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The Effects of Different Types of Tamping Operations on the Degradation of Railway Track Geometry

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Abstract

Throughout the accumulation of transported loads, the railway track accumulates geometric defects that can negatively impact its mechanical behavior, reducing the useful life of its components. These geometric defects can become more pronounced after construction, ballast cleaning, or total renewal. In such scenarios, efficient tamping is crucial to prevent the accelerated appearance of geometric defects. Some studies have demonstrated increased track stability with multiple insertions of tamping tines, when compared to single insertion, in such track conditions. However, the impact on geometric quality and its degradation rate still requires assessment. The present study evaluates the impact of applying tamping of single or multiple insertions on the track geometric quality and its degradation rate. For this, sections of the Carajás Railway had their geometric parameters monitored immediately after the renewal process until an accumulation of 195.8 million gross tons. Geometric degradation was modeled using linear, exponential, and logarithmic regressions on the geometric dataset. Among these, logarithmic regression demonstrated the best fit. Multiple insertion demonstrated a lower rate of geometric degradation, despite presenting lower initial geometric qualities. Future investigations will evaluate if this phenomenon is directly attributable to the tamping type or to characteristics associated with the experimental section.

Keywords: railway track, heavy haul line, maintenance, monitoring, tamping operation, geometric degradation.

1 Introduction

Over the accumulation of transported loads, the railway track experiences geometric defects that can negatively impact its mechanical behavior, reducing the service life of its components and, ultimately, potentially leading to derailment risks [1,2]. Therefore, the track geometry should be measured periodically, in order to serve as a tool for maintenance management, and an indicator of sections where interventions are necessary, seeking quality and safety in transportation [3].

The parameters used as a reference for monitoring the geometric quality of the track include the gauge, superelevation, twist, vertical and transversal alignments [4]. Among these, vertical alignment is considered the most crucial and is widely used as a reference for maintenance management [2,5]. The gauge is the smallest distance between two rails, usually measured 16 mm below the running surface. On the other hand, superelevation is the height difference between the rails. Twist is determined as the rate of change of superelevation, measured at two cross-sections spaced 10 m apart. Additionally, vertical alignment is the length of a vertical arrow, measured at the center of a 20 m chord. Finally, transversal alignment is the length of a transverse arrow, measured at the center of a 20 m chord.

As geometric quality index, direct standard deviations (STD) of geometric parameters can be employed, a practice utilized in Europe, Asia, Middle Eastern countries, and recommended by the European Railway Research Center [3,6–8]. For instance, a high STD would indicate poor geometric quality of the track, potentially claiming maintenance intervention, depending on established thresholds [1,9,10]. To properly model the geometric degradation that occurs with the accumulation of transported loads, linear, exponential, and logarithmic regression models have been widely used in the literature [5,11]. In these regressions, STD is used as the dependent variable and load accumulation as the independent variable. Linear regression is the most suitable for describing and predicting the behavior of track quality, presenting the best fit compared to exponential and logarithmic models. Logarithmic functions are more suitable for behavior immediately after renewal or tamping, but have the disadvantage of underestimating the final quality [11].

The most currently employed maintenance practice for correcting the geometric defects is the alignment, leveling, and tamping operation. In this process, the superstructure (rail, sleeper, and fastenings) is lifted to correct the pre-existing geometric defects, and subsequently, tamping tines are inserted, closing beneath the sleepers to squeeze and compact the ballast layer. This is done to fill the void created between the ballast surface and the base of the concrete sleeper, forming a rigid column that will support the railway superstructure in the desired position [12].

The effectiveness of tamping maintenance depends, among other factors, on the frequency and amplitude of vibration of the tamping tines, the amount of track lifting, the duration of ballast squeezing by the tamping tines, and the number of times they are inserted into the ballast layer. In terms of vibration, tamping activities can occur at 35 Hz or 42 Hz, while different vibration amplitudes range from 4 mm to 10 mm [13–21]. These two parameters are not typically easy to modify, as they depend on the characteristics of each type of tamping machine, unlike the remaining parameters.

The amount of track lifting depends on the magnitude of the geometric defect or the type of maintenance activity. For instance, larger geometric defects may require greater lifts to enable their correction. Similarly, in the construction or maintenance activities involving ballast cleaning or total renewal, higher lifts are required, as these activities involve the launching or complete replacement of the ballast layer. In general, higher amounts of lifting result in lower lateral resistances, vertical stiffness, and compactness of the ballast layer [14,22]. For these reasons, Shi et al. [14] and Xiao et al. [22] recommend a maximum lifting value between 20 and 30 mm.

The squeezing time is usually determined by railway operators and the performance of the tamping machine, with the operator setting it on the machine during maintenance [19]. The ballast condition can also influence the squeezing time. For example, a more clogged ballast may exhibit higher stiffness, requiring an extended duration for the correct insertion and closing movement of the tines within the ballast layer. Without sufficient time, the tines may exit the ballast layer without completing the service adequately. In contrast, a new (loose) ballast offers less resistance for the movement of the tines, requiring a shorter squeezing time. For these reasons, different squeezing times are found in the literature, ranging from 0.6 s to 1.8 s [13–16,19,21–23].

