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Light rail ballasted track geometry quality evaluation using track recording car data

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Abstract

A deep understanding of the track quality degradation process is essential for an efficient and safe operation of Light Rail Train (LRT) systems. Its understanding allows infrastructure managers to determine maintenance strategies that account for RAMS (reliability, accessibility, maintainability and safety) and to pursue the extension of the service life of an asset in a cost efficient manner; thus lowering its Life Cycle Cost (LCC). For LRT systems, this is important to remain competitive in the urban transportation sector. However, the methods to determine the TQ of LRT systems are limited or inappropriate. To determine appropriate values and standards the issue deserves more attention. To establish a clear guide for the determination of the LRT track quality (TQ) and its deterioration process, this paper first seeks to set a clear definition of track quality as well as determines the most important parameters involved. Central to this study; however, is to first establish the use of available data obtained from a Track Recording Car (TRC). This is done for two tangent ballasted tracks of about 2 km located in a Southern German city. An important part of the study is the treatment of the data to determine the geometry quality of the track and its deterioration. In this paper track geometry deviation and irregularities are determined statistically using the Track Geometry Index (TGI) and DIN EN 13848-5, which set intervention limits. Once the TGI and irregularities are established, the track deterioration rate is calculated and compared for the two tracks. The comparison serves as the basis to determine the stage of deterioration of each track and effectiveness of interventions. The deterioration rate and intervention limits are important aspects for the determination of predictive maintenance interventions that allow for the optimization of the LCC of assets.
Keywords: track quality, track recording car, track data treatment, track deterioration rate, track degradation, maintenance intervention limits.

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1 Introduction

Track quality plays a key role in the safe and efficient operation and maintenance of railway systems; including LRT systems. The operation and maintenance phase of an LRT system represents around 60% of the LCC; hence, offering a potential to drive the LCC of an asset down across its service life (VDV [1]). However, track quality (TQ) needs to be studied for the specific system analyzed since the subject under study, the track, has different priorities and characteristics for different systems (Liu *et al.* [2]) e.g. LRT vs. freight train.

A step towards understanding TQ is to clearly understand the meaning of quality, which should include limits of intervention to maintain or restore it. In order to maintain uniformity and standardization, the limits need to be in accordance with current widely used norms (e.g. DIN norms). Today, it is widely accepted that TQ is measured by the deviation of the track geometry parameters from their designed values in accordance to limits that account for passenger comfort and operation safety (Liu *et al.* [2]). However, an acceptable level of track maintainability, reliability, accessibility and safety (RAMS), in close coordination to the associated LCC of an asset (Tzanakakis [3]) should also be considered since these aspects assist TQ studies into setting appropriate objectives and working methodologies. Additionally, as data is paramount to perform the analysis, a central aspect of this paper is to use the data from a TRC. Hence, this paper works towards the understanding and treatment of the available data, which is later analyzed through statistical methods to determine the track's history and deterioration process as one of the first steps to determine the quality of the track. As it can be expected, a high volume of data would provide a more accurate prediction of the deterioration rate. However, at this time the data is limited and such statistical approach is not possible.

2 Track quality and deterioration rate

2.1 Track quality definition

Track quality relates to the system under study (e.g. High Speed vs. Cargo Train or a combination of both) since for example the traffic on the track (i.e. dynamic effects, speeds, and loads) influences the track geometry (Ferreira and Murray [4]), which per the discussion below affects the quality. This is not exception for LRT systems, where construction standards, speeds and loads differ from other systems. To help determine the quality of LRT tracks in the future, this paper seeks to establish a working definition understanding that track quality in general depends on the condition of the track which in turn is divided into geometrical and structural condition (Xu *et al.* [5]).

