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EVALUATING TRACK GEOMETRICAL QUALITY THROUGH DIFFERENT METHODOLOGIES

Abdur Rohim Boy Berawi[1*], Raimundo Delgado[2], Rui Calçada[2], Cecilia Vale[2]

[1]*Transportation System,* MIT - *Portugal Program, University of Porto,*
Rua Dr. Roberto Frias, s/n 4200-465 Porto, Portugal
[2]*Department of Civil Engineering, Faculty of Engineering, University of Porto,*
Rua Dr. Roberto Frias, s/n 4200-465 Porto, Portugal

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ABSTRACT

The implementation of High Speed Railway (HSR) networks involves a large amount of financial support imposing, not only at the conception and design level, but also during the line operation, a demanding, a complete, and a rigorous estimation of the total cost involved in the life cycle of the system. By using appropriate tools for estimating HSR life cycle costs (LCC), it is possible to minimize the final cost and, at the same time, to identify the most important aspects and parameters influencing the cost evaluation. Research, therefore, is not only required on the LCC modeling, but also on the estimation of major degradation factors and in the assessment of its impact on the maintenance needs. This paper deals with this former aspect.

The various methodologies for evaluating the geometrical track quality are presented and compared to each other, namely the J Synthetic Coefficient, the Indian TGI and also the approach presented in the European Standard EN 13848-5. In order to compare these three methodologies, they are applied to a railway stretch of the Portuguese Northern Railway Line. By doing so, the prediction of track degradation rate within the period of research can be determined, which possibly is used in the future for defining cost-effective maintenance strategies.

Keywords: Maintenance optimization; Regression analysis; Track degradation model; Track geometry; Track quality index

1. INTRODUCTION

In recent years, studies on railway track degradation have attracted a great deal of attention. Intensive research activities have been conducted by many organizations targeting not only to secure a high level of safety and reliability of infrastructure systems, but also to diminish the problems associated with the degradation of performance in terms of ride quality, comfort, etc. For this reason, many railway Infrastructure Managers (IMs) spend a substantial proportion of their budget on the Maintenance and Renewal (M&R), which makes up a considerable part of total railway operating cost and accounts for up to 70% from total life cycle cost of track infrastructure (Jianmin, 2007). With this huge amount of financial expenditure, undoubtedly, a small reduction in the maintenance cost will bring a significant impact, particularly on the overall life cycle cost.

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[*] Corresponding author's email: boy_berawi@yahoo.com, Tel. +351-225082178

Several approaches and methodologies to evaluate track degradation for track maintenance optimization have, therefore, been developed during the last few years, from simple models that are just concentrated on one individual track component to the most comprehensive ones which embrace all major factors in the track degradation. According to the available literature, these predictive models may be considered based on two aspects (Sadeghi & Asgarinejad, 2007):

- Track Degradation considered from structural aspect
- Track Degradation considered from geometrical aspect.

In the first aspect, track degradation model is based on the growth of physical structure conditions. Parameters influencing track degradation, including passage tonnage, train speed, ballast characteristics, rail types, etc., are investigated and the correlations among them are analyzed to derive a general equation that quantifies the rate of degradation. The good reviews of some of these are given in (Sato, 1995; Zhang et al., 1999). Conversely, track degradation models in the second aspect use geometrical parameters as the main degradation criteria. In order to measure the track conditions by using this model, typically the track is divided into several shorter sections and geometry statistics are performed to each of them. The geometry statistics are then summed up to give a measure of overall segment quality, which is commonly called Track Quality Indices (TQIs). Use of TQIs provides the possibility to assess railway track performance indicators, to design interventions, and to compare track performances before and after the interventions. (Fortunato et al., 2007).

The present research aims to improve the understanding on the mechanism of degradation, their likelihood to occur in the railway track, and their evolution over the entire lifetime. For these interests, the Track Quality Indices (TQIs) has, therefore, been chosen in the analysis. All the aspects related to TQIs, starting from their reflection in the assessment of railway quality, the role of each geometrical variable to form the index value as well as their implementation, will be discussed.

