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Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 2014 228: 496 originally published online 25 March 2013
DOI: 10.1177/0954409713482239

Original Article

Institution of MECHANICAL ENGINEERS

Journal of RAIL AND RAPID TRANSIT

Proc IMechE Part F:
J Rail and Rapid Transit
2014, Vol. 228(5) 496–503

DOI: 10.1177/0954409713482239
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Evaluation of track geometry maintenance for a heavy haul railroad in Sweden: A case study

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Abstract
The measurement and improvement of track quality are key issues in determining both the restoration time and cost of railway maintenance. Applying the optimal tamping strategy helps reduce maintenance costs, making operations more cost-effective and leading to increased safety and passenger comfort. In this paper, track geometry data from the iron ore line (Malmbanan) in northern Sweden, which handles both passenger and freight trains, are used to evaluate track geometry maintenance in a cold climate. The paper describes Trafikverket's (Swedish Transport Administration) tamping strategy and evaluates its effectiveness in measuring, reporting and improving track quality. Finally, it evaluates the performance of the maintenance contractor and discusses the importance of the functional requirements stated in the outsourcing contracts.

Keywords
Maintenance, railway track geometry, tamping

Date received: 30 November 2011; accepted: 18 February 2013

Introduction

Today's railway industry handles an increasing number of trains that travel at higher speeds and have higher axle loads; this combination of circumstances can result in faster degradation of railway assets and higher maintenance costs. To ensure track safety and maintain high quality standards, an optimized and cost-effective track maintenance strategy is required that is based on technical and/or safety limits that meet cost-effective maintenance thresholds.

Track geometry maintenance (tamping) is a maintenance action used to compact ballast and correct track geometry faults such as incorrect alignment (lateral deviation) or incorrect longitudinal level (vertical deviation). The parameter that usually drives the need for tamping is the short wavelength longitudinal level.[1] In Sweden, the annual cost of tamping is about 100–120 MSEK (approximately 11–13.5M€), and the total amount of tamped track is around 1700 km, about 14% of the total track length.[2]

Empirical models of track geometry degradation to create a better understanding of the degradation have been reported in the literature.[3–5] Several studies have been performed on ballast degradation due to cyclic loads[6–8] and the effects of variables such as speed and axle load on track deterioration have also been investigated.[9–11] However, it has been claimed that current standards and assessment methods may not be adequate for track maintenance, since they do not consider dynamic responses at the wheel–rail interface.[12,13]

In this paper, the Swedish Transport Administration's (Trafikverket) strategy for tamping is described, its efficiency evaluated and the quality and accuracy of data discussed. However, this study does not analyse the ballast degradation and its effect on track geometry degradation; it only considers the longitudinal level due to its significant effect on track quality. To this end, track geometry data from a section of the iron ore line (Malmbanan) between Boden and Gällivare in northern Sweden are considered. It has been found that time utilization in tamping is not very effective[2] with only about 25% of the available time being used for maintenance execution. The main reason for this low efficiency is the limited amount of

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access time to the track. Thus, there is a need to optimize the track geometry maintenance strategy. In particular, an estimation of track degradation and its consequences is required to optimize track maintenance.[14] With this knowledge, the right time for inspection, maintenance and renewal can be estimated.

Background information about the case study

The iron ore line runs from Narvik to Riksgränsen (Ofotenban) in Norway and from Riksgränsen to Boden in Sweden (Malmbanan). The Swedish mining company LKAB transports iron ore from its mine in Kiruna to Narvik and from its mine in Vitåfors, near Malmberget, to Luleå. In 2000, LKAB increased the axle load on the Malmbanan line from 25 to 30 t and the maximum speed of the loaded train from 50 to 60 km/h. This change is expected to result in higher track geometry degradation levels. In addition to iron ore transportation, the line is used by passenger trains and other freight trains. The train speeds vary from 50 to 60 km/h for loaded iron ore trains, 60–70 km/h for unloaded ones and 80–135 km/h for passenger trains.