Quality according to ISO [6] is "the degree to which a set of inherent characteristics (i.e. distinguished features) fulfils requirements." From this definition track quality can be defined as "the degree which a set of track characteristics (e.g. parameters describing geometrical and structural conditions) fulfil specific requirements such as passenger comfort, RAMS and LCC." The fulfilment of these requirements is evaluated through specific limits that determine the current state of a track or needs for interventions to restore its quality. Currently, TQ is commonly analyzed through its geometrical condition (Xu *et al.* [5]) and characterized by the deviation of the position of the rail in a three-dimensional space in terms of gauge, cross level, left and right longitudinal level (vertical), left and right alignment and twist, which in general are called track irregularities (Liu *et al.* [2]). Compounded standard deviations of the given parameters are used to create TQ indices, which are compared to intervention limits that ensure comfort and safety. However, per the previous discussion, this is not enough since overall quality, including both geometrical and structural conditions (e.g. track stiffness), is also delivered by economic factors involving an initial investment and subsequent maintenance efforts (Veit [7]). Based on this, good quality should include a balance between maintainability and an initial quality. This is because the quality of a product creates a link between operating and investment costs (VDV [1]). Additionally, the LCC of an asset should be considered which is used in connection to either of two basic strategies, definition of the budget in advance as a basis for calculating the maximum achievable product quality or definition of the maximum quality in advance (e.g. in relation to availability, reliability, comfort) as the basis for calculating the LCC budget (VDV [1]). According to Veit [7] quality and rate of change should always describe track geometry quality. This paper focuses then on first determining the geometrical quality of a track as the first step to achieve overall TQ which also includes structural conditions. As such, it also seeks to determine the rate of deterioration from available data to later (in future studies) perform the required analysis of overall track quality in accordance to RAMS and LCC.

2.2 Track quality deterioration and degradation

Track quality deterioration is the process undergone by a track that deviates it from its original design in regards to geometrical and structural parameters; this ultimately leads to its degradation (i.e. diminution or reduction of strength, efficacy, or value) in terms of pre-established limits, which by the previous discussion should account for the safe and cost efficient operation and renovation of the track. In general, according to Sadeghi and Askarinejad [8] the deterioration of a track can be divided in three interrelated aspects, the sub-structural aspect, the super structural aspect and the track geometrical aspect. Each of these lead to a degradation of their corresponding track subsystem; affecting the other two aspects. For example, the deterioration of the track geometrical aspect, analyzed in this paper, leads to the degradation of the track geometry; however, this is a symptom and the causes of deterioration my lay on contributing factors such as structural characteristics of the track (Xu *et al.* [5]). This agrees with Suiker [9], which mentions that track deterioration results from the passage of a large number of train axles, which in ballasted tracks is formed mainly by plastic deformations generated in the granular substructure (i.e. mainly in the ballast layer in LRT systems). Understanding the deterioration process is paramount for predicting the degradation of track quality. In this paper the term deterioration will be used since only track geometry deviations are analyzed and not losses of mechanical properties (i.e. degradation).

2.3 Track quality deterioration rate

The deterioration rate can be defined as the degree at which the track quality declines over time. The track deterioration can be geometrical or structural in character (Berawi *et al.* [10]) and the reaction of a vehicle running on it might differ form system to system and level of track degradation, i.e. changing of track parameter values in a short distance (e.g. short to medium wavelengths) influence passenger comfort and operation safety. As exposed by Xu *et al.* [5], track deterioration depends on factors such as formation condition, in specific in relation to the effectiveness of the drainage system, ballast quality, traffic loading, type of track construction, dimension of track components, curvature, quality of materials, etc. Furthermore, Xu *et al.* [5] explains that the deterioration rate of a track depends firstly on the initial quality (e.g. slower deterioration) and secondly on the current quality, which if excessively decreased, leads to inefficient quality restoration.

2.4 Track geometry parameters

Five parameters, gauge, vertical level, lateral alignment, cross level and twist are used to describe the layout of a track and to determine its geometrical quality (Fig. 1). In many modern LRT systems parameters are measured with TRCs and deviations established through statistical methods. Deviations are compounded and weighted to develop track quality indices (Berawi *et al.* [10]).