Regarding the number of insertions of the tamping tines, the single insertion is typically employed in corrective maintenance. Nevertheless, in exceptional circumstances, such as areas requiring increased track lifting or in locations with special characteristics, like regions with soil of low bearing capacity, turnouts, etc., two or three insertions may be applied [24]. Recent studies have investigated the use of double insertions for application after railway construction, ballast cleaning or total renewal. These procedures lead to a ballast layer that is significantly non-densified, increasing its susceptibility to settlement [25]. Therefore, the increased number of insertions aims to ensure a more compacted ballast layer, enhancing track stability and preventing the rapid development of new defects and the risk of accidents.

Xiao et al. [22] evaluated the use of double insertion, aiming its application in newly constructed railways. When compared to the single insertion, multiple insertion achieved increases of 65% to 57% in lateral resistance, meaning that the track remained more stable against lateral movements. On the other hand, Pereira et al. [21] conducted tests on the Carajas Railway (Brazil), which is a "heavy haul" line (32.5 ton/axle, 80 km/h). It was observed that double insertion resulted in a greater densification of the ballast layer compared to single insertion. In this regard, the application of multiple insertion can also lead to a more stable ballast layer against deformations.

Despite the importance of alignment, leveling, and tamping operations for correcting geometric defects, these activities can also contribute to the degradation of the ballast layer due to particle breakage during insertion and movement of tamping tines, leading to an increase in the geometric degradation rate [9,17]. Furthermore, this type of maintenance has a certain impact on track productivity because, in addition to requiring a certain amount of time to carry out the service itself, there may be reductions in the operational speed of trains after reopening to traffic. In this sense, optimizing tamping efficiency is crucial to prevent the accelerated emergence of geometric defects, thereby minimizing the need for additional maintenance cycles. This is especially important after construction, ballast cleaning, or total renewal of the railway, where the track is more susceptible to accumulating such defects. The research by Xiao et al. [22] and Pereira et al. [21] highlights enhanced track stability through double insertions. However, further assessment is necessary to understand how this tamping method affects geometric quality and its degradation rate, during the accumulation of transported loads, critical parameters for the operation and maintenance management.

In this context, the objective of this study is to assess the impact of applying single or multiple (double) insertions of tamping tines on the geometric quality and degradation rate of the railway track. The assessment was conducted in the context of a newly constructed railway or one that has undergone ballast cleaning or complete renewal. To achieve this, two sections (single and multiple insertions) of the Carajas Railway were selected, and their geometric parameters were monitored immediately after the renewal process until reaching an accumulation of 195.8 million gross tons (MGT), corresponding to fourteen months of track operation. To characterize the geometric degradation, in both single and multiple insertion sections, regression analyses including linear, exponential, and logarithmic models were conducted on the geometric dataset.

2 Methods

The two selected sections for this study were straight, had a length of 50 meters, and are located on Line 1 of the Carajas Railway, a significant railway in Brazil (Figure 1). This railway utilizes wagons with a capacity of 32.5-ton/axle and, in 2022, transported a total of 174 million tons of cargo, with 99% of it being iron ore [26]. Regarding its characteristics, this railway is composed of RE 136 rails, a wide gauge of 1.6 m, monoblock concrete sleepers, elastic fastenings, a ballast layer with a thickness of 30 cm, and a subballast layer with a design thickness of 30 cm.

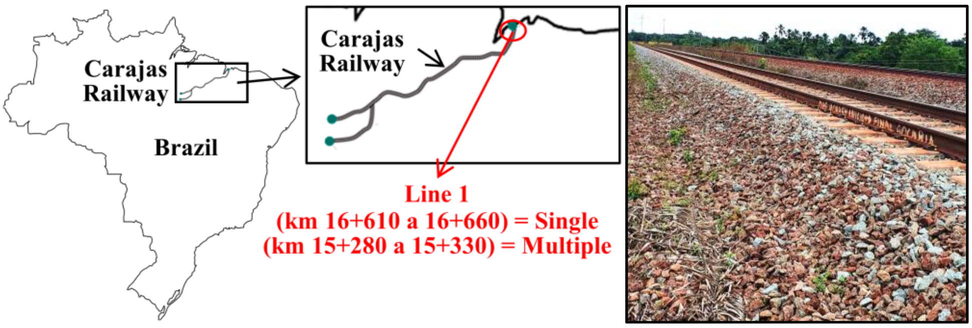


Figure 1: Location of experimental sections

During the renewal of Line 1, the replacement of rails, sleepers, fastenings, and ballast cleaning was carried out. After the completion of these steps, alignment, levelling, and tamping operations were performed, according to the parameters presented in Table 1. In the ballast cleaning stage, only a fraction of the material was reintroduced to the track. This was necessary because, over the service life of the layer, degradation occurs, leading to the generation of fine material (< 25 mm). The removal of the fine material is essential to ensure that the layer conforms to the specified design particle size distribution. For this reason, after the ballast cleaning, only a residual layer of 15 cm remained. To achieve the final thickness of 30 cm for the ballast layer, it was necessary to replace with new ballast and apply three track liftings (~ 100 mm, 40 mm, and 20 mm), each followed by a tamping process involving a single or multiple insertions.