The specimen used in this paper comes from the 8 years collection of historical data of one rail track stretch in Portugal, subjected to mixed traffic. The maximum train speed in this rail track in study is 220 km/h. Although the rail track in study presents approximately 1 km long, this paper is intended to show moreover how the method of TQI's is put into practice in the quality measurements of the railway. With this approach, we are able to predict the likely rate of track degradation within the period of research, which may be used in the future for defining maintenance models.

2. GEOMETRICAL TRACK DEGRADATION CONCEPT

Generally, the major contributors to the track degradation can be categorized in three different areas, i.e. the initial value of Track Quality Indices (TQIs), traffic, and maintenance (IMRT, 2005). Track Quality Index is defined as a numerical value that represents the relative condition of the track surface geometries (El-Sibaie & Zhang, 2004). Sadeghi and Askarinejad (2008) distinguished TQI into two dependent variables. The first variable is the Track Geometry Index (TGI), which is defined as a function of one or more of the main geometry parameters such as profile, alignment, gauge, cant, and twist (Figure 1). The specification for each parameter is detailed as follows. Profile and alignment are delineated with the track geometry of each rail projected longitudinally against the vertical and horizontal plane, respectively. Any changes in the elevation of the two rails relative to a designated level is called profile deviation, while the lateral variation of the rails to a given centerline of the track contribute to alignment irregularities. Gauge specifies the inner distance between two rails measured at 16 mm below the top surface of the railhead. In Portugal, the gauge for primary Railway Lines is 1,668 mm although a wide variety of gauges are used around the world. The term of gauge irregularities, therefore, will refer to the deviation of the track from this specified value. Cant irregularities measure the amount of vertical deviation between two flat rails from their designed value. This designed value, commonly known as super-elevation, helps to compensate the centrifugal force of the vehicle on a given curve. Consequently, cant is not considered as defect unless it deviates from the predetermined super-elevation. The last parameter, twist, is also associated with super-elevation. It measures the difference in the super-elevation between two points taken at a separate fixed distance along the track.

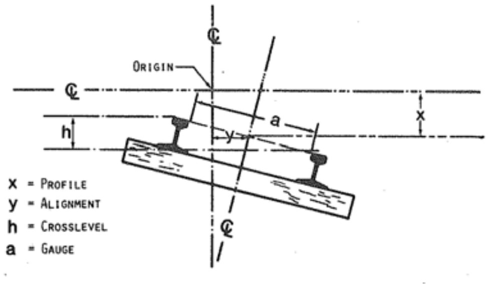

Figure 1 Track Geometry Parameters (Bing & Gross, 1983)

Still according to Sadeghi and Akbari (2008), the second variable of TQI is defined as the Track Structure Index (TSI), which expresses the condition of the track structure, including the condition of rail, sleeper, ballast and drainage systems. In this paper, only the TGI will be analyzed.

Traffic is another major parameter influencing track geometry condition. Ferreira and Murray (1997) divide traffic related deterioration factors into three groups; dynamic effects, speeds, and loads. The dynamic effects vary with the type of vehicle on the track, from heavy haul freight traffic to passenger trains and from fast passenger unit to lower speed mixed traffic. As a result, the track bed is subject to a wide range of bearing and bending stresses that may come not only because of the static mass of vehicles, their wheel-sets and their cargo, but also from the dynamic actions such as lateral forces in curves, acceleration, vibration and imperfection on the rail surfaces. As the speed increases, the dynamic forces will influence the deterioration of track geometry significantly and lessen at low speed.

The last parameter, maintenance action, which consist of activities of tamping, grinding, ballast cleaning, lubrication, replacement etc., is also affecting the ratio of track degradation. For instance, when the tamping action is performed, the ballast under the ties is re-compacted to provide the proper load bearing. The ties thus distribute the weight of the rail and rolling stock and keep the track properly aligned, that in turn, impede the acceleration of rail degradation rate.

3. TRACK QUALITY INDICES (TQI'S)

As discussed earlier, in order to evaluate the condition of a railway track, an appropriate assessment technique namely Track Quality Indices (TQI's) is used. Some methods by which track quality indices can be obtained are discussed below.

