} \int_{t_{\mathrm{pi}}}^{T_i} c_p \left[Q_i(t_i) - L_p \right] dt_i}{\sum_{i=1}^{n+1} T_i} \tag{7}$$

where $\mathbf{T}$ is the set of tamping intervals, that is, $\mathbf{T} = (T_1, T_2, \ldots, T_{n+1})$ when there are n times of tamping in a life cycle of ballast.

OPTIMAL POLICIES OF TRACK TAMPING AND RENEWAL

On the basis of the current practice of railway maintenance, three T&R policies can be considered:

- Fixed intervention level,
- Constant interval of tamping, and
- Optimal nonconstant intervals of tamping.

Policy 1. Fixed Intervention Level

In this policy, tamping threshold is kept at a fixed intervention level (threshold), L. That is, tamping will be conducted when TQI is measured or predicted up to a specific level. This policy is widely used in railway asset management. In this case, both tamping threshold and ballast service life to renewal will be the optimizing variables in order to obtain the optimal T&R policy. The task here is to find an optimal number of tamping cycles before renewal by minimizing LCC*p* subject to track quality being kept below the intervention level. Another constraint is that service life to renewal has to be less than the maximum limit of ballast service life (B_l).

Let L_{acpt} denote the maximum acceptable level of TQI, and then the optimization model can be given by the following:

$$\text{minimize } C(n, \mathbf{T}) \tag{8}$$

$$\text{subject to } Q_i(T_i) = L \le L_{\mathrm{acpt}} \quad \text{for } i = 1, 2, \ldots, n+1 \tag{9}$$

and

$$\sum_{i=1}^{n+1} T_i \le B_l \tag{10}$$

Algorithm A

The problem here is to find the optimal intervention level L^* and number of tamping cycles n^*. It is known that the necessary condition of the optimal intervention level is

$$\frac{\partial C(n, \mathbf{T})}{\partial L} = 0 \tag{11}$$

Note that from Equation 9 one knows that for Policy 1, intervals of tamping $\mathbf{T}$ are the functions of intervention level L.

Let $\Delta C(n,\mathbf{T}) = C(n,\mathbf{T}) - C(n-1,\mathbf{T})$, and then the necessary condition of the optimal number of tamping cycles satisfies

$$\Delta C(n, \mathbf{T}) \le 0 \text{ and } \Delta C(n+1, \mathbf{T}) \ge 0 \tag{12}$$

Based on direct local search, the following bisection procedure is presented to search for the optimal n^* and L^*:

Step A1. Divide $[L_p, L_{\mathrm{acpt}}]$ into m equal intervals and obtain $m + 1$ values of intervention level $(l_1, l_2, \ldots, l_{m+1})$ with $l_1 = L_p$ and $l_{m+1} = L_{\mathrm{acpt}}$.

Step A2. For each l_i, find n_i from Formulae 9 and 10, and calculate $C(n_i,\mathbf{T})$, and obtain the level l_k with minimal LCCp.

Step A3. Set the search area $[l_a, l_b]$ by letting $l_a = l_{k-1}$ and $l_b = l_{k+1}$.

Step A4. Calculate $d_a = \partial C(n,\mathbf{T})/\partial L$, $c_a = C(n,\mathbf{T})$ for $L = l_a$, and calculate $d_b = \partial C(n,\mathbf{T})/\partial L$, $c_b = C(n,\mathbf{T})$ for $L = l_b$.

Step A5. If $\left|(c_a - c_b)/c_a\right| < 10^{-4}$, stop the searching; the optimal intervention level is then $L^* = l_a$, and optimal n^* is obtained from Formula 12; otherwise, continue the procedure.

Step A6. Let $l_c = (l_a + l_b)/2$ be the midpoint of the current interval and calculate $d_c = \partial C(n,\mathbf{T})/\partial L$ for $L = l_c$.

Step A7. If $d_a d_c > 0$, then let $l_a = l_c$; otherwise, let $l_b = l_c$; and go back to Step A4 to continue the search.