The annual passing tonnage on the track is about 13.8 MGT. The track consists of UIC 60 rails and concrete sleepers. The ballast type is M1 (crushed granite), and the track gauge is 1435 mm. The region is subject to harsh climate conditions: snow and extreme temperatures, ranging from −40°C in winter to +25°C in summer.[15]

Track quality monitoring and maintenance

To monitor track quality, Trafikverket regularly (every 1 to 2 months between April and October) uses an inspection car to measure the deviation of the track using both an inertia measurement system and an optical system. An accelerometer measures the acceleration of the vehicle; based on the recorded accelerations, the vertical and lateral deviation of the track is calculated for consecutive 25 cm intervals.

Based on these 25 cm interval measurements, the standard deviation, σ_S, of the monitored cant error (C) and the average monitored lateral position error of the high rail (S_{High}) (see Figure 1 and equation 1) are calculated for 200 m sections. The standard deviation of the average monitored vertical error for the left and right rail, σ_H, is also calculated for 200 m sections

$$\sigma_S = \sigma_C + \sigma_{SHigh} \quad (1)$$

Trafikverket uses several condition indices to describe the condition of the track, the most important of which are the Q-value and K-value. These are calculated based on the standard deviation of the vertical and lateral displacements, σ_H and σ_S, and the comfort limits that define the acceptable standard deviation of the longitudinal level for 200 m track sections (see Table 1). The Q-value indicates the quality of the track geometry and is calculated by the following formula

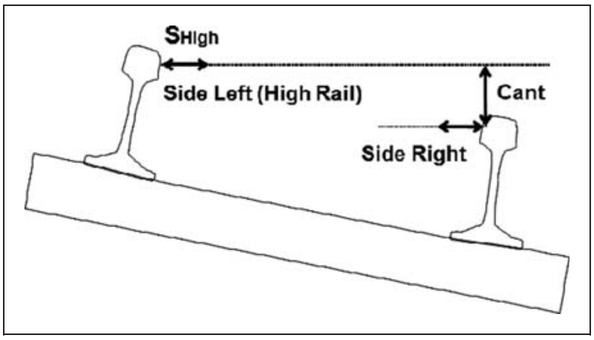

Figure 1. Calculation of σ_S.

$$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{Hlim}} + 2\frac{\sigma_S}{\sigma_{Slim}}\right] \Big/ 3 \quad (2)$$

where σ_{Slim} is the comfort limit for the σ_S value, defined for different track classes (see Table 1) and σ_{Hlim} is the comfort limit for the σ_H value, defined for different track classes (see Table 1).

The other index, the K-value, is the ratio between ($\sum l$), the total length of the track with standard deviations below the comfort limits, and the total length of track (L). This index is used to obtain an overall picture of the track condition over a long distance and is calculated by the equation (3)

$$K = \frac{\sum l}{L} \times 100\% \quad (3)$$

In addition to the Q-value and the K-value, two fault limits are defined for 25 cm track sections, B-faults and C-faults. C-faults identify the limits for the execution of corrective maintenance (Intervention limits) (see Figure 2) whereas B-faults identify the limits for the execution of preventive maintenance (Alert limits).[16] However, in interviews carried out with the line contractor revealed that, in reality, B-limits are not always used by the contractor as a criterion for preventive maintenance execution. Although these limits are defined for a point failure (25 cm), the fault normally occurs over a length of at least 1 to 5 m due to rail stiffness.

The track of the iron ore line consists of alternating sections with quality classes K2 and K3.[16] Each of these quality classes has a different allowable speed, dissimilar fault thresholds and comfort limits for local trains (see Table 1).

Trafikverket outsources the tamping of each line to different contractors, mostly using performance contracts. In this type of outsourcing, it is up to contractors to select appropriate methods and plan the

Table 1. Comparison of the allowable limits between K2 and K3.