3.1. J Synthetic Coefficient

J synthetic coefficient is used as an indicator of the track quality based on the standard deviation evolved by Polish Railways (Madejski & Grabczyk, 2002). Four track geometry parameters are considered in this index: vertical irregularities, horizontal irregularities, twist, and gauge. The equation for calculating J synthetic coefficient is:

$$J = \frac{S_z + S_y + S_w + 0.5 * S_e}{3.5} \tag{1}$$

where S_z, S_y, S_w and S_e are the standard deviation of vertical irregularities, horizontal irregularities, twist, and gauge, respectively. The standard deviation for each measured parameter is calculated by the following equation:

$$S = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{i=1} - \overline{x})^2} \tag{2}$$

Based on the above equation, n is identified as the number of signals registered on the track being analyzed, x_i represents the value of geometry parameters at point i and $\overline{x}$ is the average value of the measured signals. The J synthetic track quality coefficient also specifies the allowable deviation of J, determining the track condition with respect to the state defined by the track operating appropriately on one side and the track requiring maintenance on the other.

Table 1 Allowable deviations of J coefficient based on line speed (Madejski & Grabczyk, 2002)

Speed [km/h]	J Coeff. [mm]	Speed [km/h]	J Coeff. [mm]
80	7.0	150	2.3
90	6.2	160	2.0
100	5.5	170	1.7
110	4.9	180	1.6
120	4.0	190	1.5
130	3.5	200	1.4
140	2.8	220*)	1.1

*) Calculated through extrapolation

3.2. Track Geometry Index (TGI)

Indian Railways has developed a formula to represent the quality of track called TGI. This model is based on the standard deviation of different geometry parameters over a stretch of 200 m segment. TGI is calculated for each segment and the average value of such segments in every km gives the general TGI value (Talukdar et al., 2006). With respect to the effect of each geometry parameter on the ride quality, TGI has given different value for various geometry parameters as shown in the following formula:

$$TGI = \frac{2UI + TI + GI + 6AI}{10} \tag{3}$$

where UI, TI, GI, and AI are the index for unevenness, twist, gauge, and alignment respectively. For each measured track parameters, the index is calculated from the relation:

$$GI, TI, AI, UI = 100 \times e^{-\left(\frac{SD_{mes} - SD_n}{SD_{maint} - SD_n}\right)} \tag{4}$$

where SD_{mes} is the standard deviation of measured geometry parameters, SD_n represents the standard deviation prescribed for newly laid track and SD_{maint} is the prescribed standard deviation for maintenance. The standard deviation values used in Equation 4 are specified in

Table 2. For the classification of track condition according to the required maintenance is given in Table 3.

Table 2 Standard deviation (SD) values (Sadeghi& Asgarinejad, 2008)

Parameters	Chord Length	SD for newly laid track	SD for maintenance with max. speed ≥ 105 km/h	SD for maintenance with max. speed < 105 km/h
Unevenness	9.60	2.50	6.2	7.2
Twist	3.60	1.75	3.8	4.2
Gauge	1.00	1.00	3.6	3.6
Alignment	7.20	1.50	3.0	3.0

Table 3 TGI Classification for maintenance (Talukdar et al., 2006)

No	TGI Value	Maintenance requirement
1	TGI > 80	No maintenance required
2	50 < TGI < 80	Need basic maintenance
3	36 < TGI < 50	Planned Maintenance
4	TGI < 36	Urgent Maintenance

3.3. European Standard EN 13848-5

The rail track geometry on the sample segment has also been evaluated in accordance with European Standard EN 13848-5 (CEN, 2005). With respect to the Standard, three track geometry parameters are considered: longitudinal level, alignment, and gauge. The measurement of longitudinal level and alignment are conducted based on the standard deviation of irregularities on a 200 m long segment, while the irregularities on the Gauge is measured based on a mean value of 100 m long segment. Apart from that, specification of geometry irregularities with wavelength domain in the range of 3 m < λ ≤ 25 m is another required parameters to be calculated in the standard deviation.

The allowable thresholds for geometry parameters based on the European Standards are given in Tables 4-5.