Policy 2. Constant Interval of Tamping

In some railway industries, ballast tamping is conducted at a constant interval of traffic load. The problem here is to find the optimal interval (T_c^*) for minimizing the life-cycle cost of ballast. Therefore, the optimization model is given by the following:

$$\text{minimize}\, C(n,\mathbf{T}) \tag{13}$$

subject to

$$T_i = T_c \quad \text{for } i = 1,2,\ldots,n+1 \tag{14}$$

and

$$(n+1)T_c \le B_l \tag{15}$$

$$Q_i(T_c) \le L_{\text{acpt}} \tag{16}$$

Algorithm B

From Equations 13 to 16, it can be seen that there are two decision variables in the problem; these are optimal interval T_c and number of tamping cycles n. For a specific number of tamping activities in ballast life cycle, the optimal interval of tamping satisfies

$$\partial C(n,\mathbf{T})/\partial T_c = 0 \tag{17}$$

Besides, from Constraints 15 and 16 it is known that the tamping interval must not be larger than T_{ul}, which is determined by

$$T_{\text{ul}} = \min\left\{B_l/(n+1), Q_{n+1}{}^{-1}(L_{\text{acpt}})\right\} \tag{18}$$

The following algorithm is presented here to search for the optimal T_c^* or n^*.

Step B1. Starting from $n = 0$, calculate T_c from Equation 17 by using bisection method according to the procedure from Steps A1 to A7;

Step B2. Test whether T_c satisfies Constraints 15 and 16 or not; if yes, go to Step B3 to continue; if not, set $T_c = T_{\text{ul}}$.

Step B3. Calculate cost function $C(n,\mathbf{T})$ and $\Delta C(n,\mathbf{T})$.

Step B4. If $\Delta C(n,\mathbf{T})$ doesn't satisfy Condition 12, set $n = n + 1$ and go to Step B1.

Step B5. Otherwise, stop the search and get the optimal T_c^* and n^*.

Policy 3. Optimal Nonconstant Intervals of Tamping

In this policy, tamping intervals are not necessarily set to be constant like Policy 2, or are determined by the fixed intervention level as Policy 1. In other words, all the intervals of tamping $T_1, T_2, \ldots, T_{n+1}$ are the decision variables, and their sum gives the service life to renewal. The problem here is to determine the tamping intervals to minimize the ballast LCC. Thus, the optimal Policy 3 is determined by the following:

$$\text{minimize}\, C(n,\mathbf{T}) \tag{19}$$

subject to

$$Q(T_i) \le L_{\text{acpt}} \quad \text{for } i = 1,2,\ldots,n+1 \tag{20}$$

and

$$\sum_{i=1}^{n+1} T_i \le B_l \tag{21}$$

Obviously, Policy 3 represents a general case for M&R of ballast, and Policy 1 and Policy 2 can be thought of as the special cases of this policy. Therefore, the optimal solution of policy should be the best one among the three policies subject to practical constraints.

Once the optimal tamping intervals $T_1^*, T_2^*, \ldots, T_n^*, T_{n+1}^*$ are obtained, the tamping can then be scheduled. The employment of the policy is similar to the policy of constant interval, which is planned according to tonnage, whereas for Policy 1, tamping is triggered by TQI. But the problem of optimization is more complex for Policy 3 than for the other two policies, because many more variables need to be determined. To search for the solutions, an iterative algorithm is designed as follows.

Algorithm C

Similar to the analysis in Algorithm B, the necessary condition of the optimal interval of tamping is

$$\partial C(n,\mathbf{T})/\partial T_i = 0 \quad \text{for } i = 1,2,\ldots,n+1 \tag{22}$$

In this algorithm, the optimal intervals of tamping will be determined sequentially from $i = 1$ to $n + 1$. For the ith tamping interval, the optimal tamping interval is searched for by using Equation 22 with the other intervals of tamping fixed. After sequential searches for optimal tamping intervals, the original intervals may have changed. Given this scenario, it follows that the solution, T_i, may no longer be optimal. Hence, an iterative process has to be employed to obtain an optimal solution to the problem. The following algorithm is presented here to optimize the ballast tamping and renewal for Policy 3.