Types of insertion	Squeezing time (s)	Frequency (Hz)	Amplitude (mm)	Track liftings (mm)
Single	1.0	35	5	≈ 100, 40 and 20
Multiple	0.8			
	0.8			

Table 1: Tamping parameters evaluated in this research

In the alignment, levelling, and tamping operations, the machine model Dynamic Stopfexpress 09-3X was utilized (Figure 2a). For measuring track geometry, the Track Recording Car (TRC) model EM100 was employed (Figure 2b). This vehicle measures all geometric parameters of the track at 0.25 m intervals, while maintaining operational speed, and is widely adopted for continuous assessment of geometric quality in railway networks [14,27,28].


(a) (b)

Figure 2: (a) Tamping machine model Dynamic Stopfexpress 09-3X, and (b) Track Recording Car model EM100

The geometric parameters evaluated in this study include vertical alignment (20 m), superelevation, and twist (10 m). Gauge and transversal alignment parameters were not taken into consideration due to the minimal impact that the tamping operation has on these parameters [10]. In the case of vertical alignment (20 m), the average value of both rails was used, a common practice in the literature. Additionally, the superelevation parameter was considered, even with the sections being a tangent (straight) track, defining any value different from zero as a geometric defect, as straight sections are designed to have no superelevation.

The geometric monitoring began after the completion of the track renewal and extended until the accumulation of 195.8 MGT, corresponding to a 14-month period of track operation. The evaluation period covered both the dry season (July to December) and the rainy season (January to June), which are characteristic of the region [29] (Figure 3). Finally, when 45.7 MGT were accumulated, a corrective tamping of single insertion was performed on both sections, which is commonly employed on the Carajas Railway for this type of maintenance strategy.

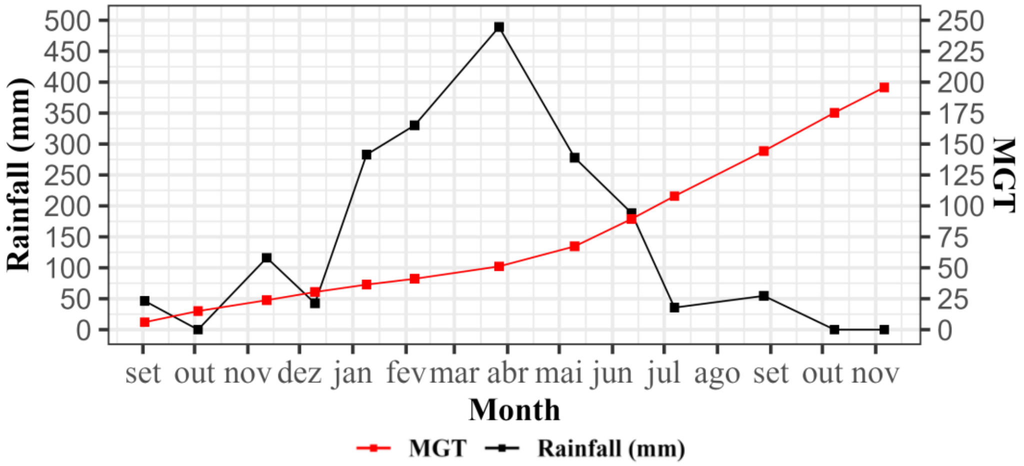


Figure 3: Monthly rainfall and accumulation of MGT versus geometric measurement dates by the TRC (Monthly rainfall data from [30])

When employing geometric measurements using a TRC, there is a risk of synchronization errors occurring between measurements taken at different times. These errors can be attributed to the possibility of the TRC wheels sliding along the rail surface, as these wheels play a key role in spatializing each measurement point along the railway [31]. To address this issue, an algorithm was implemented that utilizes the Euclidean Distance Function to correct synchronization, following the approach used by Fellinger [31] and Marschnig et al. [32].

The correction algorithm utilized the initial run of the TRC as a reference for subsequent runs, employing only the vertical alignment (20 m) as a benchmark for other geometric parameters. Subsequently, the positions of all successive runs were adjusted by 50 m (every 0.25 m) in both forward and backward directions along the track. These adjusted positions were then compared to the reference run using Equation 1:

$$ED_{M_R|M_n} = \sqrt{\sum_{i=1}^{L}\left(y_{i|M_R} - y_{i|M_n}\right)^2}, \qquad (1)$$

where $ED_{M_R|M_n}$ is the Euclidean Distance between the reference measurement and the measurement "n", L is the length of the section to be synchronized, $y_{i|M_R}$ is the geometric parameter of the reference measurement, and $y_{i|M_n}$ is the geometric parameter of measurement "n". The correct synchronization position was determined by the one that resulted in the smallest Euclidean Distance value. For instance, Figure 4 illustrates a time-series of TRC runs for the vertical alignment (20 m) both before and after the implementation of the synchronization algorithm.