Table 4 SD Threshold values for profile and alignment (CEN, 2005)

Speed	Wavelength domain [mm]	
	Profile	Alignment
80 < V ≤ 120	1.8 – 2.7	1.2 – 1.5
120 < V ≤160	1.4 - 2.4	1.0 – 1.3
160< V ≤ 220	1.2 – 1.9	0.8 – 1.1
220 < V ≤ 300	1.0 – 1.5	0.7 – 1.0

Table 5 Distance limit between specified gauge and mean over 100 m segment (CEN, 2005)

Speed [km/h]	Difference between specified gauge and mean gauge over 100 m segment (mm)					
	Safety Limit (SL)		Intervention Limit (IL)		Alert Limit (AL)	
	Min	Max	Min	Max	Min	Max
80< V ≤ 120	-7	+27	-6	+25	-5	+22
120< V ≤160	-5	+20	-4	+18	-3	+16
160< V ≤ 220	-5	+20	-4	+18	-3	+16
220< V ≤ 300	-5	+20	-4	+18	-3	+16

4. CASE STUDY

For the purpose of this paper, a case study on 1 km straight segment located in Portuguese Northern Railway Line has been done. The data were obtained from Track Recording Car (TRC), which provides information about track geometry parameters in two wavelength ranges. The use of this vehicle makes it possible to record any variations on the track in every 0.25 m, while still keeping on running with max. speed of 120 km/h. In order to evaluate the track in terms of its quality and to compare its behavior, two different time periods were considered, which are the periods before and after renewal actions.

4.1. Track shift adjustment

In order to synchronize the individual measurement data, the researcher uses the data from two track geometry measurement surveys; one as a reference, while the other is treated as the dataset to be shifted. Both data are then plotted in MATLAB and by performing a cross correlation algorithm at specified intervals, the shifted data is matched to the reference track. The coefficient correlation is expressed as follows:

$$r_k = \frac{\sum_{t=1}^{N}(x_t-\bar{x})(x_{t+k}-\bar{x})}{\sum_{t=1}^{N}(x_t-\bar{x})^2} \tag{5}$$

where x_t is data value at time *t*, *k* is the lag, and the overall mean is given by:

$$\bar{x} = \sum_{t=1}^{N}\frac{x_t}{N} \tag{6}$$

After the synchronization, the start and the end points of each track are identified and grouped for the analysis.

4.2. Evaluation results

In order to make the analysis comparable between the European Standard EN 13848-5 and the two universal quality index (J synthetic coefficient and TGI), we have divided the track into 200 m-long segment and we observe the evolution of the track condition. The regression analysis is imposed on the resulted indices for each period in each data measurement. The advantage of using this method is that it can show the accuracy of our prediction to determine value from regression squared (R^2), with the magnitude range between 0 and 1 (Sadeghi & Askarinejad, 2009). The higher R^2 means the more significant correlation among the data points and the more accurate the prediction of degradation rate. Some results of the quality computation are given in the Figures 3 to 7.