Step C1. Start iteration from $k = 1$ and let $n = 0$.

Step C2. Initialize the solution by setting $T_i = B_l/(n + 1)$, for $i = 1, 2, \ldots, n + 1$.

Step C3. Start from $i = 1$ until $i = n + 1$ to find sequentially T_i from Equation 22 by using the bisection method according to the procedure from Steps A1 to A7.

Step C4. Compute cost function $c_k = C(n,\mathbf{T})$ for the kth iteration from Equation 7.

Step C5. If the cost function tends to be stable, that is $|(c_k - c_{k-1})/c_k| < 10^{-4}$, go to Step C6; otherwise, set $k = k + 1$ and go to Step C3 to continue the iteration.

Step C6. If Condition 12 is satisfied, stop the procedure; otherwise, set $n = n + 1$ and go to Step C2.

These three algorithms have been programmed using Visual Fortran 6.6. Experience has shown that when executing the program on a personal P3 computer, searching for the solutions of Policy 1 and Policy 2 takes only a few seconds, and that of Policy 3 takes about 5 to 8 minutes for its iterative calculation.

AN EXAMPLE

An example is given here to illustrate the performance of the model and algorithms. In this example, a high-speed passenger train line with ballasted and concrete sleeper track is considered. A focus is given on the vertical geometry in the analysis of track quality. The deterioration data are based mainly on Riessberger's study (*13*) and tamping data come from the earlier asset management work at Birmingham University (*14*). The deterioration rate (α_i) increases linearly from 0.09 to 0.14 mm/MGT for ballast from new to a specific service life of 200 MGT. For the other parameters in the deterioration model, their respective values are $q_a = 0.3$ mm, $\theta_i = 2.86$, and restoration ratio $\beta = 0.92$. Ballast renewal costs as much as \$318,600 (£180,000 with an exchange rate of 1.77) per mile (mile is still used instead of SI unit on the Railway Network in the United Kingdom) and the price of tamping per mile is \$7,080 (£4,000). The coefficient of penalty cost per mile track $c_p =$ \$2,660 (£1,500) for track quality being 1 mm over the specific penalty level. The initial penalty level $L_p = 2.4$ mm, and the maximum acceptable level of TQI, $L_{acpt} = 5.0$ mm.

Using the Fortran program based on the LCC model of ballast and the algorithms, the optimal solutions for the three policies can be obtained. The results are summarized in Table 1. The table shows that from an economic point of view, the ranking of the policies is Policy 3, Policy 1, and then Policy 2. The minimal LCC*p* of Policy 3 is 10% lower than that of Policy 2. It is interesting that the optimal service lives to renewal for the three policies are quite close to each other (156 to 160 MGT) and so are the numbers of tamping activities in a life cycle (13 to 14 activities).

Figure 1 shows the results of the optimization of ballast T&R under Policy 1. The curve represents the minimum LCC*p* at different intervention levels. In this example, the optimal intervention level is about 3.0 mm with LCC*p* being \$2,920. When tamping intervention level is set at a value lower than the optimal one, the cost is higher because tamping is performed more frequently from the very beginning. For a higher threshold, life-cycle cost is also higher than the optimal one simply because the poorer ride quality causes penalty cost to rise.

Minimum life-cycle costs at different service lives to renewal for the three policies are given in Table 2. In general, Policy 3 produces the most economic solution for every service life to renewal among the three policies. For service life from 80 to 200 MGT, the LCC*p* of Policy 1 is lower than that of Policy 2. For each policy, when the service life to renewal is less than the optimal one, the LCC*p* is decreasing with additional traffic load, and especially when it is less than 120 MGT, the LCC*p* decreases more rapidly. Conversely, the LCC*p* is increasing in traffic load when the service life to renewal is beyond the optimal one. It can also be seen from Table 2 that if renewal is conducted at the specific service life of 200 MGT, then ballast LCC*p* for three policies will be 14%, 9.2%, and 8.2% higher than that of the corresponding optimal ones, respectively. This represents the benefit of the renewal decision based on ballast economic life.