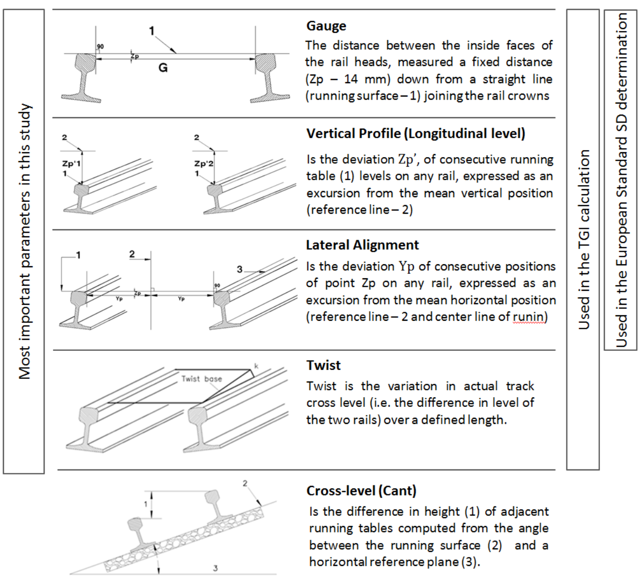

Figure 1: Geometry parameters (DIN EN [11] and Lewis [12]).

2.5 Track geometry quality intervention limits

In order to determine whether deviations of track geometry parameters are acceptable, limits need to be established; based on widely used standards such as the DIN EN 13848-5 (called simply DIN standard in this paper), which set three characteristics limits:

Table 1: Track defect limit levels (DIN EN [13]).

Alert Limit (AL)	If a limit value is exceeded, an action to correct the error has to be considered in the regularly planned maintenance
Intervention Limit (IL)	If a limit value is exceeded, an action to correct the error has to be done immediately before the next inspection
Safety Limit (IAL)	If a limit value is exceeded, an action should be done to reduce the risk of derailment (closing the line, reducing speed, immediate tamping, etc.)

Each of the limits depend on the speed of the system under study and are divided into two wavelengths D1 ($3< \lambda \leq 25$ m) and D2 ($25 <\lambda \leq 70$ m) (Lewis [12]). For an LRT system the following limit values applied for the alignment, longitudinal and gauge defects:

Table 2: Allowable limits for deviation of track geometry parameters (DIN EN [13]).

Track Geometry parameter	**Speed (km/h)**	**Alert Limit (AL)**		**Intervention Limit (IL)**		**Safety Limit (IAL)**	
		Wavelength range (mm)		Wavelength range (mm)		Wavelength range (mm)	
		D1	D2	D1	D2	D1	D2
Longitudinal profile	V ≤ 80	12–18	N/A	17–21	N/A	28	N/A
Alignment	V ≤ 80	12–15	N/A	17–21	N/A	28	N/A
-		Min.	Max.	Min.	Max.	Min.	Max.
Gauge	V ≤ 80	-7	25	-9	30	-11	35

As it can be seen, for speeds equal or lower to 80 km/h (i.e. LRT systems) all parameters indicate D1 wavelengths (Lewis [12]). In the case of gauge, maximum and minimum values are considered regardless of the wavelength. For a narrower gauge the minimum value in the table is used and vice versa, for a wider gauge the maximum value from the table is taken. In addition, DIN standard provides the possibility to check the geometrical quality of the longitudinal profile and alignment based on a standard deviation for the D1 wavelength range; however, the standard deviation provided only considers an AL, which is not suitable for the evaluation of seriously degraded tracks. To overcome this issue, this study combines the DIN values with values provided in Lewis [12], which specifies standard deviations for poor (IL) and very poor (IAL) quality bands (Table 3). Worth mentioning is that for the tracks under investigation in this study, the alignment did not have an influence on TQ since resulting SDs were much lower than the IL (e.g. max of 1.2 mm for one track and 3 mm for another, both values are well below the Good quality band expressed by Lewis [12]). It should be mentioned that although the limits set by Lewis [12] are for conventional railway systems (including high speed systems), the quality band labelled as good can be related to the AL limit of the European standard for 80 km/h, which as seen in Table 3, is lower and hence more stringent. However, for an initial state of research for LRT systems, values established in Lewis [12] would be taken as suitable, since they consider ride comfort and safety for high speed lines which are more critical than slow speed systems.

Table 3: Allowable limits for standard deviation of track geometry parameters (DIN EN [13]) and Lewis [12].

Speed (Km/h)*	Longitudinal level				
	DIN (AL)	Good (AL)	Satisfied -	Poor (IL)	Very poor (IAL)
16–32	–	5.2	7.4	8.3	9.9
40–48	–	4.3	6.1	7.0	7.7
56–65	–	4.1	5.8	6.7	7.2
72–80	**2.3–3.0^{+}**	3.8	5.4	6.3	6.7
88–97	–	3.5	5.0	5.9	6.3

*Conversion form mph to km/h $^{+}$ for speeds equal or below 80 km/h.