		Comfort limits		B-fault limits	C-fault limits
Quality class	Maximum allowable speed for local trains (km/h)	σ_{Hlimit} Standard deviation of vertical position (mm)	$\sigma_{S\ limit}$ Sum of standard deviations of cant and lateral positions (mm)	Maintenance limit for vertical deviation for 25 cm interval (1–25 m wavelength) (mm)	Intervention limit for 25 cm interval (1-25 m wavelength) (mm)
K2	105–120	1.5	1.9	7	12
K3	75–100	1.9	2.4	10	16

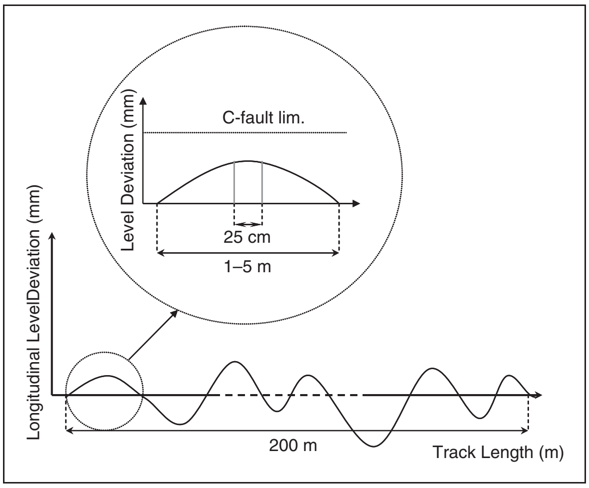

Figure 2. Illustration of C-fault limits.

necessary work. They are responsible for both regular measurements of track geometry and tamping, and they base their execution of tamping on the calculated *Q*-values and C-fault limits.

Tamping is executed as either preventive maintenance or corrective maintenance. Execution of tamping as a result of a C-fault is considered corrective maintenance; tamping based on the *Q*-value is considered preventive maintenance. This means that if the *Q*-value of the track section falls below the contractual limit and/or there is deviation in the track greater than the C-fault limits (intervention limits), tamping should be performed. Tamping is obligatory (i.e. required by regulation) if the C-fault value exceeds the C-fault limit.

In the performance contracts, two limits are specified for the *Q*-value, a goal limit and a contractual limit. If the actual *Q*-value of the track is higher than the goal limit, contractors receive a bonus, wheras if it is below the contractual limit, they must pay a penalty.

The main phases of Trafikverket's maintenance strategy are shown in Figure 3. The figure shows how the maintenance decision criteria are used to specify the need for preventive or corrective tamping execution.

Data collection and data treatment

The main steps of the approach, applied in this study (Figure 4), were as follows.

1. Data collection: Inspection and maintenance data were collected for a certain time period.
2. Data processing: The extracted data were processed through consultations with experts. This step was carried out to assess the data quality and to account for missing data.
3. Apply UIC ride comfort limits graph[1]: This graph was used to define an intervention limit based on the maximum allowable speed on the track. This defined limit was applied as a benchmark to evaluate tamping execution at different tamping intervals.
4. Apply UIC tamping intervention graph[1]: The tamping intervention graph, developed by Austrian Railways, was used to evaluate the maintenance efficiency.

Track section 118, between Boden and Gällivare, was selected for the case study. To ensure comparable data, only tangent segments of 200 m from quality class K2 were considered and other parts of the track, such as curves and stations, were ignored.

As the first step, the tamping and inspection data for the selected track for the period 2007–2009 was extracted from two Trafikverket databases, BIS (track information system) and Optram. BIS contains information on Trafikverket's infrastructure and facilities, agreements, the history of tamping (such as location