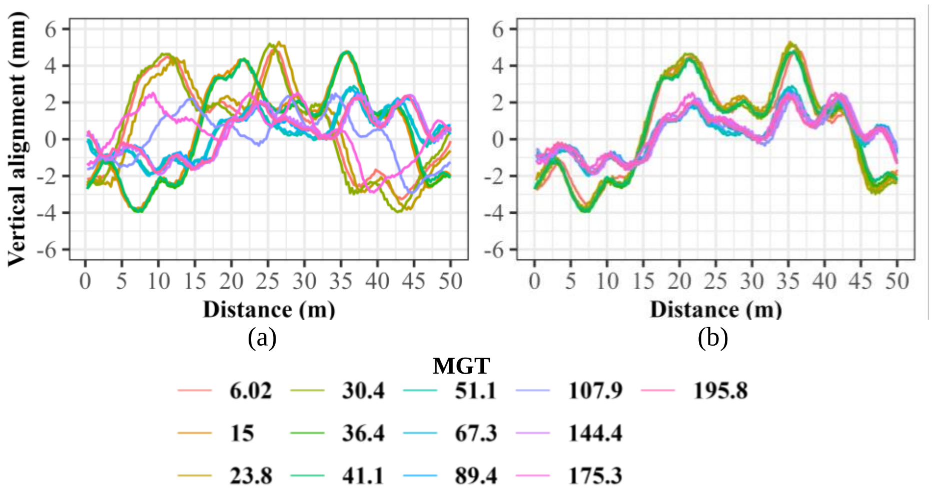


Figure 4: Example of different TRC runs, over the accumulation of MGT, for vertical alignment (20 m): (a) original data and (b) synchronized data after the algorithm implementation

To quantify the impact of the different tamping types on the geometric quality and degradation rate of a railway track, it was decided to use the direct standard deviation (STD) of the geometric parameters as quality indexes, as they are the most widely adopted parameters [1–3,5–10,33]. The experimental sections have 50 m in length; therefore, the window length for calculating the STD was smaller than the typically preferred lengths for this purpose, such as 100 m or 200 m [4,5,34]. Linear (Equation 2), exponential (Equation 3), and logarithmic (Equation 4) regression models were chosen to fit the geometric degradation of the track, as these models have been widely used in the literature for accurately modeling track degradation [5,11]. Finally, to assess the performance of each regression model, the Root Mean Squared Error (RMSE) was calculated, where a lower value signifies a better fit of the data for a given regression model (Equation 5).

$$Q_{(MGT)} = Q_i + a \cdot MGT \,, \tag{2}$$

$$Q_{(MGT)} = Q_i \cdot e^{a \cdot MGT} \,, \tag{3}$$

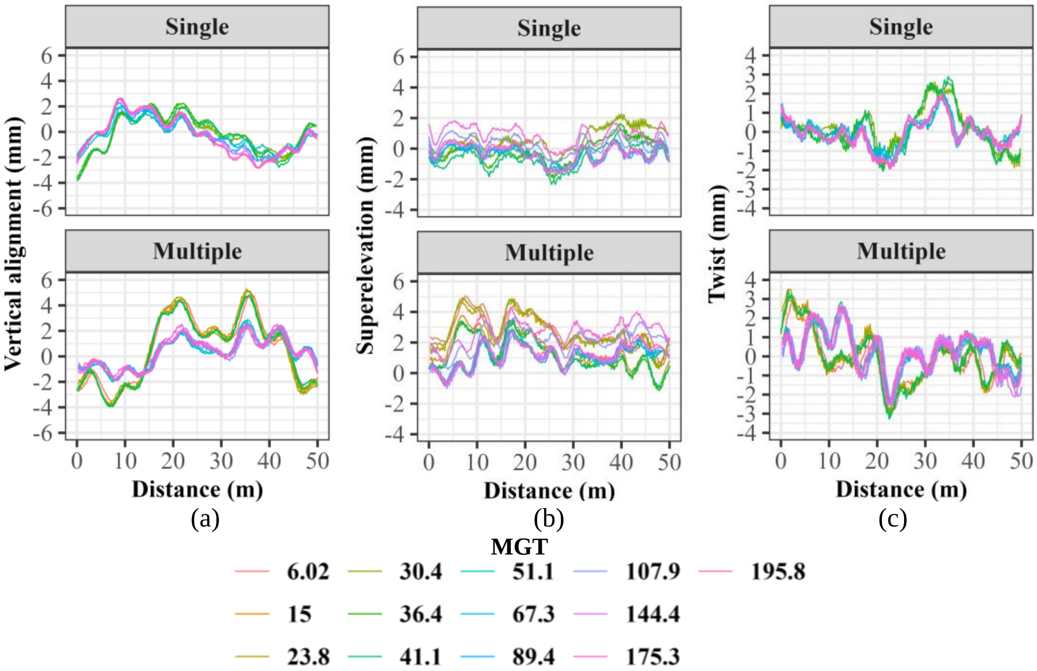
$$Q_{(MGT)} = Q_i + a \cdot \log\left(MGT\right), \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - p_i\right)^2} \,, \tag{5}$$

where $Q_{(MGT)}$ is the predicted geometric quality (STD) of a given geometric parameter of the track at a specific MGT, Q_i is the initial quality (STD) of a given geometric parameter of the track, and a is the geometric degradation rate, n is the number of samples, y_i is the observed value for sample i, and p_i is the value predicted by the model for the degradation associated with the sample i.