Table 3 gives tamping intervals of optimal solution for each policy. It can be seen that initial intervals of tamping for Policy 1 are largest among the three policies. However, the interval reduces rapidly with increasing numbers of tamping activities, and after six cycles of tamping, the intervals become the smallest. Tamping under Policy 1 must be employed more and more frequently to keep TQI within a certain level because the efficiency of tamping is decreasing. Basically, the tamping intervals of Policy 3 go between those of Policy 1 and Policy 2. Furthermore, a comparison of Policy 1 and Policy 3 suggests that at the initial stage of ballast life, earlier tamping intervention could be more cost-effective for intervention level policy. This could explain why some railway networks employ preventive tamping at an earlier stage of ballast life.

For a better understanding of the properties of the three policies, consider eight options based on the three policies and make a comparison between them. The options include:

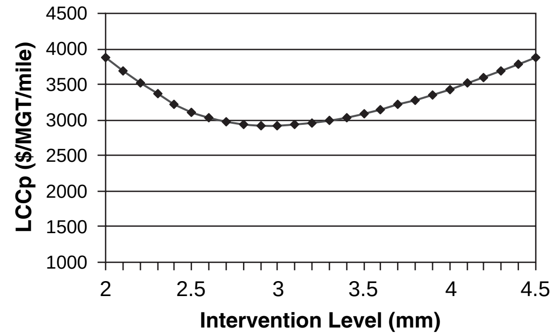

FIGURE 1 Minimum LCC*p* versus intervention level.

TABLE 1 Summary of Optimal Solutions for Three Policies

Policy	Minimal LCC*p* (\$)	Optimal Ballast Service Life to Renewal (MGT)	Optimal Number of Tamping Activities in a Life Cycle
1	2920	156	13
2	3160	154	13
3	2870	160	14

TABLE 2 Minimal LCC*p* Versus Service Life to Renewal

	Minimal LCC*p* (\$/MGT/mi)		
Service Life to Renewal (MGT)	Policy 1 (Fixed Intervention Level)	Policy 2 (Constant Intervals)	Policy 3 (Optimal Intervals)
80	4340	4410	4340
90	3940	4030	3940
100	3630	3750	3630
110	3390	3530	3380
120	3210	3380	3190
130	3070	3260	3060
140	2980	3200	2960
150	2940	3160	2890
160	2940	3160	2870
170	2990	3200	2890
180	3060	3260	2940
190	3170	3340	3010
200	3330	3450	3110

TABLE 3 Tamping Intervals for Each Policy

Sequential Number of Tamping Interval	Tamping Intervals (MGT) Policy 1 (Fixed Intervention Level) (3.0 mm)	Policy 2 (Constant Intervals)	Policy 3 (Optimal Intervals)
1	30.0	11.0	24.9
2	22.2	11.0	19.2
3	17.7	11.0	14.9
4	14.7	11.0	13.3
5	12.4	11.0	12.0
6	10.6	11.0	10.8
7	9.2	11.0	9.8
8	8.0	11.0	8.9
9	7.0	11.0	8.1
10	6.1	11.0	7.3
11	5.4	11.0	6.6
12	4.7	11.0	5.9
13	4.2	11.0	6.1
14	3.6	11.0	6.1
15	N/A	N/A	6.1

N/A = not applicable

Option 1a. Optimal intervention level (3.0 mm) and optimal service life to renewal (156 MGT), which corresponds to Policy 1;

Option 1b. Specific intervention level (3.3 mm) and optimal service life to renewal (156 MGT). The option corresponds to Policy 1 and the specific intervention level is set at 10% higher than the optimal intervention level for the policy;