The analysis of irregularities through the DIN standard and SD deviation, through both the DIN standard (AL) and Lewis [12] (IL and IAL), serve respectively the purpose of finding local irregularities and overall track geometry quality (Liu *et al.* [2]). Hence, track quality determination requires both approaches to consider all possible situations.

2.6 Measurement of track geometry irregularities

Track geometry irregularities are today measured with TCRs, which consist of an articulated railcar attached to a control car. The TRC has three measuring systems, a camera-laser-system, a strap-down-platform and shaft encoders. The camera-laser-system determines the gauge and the alignment comparing the current condition (position) and the as built values of the rails (Benz [14]). Measuring failures can occur due to contamination of optical windows through spray from the wheels and grease thrown up from lubricators (Lewis [12]) or grease on the rail which causes the laser to be deflected away. The strap down platform has three acceleration sensors and three gyroscopes and measures the spatial movement of the vehicle or the parameters longitudinal cross level and twist, which are determined by integration of the measured parameters (i.e. acceleration and angular velocity) (Benz [14]). The shaft encoder is installed on an axle and measures the speed of the TCR. The position of the vehicle is calibrated by radio-frequency identification (RFID) tags and readers installed on the track and inside the vehicle (Benz [14]).

2.7 Geometry quality evaluation and deterioration rate determination

2.7.1 DIN EN 13848-5:2010 and Track Geometry Index (TGI)

As mentioned under the intervention limits section, two methods were chosen to evaluate the geometrical quality of the tracks under study, the DIN standard and the TGI developed by the Indian railways (Berawi *et al.* [10]). These methods are based on statistical approaches; suitable to determine the track geometry deterioration. These two methods were found appropriate for LRT systems in comparison to other methods because the limits of intervention were either too high (i.e. J Synthetic coefficient); resulting in extremely high track geometry qualities, or were based on speeds higher than 80 km/h (i.e. Five parameters of defectiveness), which is higher than the maximum speed of most LRT systems.
As explained above, under the DIN standard two criteria are used to establish the geometrical quality of a track. One is the irregularity of the track parameters; the other, their standard deviation, calculated as follows:

$$SD = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}} \tag{1}$$

where N is the number of signals measured on a track section [-], x_i the irregularity at point i [mm] and $\bar{x}$ the average value of track regularity per segment as mentioned in section 3.1 [mm].

On the other hand, the TGI represents a synthetic value, based on the average of weighted indices of the different geometry parameters (i.e. UI -unevenness index, TI -twist index, GI - gauge index and AI- alignment index) to quantify the quality of the track segment (Liu *et al.* [2]). These indices result from exponential functions that use calculated standard deviations of each parameter at different states and conditions of the infrastructure (e.g. SD_{mes} measured, SD_n as for newly laid tracks and SD_{main} for maintained tracks). The formula used is the following (further explanation is beyond the scope of this paper):

$$TGI = \frac{2UI+TI+GI+6AI}{10} \tag{2}$$

where for example $UI\ (unevenness\_index) = 100 \cdot e^{-\left(\frac{SDUmes-SDUn}{SDUmaint-SDUn}\right)}$

In the TGI method the alignment is the most important parameter followed by the longitudinal level. This importance is set through many observations of the system studied to develop the formula; hence the weighting factors might not be appropriate for the LRT system under study and should be adjusted in the future to be representative of it.

2.7.2 Deterioration rate "b" determination

To determine the deterioration rate of a track based on the statistical results, regression would be the preferred method. However, this requires large amounts of data which at present are not available. Alternatively, the TU Graz model is used. Through this method the deterioration rate b, treated as an exponent of an exponential function, can be roughly calculated mathematically with the help of variable Q_0, known as the initial quality of the track in accordance with the function $Q(t) = Q_0e^{bt}$ (Veit [15]). Hence, if two so called "quality" points, Q_1 and Q_2, at different points in time (i.e. t_1 and t_2) are known, then a system of two equations can be simultaneously solved to determine "b" (Le [16]).