3 Results

The geometric parameters of vertical alignment (20 m), superelevation, and twist (10 m) of the experimental sections are presented in Figure 5. As previously discussed, during the data synchronization adjustment, the vertical alignment parameter (20 m) was employed as the reference for all other parameters. Consequently, a more pronounced synchronization of data is evident in this parameter, with only a few residual minor synchronization errors observed in other parameters. However, these discrepancies are notably less significant compared to the scenario without any correction.



(a) (b) (c)

Figure 5: Geometric parameters of the experimental section along the accumulation of MGT.

Figure 6 presents the STDs of the vertical alignment (20 m), superelevation, and twist (10 m) versus the accumulation of MGT, accompanied by the prediction model of geometric degradation using logarithmic regression (as example). Before the corrective tamping (< 45.7 MGT), in the case of a single insertion, there were only three geometric measurements of the track. In this regard, the use of degradation prediction for all models is prejudicated due to the limited number of measurement points.

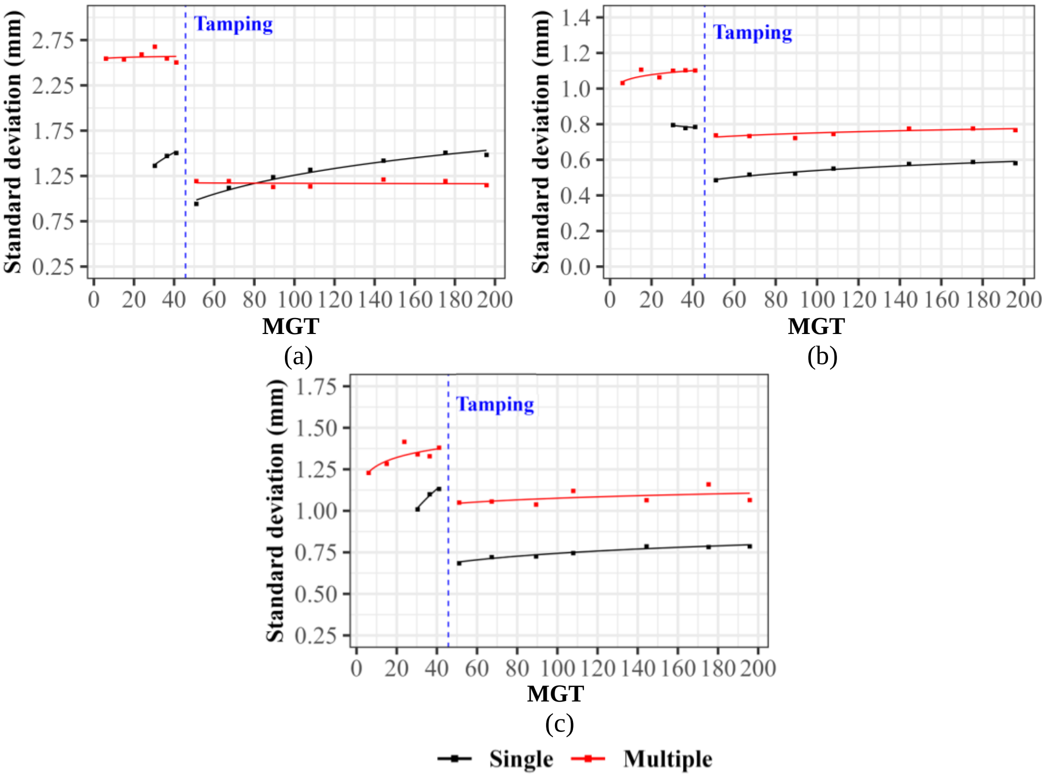


Figure 6: STD of (a) vertical alignment (20 m), (b) superelevation, and (c) twist (10 m) versus accumulation of MGT and logarithmic regression model for fitting geometric degradation.

The equations of linear, exponential, and logarithmic fitting models of the vertical alignment (20 m), superelevation and twist (10 m) are presented in Table 2. The logarithmic model was considered to have the best fit to the geometric data, as it demonstrated either a similar or lower RMSE, in most cases, when compared to the other models (linear and exponential). This behavior was expected, as logarithmic functions are suitable for track conditions similar to those in this study (after renewal or tamping) [11]. Before the corrective tamping (< 45.7 MGT), in certain instances, negative values were recorded for the initial quality of the tamping using single insertion. These values were excluded from the analyses, as they could have been influenced by the smaller dataset, and it is not possible for the initial quality to have a negative value. In a similar manner, there were instances where geometric degradation rates exhibited negative values. In such cases, it was inferred that the section did not experience degradation during the evaluation period, as it is implausible that an improvement in geometric quality would occur with the accumulation of MGT. A greater dataset could reveal potential geometric degradation that may develop over prolonged monitoring periods.