Option 1c. Optimal intervention level (3.0 mm) and specific service life to renewal (172 MGT). The option also corresponds to Policy 1 and the specific life to renewal is set at 10% longer than the average optimal life to renewal of these three policies;

Option 2a. Optimal period of tamping (11 MGT) and optimal service life to renewal (154 MGT), which is based on Policy 2;

Option 2b. Specific period of tamping (12.1 MGT) and optimal service life to renewal (154 MGT). The specific period for tamping is set at 10% over the optimal one for the Policy 2;

Option 2c. Optimal period of tamping (11 MGT) and specific service life to renewal (172 MGT). It is based on Policy 2 and the specific life to renewal is set at the same value as Option 1c for a comparison;

Option 3a. Optimal intervals for tamping, which are not necessarily constant, and optimal life to renewal (160 MGT). It is based on the Policy 3; and

Option 3b. Optimal intervals for tamping and specific life to renewal (172 MGT). The option is based on Policy 3 and the specific service life to renewal is set the same as Options 1c and 2c.

Figure 2 shows the LCC*p* for each option. It can be seen that the difference of LCC*p* between the best option (Option 3a) and worst one (Option 2c) is 11.9%. Also, by comparing Option 1a and Option 1b, LCC*p* rises only 2.7% when intervention level increases by 10%. However, LCC*p* of Option 1a is 4.7% higher than that of Option 1c with 10% addition of service life. It indicates that there is more effect on LCC*p* with increasing service life to renewal than intervention level for Policy 1. Similar conclusions are obtained for Policy 2 that service life to renewal has more effect on LCC*p* than period of tamping. But, there is not much difference between Option 3a and Option 3b. This can be seen more clearly from Table 2. For example, when service life to renewal increases 25% from 160 MGT to 200 MGT, minimal LCC*p* for Policy 3 rises only 4.8%. This indicates that for Policy 3, LCC*p* has low sensitivity to service life. This characteristic implies that under Policy 3, a plan of ballast renewal can be flexibly combined with rail or sleeper renewal by making some adjustment of its service life.

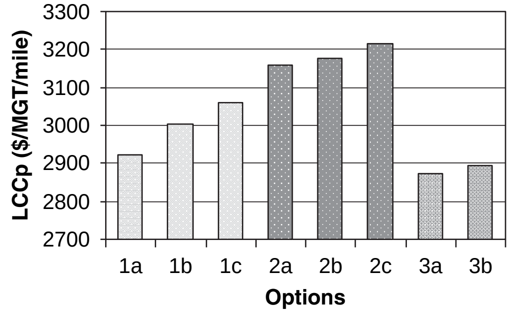

FIGURE 2 Comparison of LCC*p* among different options.

CONCLUSIONS

This paper reports the development of a life-cycle cost model of ballast with incorporating a track deterioration model and a tamping model. Based on the models, three policies of ballast T&R are considered and optimized by minimizing life-cycle cost per traffic load. Three corresponding algorithms are presented to obtain the optimal service life to renewal. Finally, an example is given to show the performance of the model. It indicates that considerable benefit could be achieved by optimizing policies of ballast T&R. In comparison, the policy of optimal nonconstant interval is the best one for its lowest LCC*p*. In addition, an important aspect of this approach is that the tamping plan is optimized together with ballast renewal using an economic analysis, and the economic life of ballast could be determined for renewal decision. In this sense, the benefit could be seen from a comparison of the renewal plan based on economic criteria with that based on ballast performance.

Although this paper only considers ballast tamping among ballast maintenance activities, the proposed methodology could be used to analyze the policies involving stone blowing or ballast cleaning, if their impacts on track quality are known for a specific railway network. In addition, the remedial work is considered to maintain the ride quality limit. However, for the maintenance regime to maintain the safety limit, risk cost will be involved in the life-cycle cost and a relationship between the risk cost and the level of track quality should be established to enable a policy analysis. Further study is needed to address these issues.

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