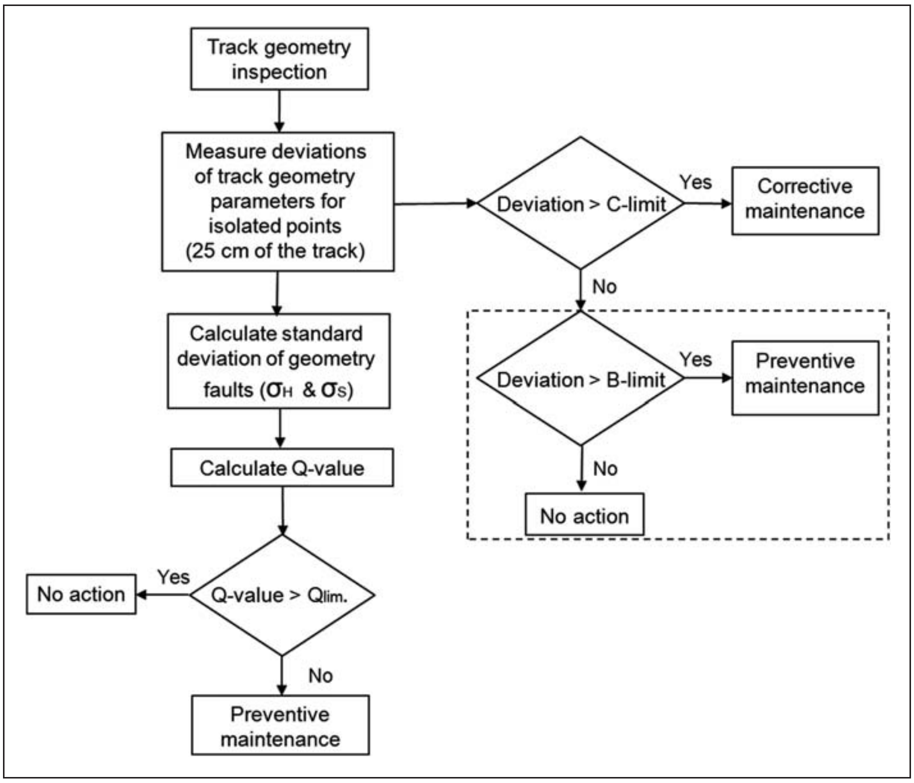

Figure 3. The steps of Trafikverket's maintenance strategy.

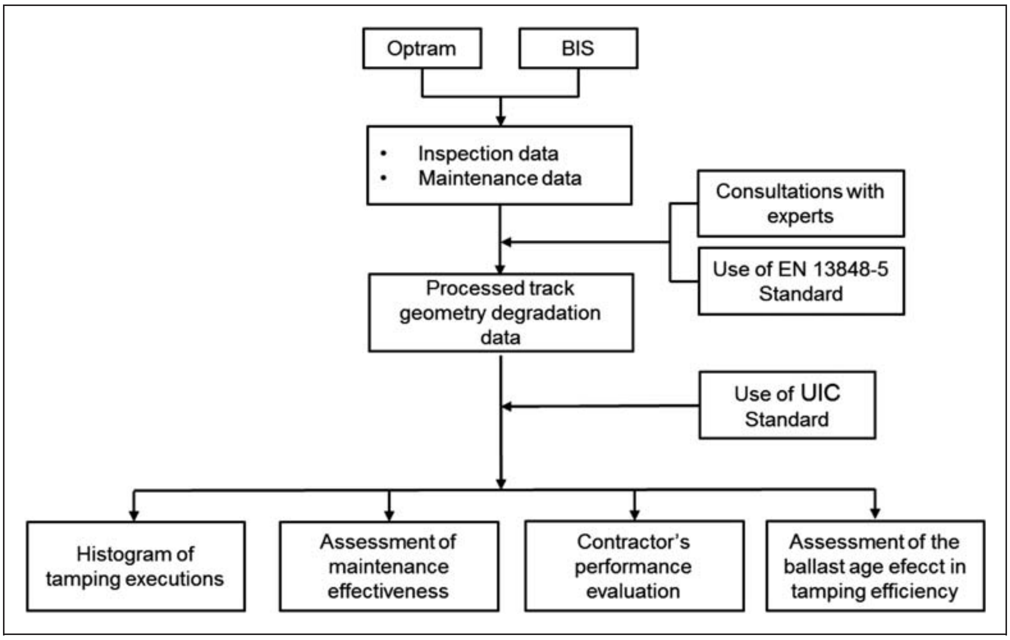

Figure 4. The approach used in this study.