3 Case study

The study is conducted on two tangent ballasted tracks located in a southern German city. Track 300 is 600 m and track 330 is 460 m. The total length under study is about 2 km; considering both ways. The maximum speed for the LRT system under study is 70 km/h; with an average speed of about 40 km/h (VDV [1]); hence the suitability of the chosen intervention limits which as explained above consider speeds of maximum 80 km/h. The data obtained for track 330 includes six inspections performed every six months since 2013; for track 300 the data provided only included four inspections. Regarding the history of the tracks, it is known that track 330 was built in 1985 and renewed in August 2014. However, for track 300 no records were provided.

3.1 Determination of irregularities and standard deviations

Irregularities were determined using the DIN standard. Standard deviations were calculated using both the DIN standard and the TGI method. For the SD methods, the track was divided into 10-meter segments, which is an appropriate dimension for the scale of the infrastructure. For example, the following graph (Figure 2) shows the state of the longitudinal level per the DIN standard for track 300 before renewal efforts.

The following graphs show the state of the track before (Figure 2) and after (Figure 3) renewal. As it can be recognized, before the renewal only few sections of the track had exceeded the limits of intervention. This exceedance could represent short wave length irregularities which would need to be investigated or measuring mistakes that need to be filtered out.

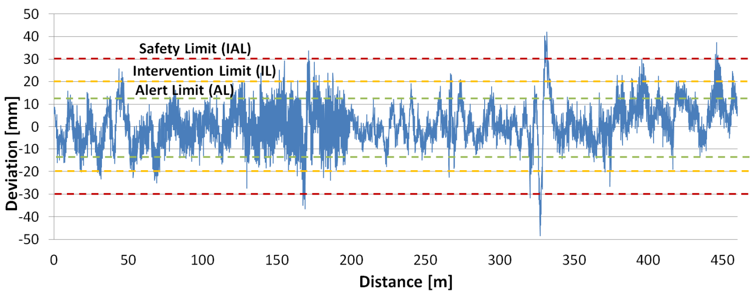

Figure 2: Track 330 longitudinal level irregularities before renewal.

On the other hand, figure 4 shows the overall geometrical quality of the track and the evolution of its deterioration calculated through the TGI method.

Through this method, different phases of the tack can be recognized. Between $Q_{1(330)}$ and $Q_{3(330)}$, the graph shows the deterioration rate before renewal. The rate was estimated using points $Q_{1(330)}$ and $Q_{2(330)}$. The trend line of "b" was then

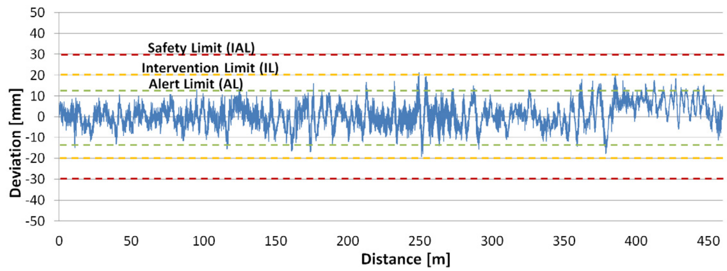

Figure 3: Track 330 longitudinal level irregularities after renewal.

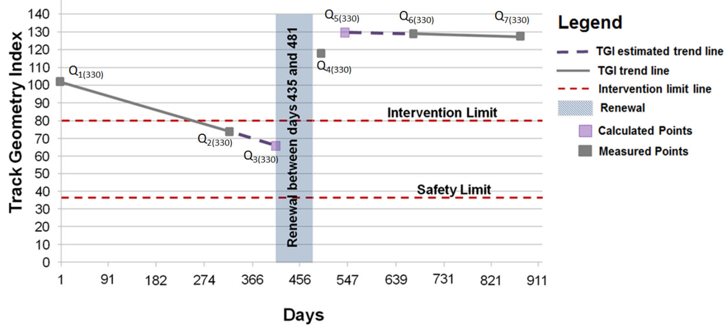

Figure 4: Evolution of the TGI of track 330.