Condition	Tamping	Regression model	Vertical alignment (20 m)		Superelevation		Twist (10 m)	
			Equation	RMSE	Equation	RMSE	Equation	RMSE
Before tamping correction	Single	Linear	$Q_{(MGT)} = 0.96 + 1.35 \cdot 10^{-2}\,MGT$	0.014	$Q_{(MGT)} = 0.83 - 1.09 \cdot 10^{-3}\,MGT$	0.005	$Q_{(MGT)} = 0.66 + 1.17 \cdot 10^{-2}\,MGT$	0.010
	Multiple		$Q_{(MGT)} = 2.57 + 2.54 \cdot 10^{-5}\,MGT$	0.056	$Q_{(MGT)} = 1.04 + 1.59 \cdot 10^{-3}\,MGT$	0.020	$Q_{(MGT)} = 1.24 + 3.58 \cdot 10^{-3}\,MGT$	0.043
	Single	Exponential	$Q_{(MGT)} = 1.03 \cdot e^{9.41 \cdot 10^{-3}\,MGT}$	0.015	$Q_{(MGT)} = 0.83 \cdot e^{-1.38 \cdot 10^{-3}\,MGT}$	0.005	$Q_{(MGT)} = 0.73 \cdot e^{1.09 \cdot 10^{-2}\,MGT}$	0.011
	Multiple		$Q_{(MGT)} = 2.57 \cdot e^{6.14 \cdot 10^{-7}\,MGT}$	0.056	$Q_{(MGT)} = 1.04 \cdot e^{1.49 \cdot 10^{-3}\,MGT}$	0.020	$Q_{(MGT)} = 1.24 \cdot e^{2.76 \cdot 10^{-3}\,MGT}$	0.044
	Single	Logarithmic	$Q_{(MGT)} = -0.27 + 1.11 \cdot \log(MGT)$	0.011	$Q_{(MGT)} = 0.93 - 9.26 \cdot 10^{-2} \cdot \log(MGT)$	0.005	$Q_{(MGT)} = -0.40 + 9.56 \cdot 10^{-1} \cdot \log(MGT)$	0.008
	Multiple		$Q_{(MGT)} = 2.53 + 2.43 \cdot 10^{-2} \cdot \log(MGT)$	0.055	$Q_{(MGT)} = 0.98 + 7.53 \cdot 10^{-2} \cdot \log(MGT)$	0.018	$Q_{(MGT)} = 1.10 + 1.70 \cdot 10^{-1} \cdot \log(MGT)$	0.037
After tamping correction	Single	Linear	$Q_{(MGT)} = 1.03 + 3.56 \cdot 10^{-3}\,MGT$	0.062	$Q_{(MGT)} = 0.50 + 6.72 \cdot 10^{-4}\,MGT$	0.011	$Q_{(MGT)} = 0.70 + 6.78 \cdot 10^{-4}\,MGT$	0.012
	Multiple		$Q_{(MGT)} = 1.17 - 2.55 \cdot 10^{-5}\,MGT$	0.031	$Q_{(MGT)} = 0.73 + 3.32 \cdot 10^{-4}\,MGT$	0.011	$Q_{(MGT)} = 1.05 + 3.89 \cdot 10^{-4}\,MGT$	0.036
	Single	Exponential	$Q_{(MGT)} = 1.04 \cdot e^{2.87 \cdot 10^{-3}\,MGT}$	0.073	$Q_{(MGT)} = 0.50 \cdot e^{1.24 \cdot 10^{-3}\,MGT}$	0.012	$Q_{(MGT)} = 0.70 \cdot e^{9.14 \cdot 10^{-4}\,MGT}$	0.013
	Multiple		$Q_{(MGT)} = 1.17 \cdot e^{-2.14 \cdot 10^{-5}\,MGT}$	0.031	$Q_{(MGT)} = 0.72 \cdot e^{4.41 \cdot 10^{-4}\,MGT}$	0.011	$Q_{(MGT)} = 1.05 \cdot e^{3.55 \cdot 10^{-4}\,MGT}$	0.036
	Single	Logarithmic	$Q_{(MGT)} = 0.94 + 9.39 \cdot 10^{-1} \cdot \log(MGT)$	0.031	$Q_{(MGT)} = 0.48 + 1.75 \cdot 10^{-1} \cdot \log(MGT)$	0.007	$Q_{(MGT)} = 0.68 + 1.77 \cdot 10^{-1} \cdot \log(MGT)$	0.009
	Multiple		$Q_{(MGT)} = 1.17 - 1.56 \cdot 10^{-2} \cdot \log(MGT)$	0.031	$Q_{(MGT)} = 0.72 + 8.07 \cdot 10^{-2} \cdot \log(MGT)$	0.012	$Q_{(MGT)} = 1.04 + 1.03 \cdot 10^{-1} \cdot \log(MGT)$	0.035

Table 2: Equations of regressions considering the linear, exponential, and logarithmic models for fitting geometric degradation.