of tamped section, length of tamping, date, etc.) and grinding and curves.[17] Optram is a system implemented in 2009 by Trafikverket to visualize and show graphically the results of time series for track geometry measurements. The system provides functionality for analysis and displays data trends.[18] To gain access to all information on tamping, it is essential to consider both systems.[2]

In BIS, tamping information can be inaccurate, since corrective tamping is not always reported to the system by the contractors because it is not a requirement.[2] Optram, which is based on inspection

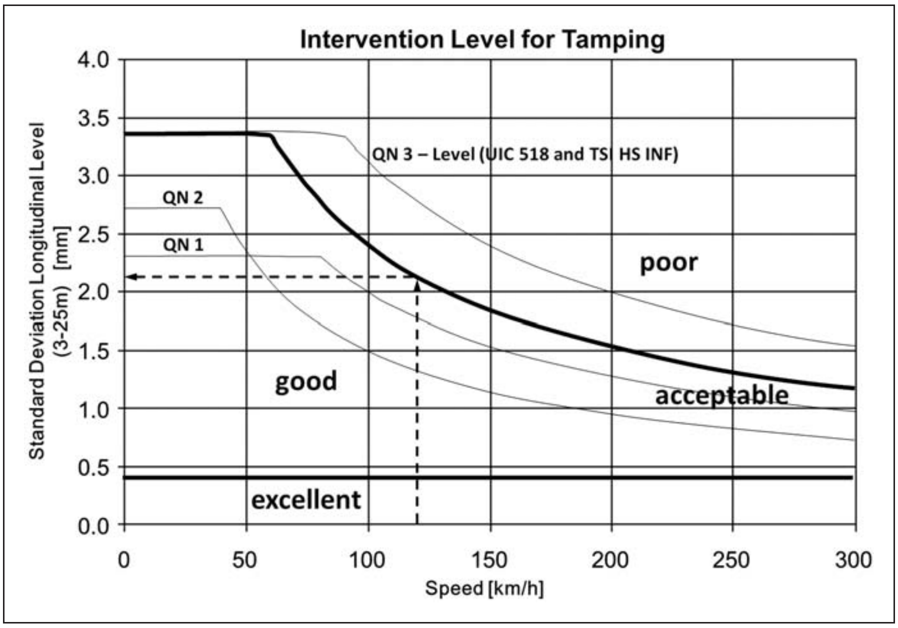

Figure 5. Lines of constant riding comfort at different speeds.[1]

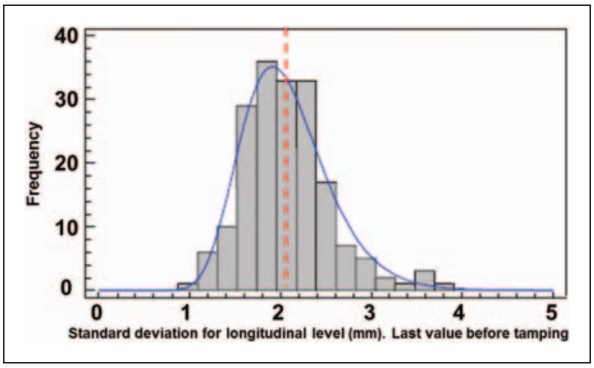

Figure 6. Histogram of tamping execution at different level intervals.

data, is more reliable; however, data in this system is only available from 2007.

The collected data has been reviewed and discussed with experts to assess its quality. The European railway standard EN 13848-5 was also considered to compare and evaluate current maintenance limits in Sweden with the suggested intervention limits in the European standard.[19] The comparison revealed that the recommended intervention limits in the standards have higher values than the maintenance limits in Sweden.

A tamping intervention graph was used To evaluate the performed tamping efficiency.[1] Here, the tamping efficiency is classified as bad, good or excellent based on how much the track quality has been improved after the tamping operation. In the original graph, the maximum value before tamping is 3 mm, and since some of the data in this case study have values larger than 3 mm, the graph was extended using trend regression analysis (this will be clearly demonstrated in Figure 7).