extended to the point of renewal taking place on day 435 ($Q_{2(330)}$). The track was renewed between day 435 and 481 and as seen, the TGI improved greatly ($Q_{4(330)}$); confirming the intervention action. However, as depicted in the graph, point $Q_{6(330)}$ shows a further geometry improvement. This improvement was assumed to correspond to the construction method used by the transportation company, which performed a second tamping six weeks after the renewal on day 541 $Q_{5(330)}$. This tamping is applied after a consolidation phase of the track, which occurs after 0.5–2 M tons of traffic (Lichtberger [17]). Point $Q_{5(330)}$ was likewise estimated by projecting the trend line of "b." The latter was calculated using points $Q_{6(330)}$ and $Q_{7(330)}$, which correspond to a time interval in which a deterioration of the geometry can be observed. In order to confirm the deterioration trend line, which also led to point $Q_{5(330)}$, more points would have to be included in the analysis in the future.

As discussed above, the TGI method assigns a large weight to the alignment parameter, which for track 330 reflects on the higher rate of deterioration observed before renewal. For track 300, however, the resulting TGI corresponded to a track in good condition. Yet, further investigations, using the SD of the DIN standard for the longitudinal level, shows that the track actually exceeded the safety limit at point $Q_{2(300)}$ (Figure 5).

The exceedance could also be observed through the analysis of irregularities using the DIN standard, which also offers a clue about possible short wave length irregularities at about distances 417 m and 485 m (Figure 6).

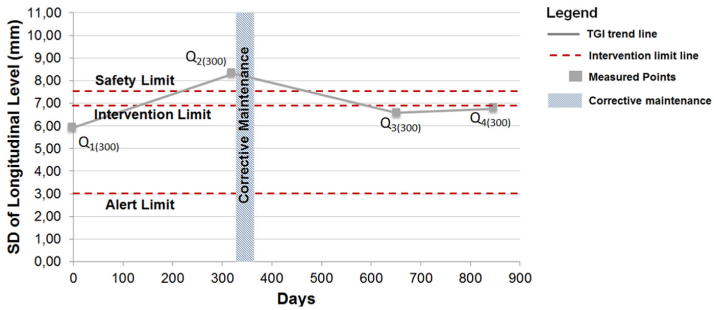

Figure 5: Evolution of SD Longitudinal level of the track 300.

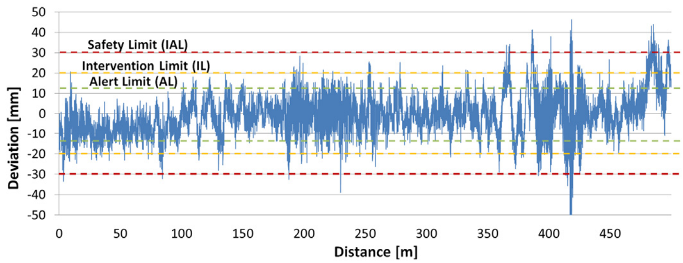

Figure 6: Track 300 longitudinal level irregularities before maintenance.

However, as seen in figure 5, the SD improved ($Q_{3(300)}$) slightly; suggesting that maintenance was carried out. Furthermore, the slight improvement, which remains below the IL ($Q_{4(300)}$), suggests that the intervention did not greatly impact the SD, which supports the assumption that the action was corrective. Moreover, the evolution of the SD deviation getting close to the intervention limit in a short period of time, suggests that the track will require a more drastic intervention (e.g. renewal) to set it back below or closer to the AL.

3.1.1 Evolution of TGI

The previous discussion showed that the track geometry undergoes an evolution process through time in response to its deterioration, maintenance or renewal. Figure 7 shows this evolution comparing simultaneously the track at different points in time. As it is seen the TGI trend line can be easily recognized as well as the history of the track (i.e. the renewal and consolidation phase) providing a clue about the development of the improvement or worsening of the track geometry at a particular point in time.