When examining the conditions before the corrective tamping (< 45.7 MGT), it was observed that the single insertion presented higher initial geometric qualities, indicated by lower STDs. On the other hand, the multiple insertion demonstrated a lower rate of geometric degradation in the parameters of vertical alignment (20 m) and twist (10 m). The corrective tamping (45.7 MT) was effective in reducing pre-existing STDs, thus improving the geometric quality of the track. However, it did not sufficiently correct the track geometry so that both sections reached the same initial geometric quality after this maintenance procedure.

After corrective tamping (> 45.7 MGT), the effect of multiple insertion became even more evident, demonstrating a lower rate of geometric degradation in all geometric parameters, especially in the vertical alignment (20 m), where practically no geometric degradation occurred during the evaluated period. The superior efficiency of multiple tamping, even after the application of corrective tamping, may be attributed to the creation of a more densely compacted column from the deeper layers of the ballast, given the application of three track liftings (100 mm, 60 mm, and 20 mm). Consequently, the corrective tamping might not have disturbed the ballast sufficiently to cause significant geometric quality losses, as its action primarily targeted the superficial layers (15 mm below the sleeper).

The results of this research corroborate the findings of Xiao et al. [22] and Pereira et al. [21], who observed enhanced track stability through multiple insertion. In this sense, the increased track stability, resulting from multiple insertion, contributed to a reduced rate of degradation during the accumulation of transported loads. Future studies should investigate the factors that may have contributed to the lower initial geometric qualities observed after the track renewal, using multiple insertion. For instance, such investigations will aim to determine whether this phenomenon is directly attributable to the type of tamping or to characteristics unique to the experimental section in question.

4 Conclusions and Contributions

This study evaluated the impact of applying single or multiple insertions of tamping tines on the geometric quality and degradation rate of a railway track. To achieve this, two sections (single and multiple insertions) of the Carajas Railway were selected, and their geometric parameters were monitored immediately after the renewal process until reaching an accumulation of 195.8 million gross tons (MGT), corresponding to 14 months of track operation. To characterize the geometric degradation in both sections, regression analyses including linear, exponential, and logarithmic models were conducted on the geometric dataset. The main results are as follows.

- The logarithmic regression had the best fit to the geometric data, as it demonstrated either a similar or lower RMSE, in most cases, when compared to the other models (linear and exponential). This behavior is consistent with other studies found in the literature, which have also suggested that this type of function is well-suited for track conditions after renewal or tamping [11].
- The multiple insertion demonstrating a lower rate of geometric degradation in all geometric parameters, especially in the vertical alignment (20 m). These

results corroborate the findings of Xiao et al. [22] and Pereira et al. [21], who observed enhanced track stability through multiple insertion. In this sense, this tamping type also contributed to the improved geometric quality.

- The multiple insertion presented lower initial geometric qualities, indicated by greater STDs. Future investigations will evaluate the factors that may have contributed to this behavior, seeking to determine whether this phenomenon is directly attributable to the tamping type or to unique characteristics of the experimental section in question.

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References

[1] E.T. Selig, J.M. Waters, “Track Geotechnology and Substructure Management”, Thomas Telford Services Ltd., London, 1994.
[2] J.J. Pires, “Integrated Maintenance Model for Heavy Haul Tracks”, Federal Polytechnic School of Lausanne, 2015.
[3] J. Sadeghi, H. Heydari, E.A. Doloei, “Improvement of railway maintenance approach by developing a new railway condition index”, Journal of Transportation Engineering, 143, 2017.
[4] AREMA (American Railway Engineering and Maintenance-of-Way), “Manual for Railway Engineering”, Lanham, Maryland (USA), 2020.
[5] I. Soleimanmeigouni, A. Ahmadi, U. Kumar, “Track geometry degradation and maintenance modelling: A review”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232, 73–102, 2018.
[6] J. Sadeghi, “Development of railway track geometry indexes based on statistical distribution of geometry data”, Journal of Transportation Engineering, 136, 693–700, 2010.
[7] A.R.B. Berawi, R. Delgado, R. Calçada, C. Vale, “Evaluating track geometrical quality through different methodologies”, International Journal of Technology, 1, 38–47, 2010.
[8] C. Higgins, X. Liu, “Modeling of track geometry degradation and decisions on safety and maintenance: A literature review and possible future research directions”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232, 1385–1397, 2018.
[9] M. Audley, J.D. Andrews, “The effects of tamping on railway track geometry degradation”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 376–391, 2013.
[10] I. Soleimanmeigouni, A. Ahmadi, I.A. Khouy, C. Letot, “Evaluation of the effect of tamping on the track geometry condition: A case study”, Proceedings

of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232, 408–420, 2018.

[11] J. Neuhold, I. Vidovic, S. Marschnig, “Preparing Track Geometry Data for Automated Maintenance Planning”, Journal of Transportation Engineering, Part A: Systems, 146, 1–11, 2020.