When the longitudinal level value goes beyond the intervention limit (IL), corrective maintenance should be performed. The IL can be defined either for isolated defects or for a 200 m track segment. Trafikverket only defines an IL for isolated defects. When the studied data belong to 200 m track segments, the UIC ride comfort limits graph ('Lines of constant riding comfort at different speeds') was used to specify the IL for the longitudinal level of 200 m track segments (Figure 5). When the maximum allowable speed of quality class K2 (120 km/h) is considered, the IL is equal to 2.1 mm. By considering the maximum speed, the IL value becomes more conservative. In this way, all possible failures in the allowable speed range are considered.

Furthermore, the effect of ballast age on tamping efficiency and the performance of the maintenance contractor were evaluated. To assess the contractors' performances the qualities of track geometry from 2004 to 2010 on a case study line and a reference line in central Sweden were collected.

Results

To provide an overview of the tamping frequency, a histogram of the standard deviations of the longitudinal level before tamping is plotted in Figure 6. The dashed line represent the IL limit defined by UIC for a poor ride comfort at 120 km/h, the maximum allowable speed in the track quality class K2. As shown in the figure, the majority of tamping was executed around the defined intervention limit (2.1 mm) which is classified as a poor track condition in the UIC document. However, a substantial amount of tamping

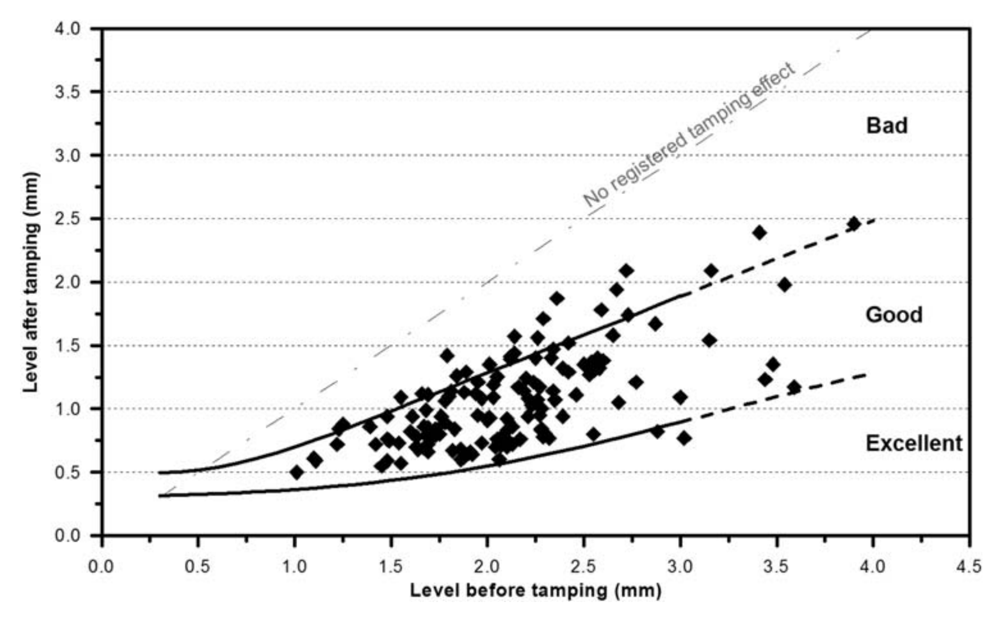

Figure 7. Efficiency of tamping.