3.2 Deterioration rate calculation and comparison

The rate of deterioration of the tracks under study was established and compared; the results provided a clue about the correctness of many of the conclusions and assumptions made. For example, as expected, after renewal the rate of track 330 in both directions improved greatly. The latter was expected according to the fact

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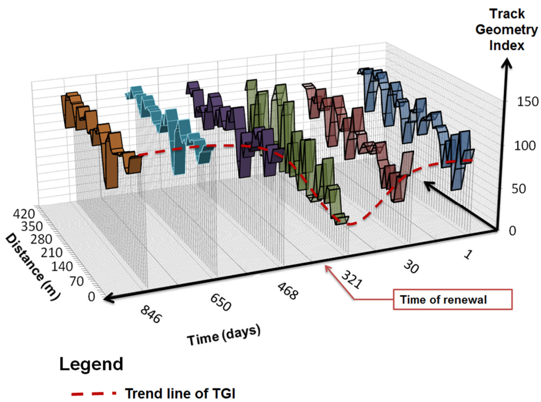

Figure 7: Evolution of TGI of track 330.

that the higher the initial quality the lower the "b" rate (Veit [7]). This great improvement was especially expected considering that the quality of the track before renewal did not represent the quality of a newly laid track, but rather the quality of a track at the end of its service life, which rate is higher. In regards to track 300, it was deduced that it was subjected to corrective maintenance around day 300. This action reestablished the track to a safe state and improved its deterioration rate "b", which, according to Veit [15], is not typical since maintenance is not able to reduce the rate of deterioration. The improvement might be due to an intervention that required the renewal of some of the track components where short wave length irregularities might have been present (e.g. re-compaction of the subgrade and new ballast) or due to the fact that the track before the intervention was not new. However, as it can be seen in the graph, the track was brought to a state that deems a safe operation, but not good enough to avoid a quick return to the previous deteriorated state, which might be due to the memory of the track (Veit [7]).

Table 4: Comparison of degradation rate before and after interventions.

Track	Track quality	Before intervention	After intervention
330 (1) inbound	SD longitudinal level	0.0005	0.00076
	SD alignment	0.0027	7.34×10^{-5}
	Track geometry index	(-)0.0011	(-)4.6×10^{-5}
300 (1) inbound	SD longitudinal level	–	0.0002
	SD alignment	–	0.00264
	Track geometry index	–	(-)5.6×10^{-5}
330 (2) outbound	SD longitudinal level	0.0045	0.0012
	SD alignment	0.05	0.00056
	Track geometry index	(-)0.0296	(-)0.00028
300 (2) outbound	SD longitudinal level	–	–
	SD alignment	–	0.00025
	Track geometry index	–	(-)0.00018

This reflects well what was discussed for track 300, which SD after maintenance remained well beyond AL and which quickly reached the intervention limit. Furthermore, as expected, the “b” value of track 300 is higher than for track 330. This is expected for maintained tracks vs. newly built or even renewed tracks. A similar conclusion can be made for some of the SD parameters of the DIN standard, which improved after renewal; however, between track 300 (1) and 330 (1), the longitudinal level shows a better rate for the maintained track, which needs further explanations. Furthermore, the data for track 300 (2) after intervention, could not be used because it provided an illogical evaluation of the track for the last inspection.

4 Conclusion

The proper treatment and analysis of data from a TCR provides an opportunity for infrastructure managers to determine the current states of their assets and to attempt the prediction of their future condition. In this paper, even limited data provided a good insight of the history of the tracks and their deterioration. It is however important to expand the analysis to more track segments to validate and complement results. An important aspect identified is the lack of intervention limits for LRT systems. Although limits for regular railway systems provided a good basis for understanding the behavior of the LRT track system, it would be beneficial to develop specific values that account for its specific characteristics (e.g. weight and speed). In terms of the evaluation of the track deterioration process through the statistical methods, expected results could be observed. In specific, the renewed track (track 330) presented a considerable geometry improvement and its deterioration rate “b” became lower. Still, attention must be paid when using the TGI method since it might not be able to identify short wave length irregularities. This was the case of track 300 for which the longitudinal level parameter of some segments displayed high irregularities; deeming the track unsafe. For the identification of short wave length irregularities, the DIN standard results more appropriate. In addition, through the standard deviation method for a specific parameter, it was also possible to identify the history of the track and its degradation process. Interesting was that for track 300 the deterioration rate improved after the corrective maintenance, which is not typical. This could be due to a large replacement of ballast and compaction of the subgrade or due to the fact that the track was not new to begin with. In future studies an analysis of more track sections is necessary to validate the observations made and to develop specific limits of intervention for LRT systems.

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