[12] O. Barbir, D. Adam, F. Kopf, J. Pistrol, F. Auer, B. Antony, “Semi-analytical approach to ballast bed modelling during compaction”, in “Proceedings of the 27th European Young Geotechnical Engineers Conference", Mugla, 2019.

[13] J. Liu, P. Wang, G. Liu, J. Xiao, H. Liu, T. Gao, “Influence of a tamping operation on the vibrational characteristics and resistance-evolution law of a ballast bed”, Construction and Building Materials, 239, 2020.

[14] S. Shi, L. Gao, X. Cai, H. Yin, X. Wang, “Effect of tamping operation on mechanical qualities of ballast bed based on DEM-MBD coupling method”, Computers and Geotechnics, 124, 2020.

[15] D.S. Kim, S.H. Hwang, A. Kono, T. Matsushima, “Evaluation of ballast compactness during the tamping process by using an image-based 3D discrete element method”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232, 1951–1964, 2018.

[16] S. Shi, L. Gao, H. Xiao, Y. Xu, H. Yin, “Research on ballast breakage under tamping operation based on DEM–MBD coupling approach”, Construction and Building Materials, 272, 2021.

[17] B. Aursudkij, “A laboratory study of railway ballast behaviour under traffic loading and tamping maintenance”, University of Nottingham, 2010.

[18] Z. Zhang, H. Xiao, Y. Zhu, T. Gan, M.M. Nadakatti, Hufei, “Macro–meso mechanical properties of ballast bed during three-sleeper tamping operation”, International Journal of Rail Transportation, 11, 886–911, 2023.

[19] C. Paderno, “Comportement du ballast sous l’action du bourrage et du trafic ferroviaire”, Federal Polytechnic School of Lausanne, 2010.

[20] J. Fischer, “Einfluss von Frequenz und Amplitude auf die Stabilisierung von Oberbauschotter”, Technical University Graz, 1983.

[21] P. Pereira, S. Tumelero, A. Gay, R. Motta, L. Bernucci, E. Moura, R. Silva, L. Oliveira, I. Melo, “Experimental and numerical evaluation of the ballast densification under different types of tamping operation”, in “Proceedings of the Fifth International Conference on Railway Technology: Research, Development and Maintenance”, Montpellier, 2023.

[22] H. Xiao, Z. Zhang, Y. Zhu, T. Gan, H. Wang, “Experimental analysis of ballast bed state in newly constructed railways after tamping and stabilizing operation”, Construction and Building Materials, 362, 2023.

[23] G. Saussine, E. Azéma, P.E. Gautier, R. Peyroux, F. Radjaï, “Numerical modeling of the tamping operation by Discrete Element Approach”, in “Proceedings of the World Congress on Railway Research”, 2008.

[24] Y. Guo, V. Markine, G. Jing, “Review of ballast track tamping: Mechanism, challenges and solutions”, Construction and Building Materials, 300, 2021.

[25] B. Indraratna, D. Ionescu, H.D. Christie, “Shear behavior of railway ballast based on large-scale triaxial tests”, Journal of Geotechnical and Geoenvironmental Engineering, 124, 439–449, 1998.

[26] ANTT (Agência Nacional de Transportes Terrestres), “Anuário do setor ferroviário”, 2023.

[27] A.L.O. Melo, S. Kaewunruen, M. Papaelias, L.L.B. Bernucci, R. Motta, “Methods to Monitor and Evaluate the Deterioration of Track and Its Components in a Railway In-Service: A Systemic Review”, Frontiers in Built Environment, 6, 1–15, 2020.

[28] J.C.O. Nielsen, E.G. Berggren, A. Hammar, F. Jansson, R. Bolmsvik, “Degradation of railway track geometry – Correlation between track stiffness gradient and differential settlement”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 234, 108–119, 2020.

[29] W.N. Trindade, L.C.C. Pereira, D.O. Guimarães, I.R. Silva, M.R. Costa, “The effects of sewage discharge on the water quality of the beaches of São Luís (Maranhão, Brazil)”, Journal of Coastal Research, 1425–1429, 2011.

[30] CEMADEN (Centro Nacional de Monitoramento e Alertas de Desastres Naturais), “Mapa interativo da Rede Observacional para Monitoramentode Risco de Desastres Naturais do CEMADEN”, 2024.

[31] M. Fellinger, “Sustainable Asset Management for Turnouts”, Graz University of Technology, 2020.

[32] S. Marschnig, G. Neuper, F. Hansmann, M. Fellinger, J. Neuhold, “Long Term Effects of Reduced Track Tamping Works”, Applied Sciences (Switzerland), 12, 1–12, 2022.

[33] L.M. Quiroga, E. Schnieder, “Monte Carlo simulation of railway track geometry deterioration and restoration”, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 226, 274–282, 2012.

[34] M. Khosravi, I. Soleimanmeigouni, A. Ahmadi, A. Nissen, “Reducing the positional errors of railway track geometry measurements using alignment methods: A comparative case study”, Measurement: Journal of the International Measurement Confederation, 178, 2021.