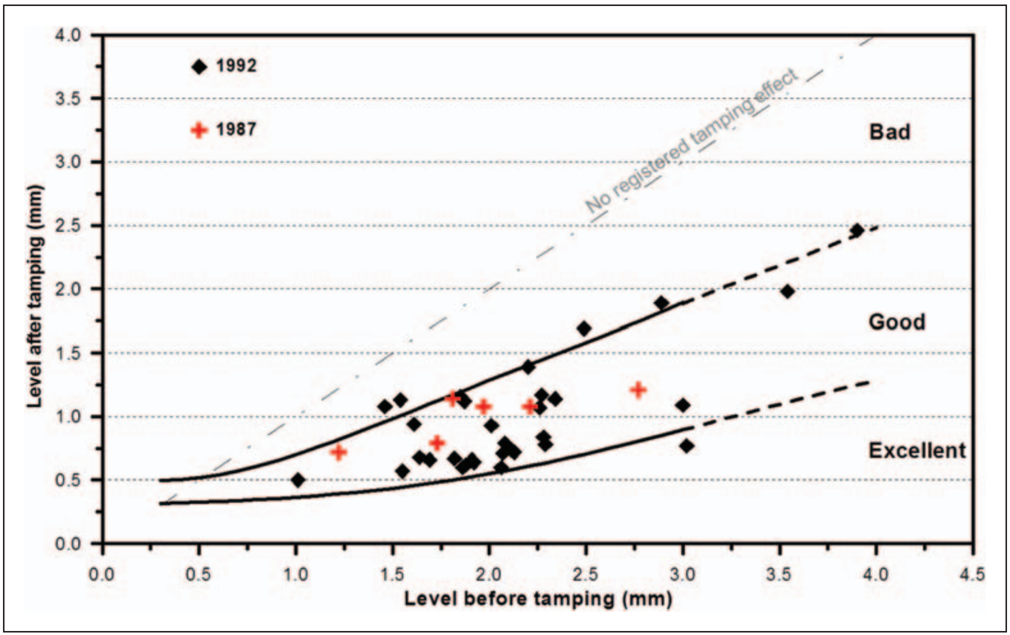

Figure 8. Comparison of ballast age in tamping efficiency.

is done at a much higher value than is expected from a ride comfort point of view.

To evaluate tamping efficiency and to understand the reduction of longitudinal level deviations caused by maintenance, all tamping points were plotted in a UIC 'Tamping Intervention' graph, see Figure 7. This evaluation shows that the tamping efficiency in the majority of the segments falls into the categories of either good or bad. However, a number of points are close to no registered tamping effect.

To explore the reasons for the high variability in tamping efficiency, the effects of a number of factors were assessed. The speed and axle load are the same for all track segments. To assess the effect of ballast age on tamping efficiency, all sections were divided into groups based on the ballast age. Then the tamping efficiency of each group was evaluated by plotting its data in the tamping intervention graph, no clear effect of ballast age could be observed. A comparison of tamping efficiency between the ballast ages of 1987 and 1992 in class 2 appears in Figure 8.

Figure 9 evaluates the contractor performance from 2004 to 2010 on a case study line (Figure 9(a)) and a reference line in central Sweden (Figure 9(b)).

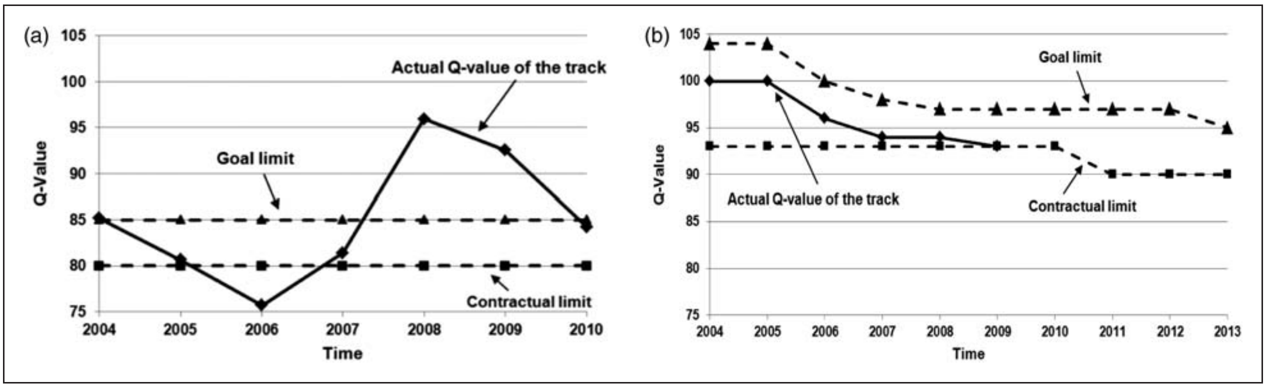

Figure 9. Evaluation of the contractor's performance (a) on the case study line and (b) on a reference line in central Sweden.

It should be noted that the contractor is the same for both lines, but the contracts are different.

Discussion

The case study was designed to analyse the efficiency of track geometry maintenance by Trafikverket. While data were available from 2007 to 2009, for more precise evaluations, data for a longer period are required. Moreover, data should be reliable and accurate, and in this case, the contractor of the line had not reported all corrective tamping. To compensate for this, graphical inspection data and expert judgment was used.

The standard deviation for the longitudinal level at which tamping is executed varies extensively during the period examined (see Figure 6). Tamping is sometimes executed at a very low level and is, therefore, not motivated by ride comfort. On other occasions, tamping has been performed at levels exceeding the ride comfort limit; on still other occasions, tamping has not been executed until almost double the level of the ride comfort limit for the standard deviation of the longitudinal level is reached. Although, tamping is not performed simply because of longitudinal level faults, this large variation indicates that its execution is not optimally planned.

Performing maintenance after the IL has been reached can result in lower maintenance efficiency. This means that the initial quality of the track cannot be obtained by normal tamping execution and instead, more than one tamping operation will be needed to achieve the initial geometry quality. However, on the other hand, performing maintenance more frequently will cause a higher deterioration rate.[1] Hence, to reduce maintenance cost and increase its efficiency, tamping should be performed before the track quality passes the IL.

The evaluation of tamping efficiency (Figure 7) reveals that the efficiency is quite low in some segments. Possibly, only parts of the segment are tamped, not the entire section, but to confirm this, more comprehensive information about maintenance history is required. Alternatively, these particular segments could have bad substructure conditions. It should also be noted that the assessment of tamping efficiency is based on results reported by Austrian Railways which, in turn, are based on different substructure conditions and a dissimilar maintenance strategy.

Tamping is carried out based on the Q-index value and C-fault. Execution of tamping with no reliability and life cycle cost (LCC) analysis can be one possible reason for the lack of tamping efficiency. Reliability and LCC analysis can help to specify cost-effective maintenance limits, a main criterion for identifying optimal maintenance and inspection intervals. Assessment of the probability of failure occurrence over time can also help optimize maintenance planning and reduce maintenance cost.

The comparison of a contractor's performance on two different lines (see Figure 9) shows different maintenance policies. With the defined contractual and goal limits, the size of the associated penalties and bonuses will encourage the contractor either to be as close as possible to the lower contractual limit or to maintain a level above the goal limit. To interpret this, different factors such as maintenance budget, functional requirements stated in the contract, amount of bonus and penalties mentioned in the contract, technical issues and maintenance decision criteria should be considered.

Conclusions

The following conclusions can be drawn from the reported study.

1. Available and accurate data on geometry conditions and performed maintenance actions are the main requirements for track degradation analysis. However, the data available for this study are inadequate for precise analysis.
2. The decision-making process for the execution of tamping does not use all defined limits for geometry parameters.
3. Evaluation of the standard deviation for the longitudinal level at which tamping is executed

indicates that the execution of tamping is not optimally planned.

4. Execution of tamping is highly dependent on the condition data and there is no well-structured track degradation analysis that helps to plan for maintenance in the long term.
5. The structure of the contract, such as the maintenance budget, the defined goals and contractual limits, the size of the associated penalties and bonuses, can have a major effect on the efficiency of maintenance strategy.

Funding

This research received financial support from Trafikverket and the Luleå Railway Research Center (JVTC).

Acknowledgements

The authors wish to thank Trafikverket and the Luleå Railway Research Center for the technical support they provided during this project.

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