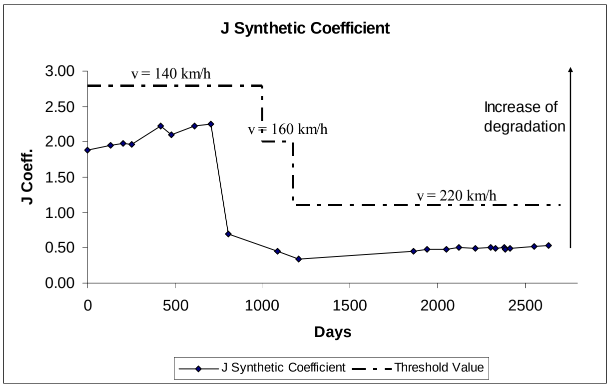

Figure 3 J Synthetic coefficient evolution for sample segment of Block 1

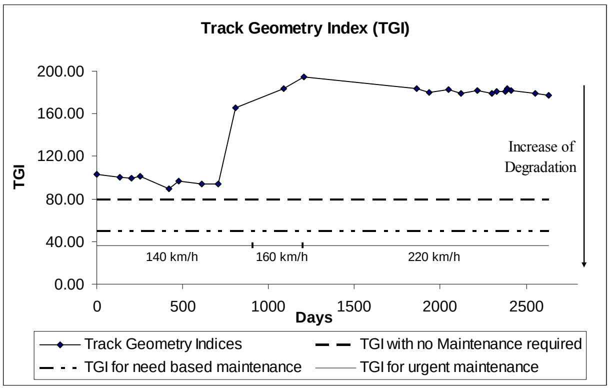

Figure 4 Track Geometry Index (TGI) evolution for sample segment of Block 1

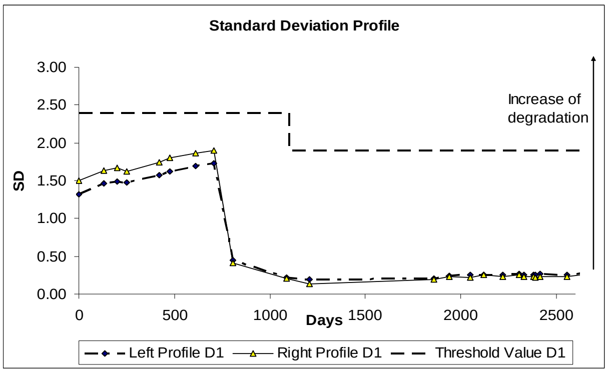

Figure 5 Profile standard deviation of Block 1

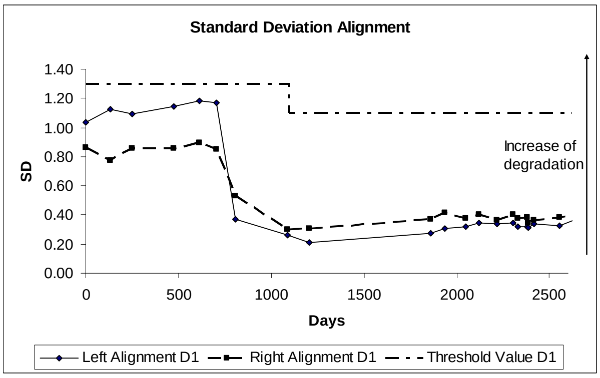

Figure 6 Alignment SD of Block 4

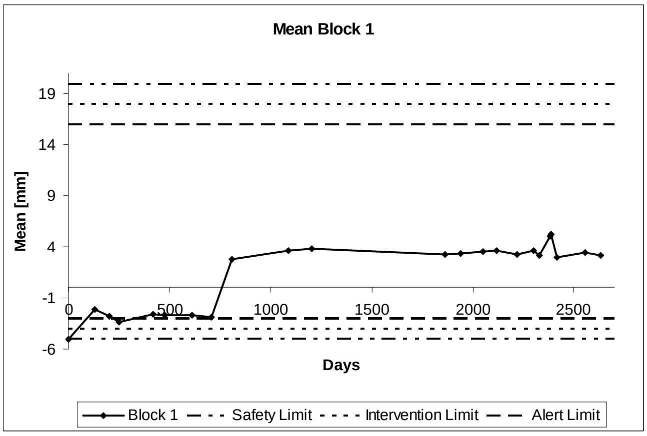

Figure 7 The evolution of mean value of Block 1

Figure 3 to 7 shows the evolution of track quality computed from November 2001 to January 2009, as in this analysis will be represented starting from day 0 to 2632. For each individual figure, two periods of time are distinguished; one is the time period before renewal consisting of 8 inspected measurements (day 0-706), and the other is the time period after renewal consisting of 13 inspected measurements (day 1205-2632). This renewal strategy is also followed by the policy to increase the line speed from 140 km/h (ordinary track) to 220 km/h (high speed track).

The evolution of track geometry index calculated by using J synthetic coefficient and TGI are shown in Figures 3 and 4 respectively. As demonstrated, the quality measurement on the track segment is in the range under the threshold value for maintenance action, which indicates that the track is suitable for train operation. Comparing the two periods of time, the renewal constructed line has revealed a significant quality improvement, a smooth degradation trend, and lower degradation rate, than the lines before renewal actions. These differences allow us to justify the feasibility of the implemented renewal strategy in the effort to obtain the established objective.

In Figures 5 and 6, the evolution of the standard deviation of the track profile and alignment for track block of 200 m length are presented respectively. Finally, in Figure 7, the evolution of the mean value of gauge is also shown. The trend of degradation, particularly in profile and alignment, were quite similar with what is shown in the previous of TQI, indicating that irregularities in the geometry parameters are still within the acceptable range of value. On the other hand, the gauge measurement has shown a slightly different result. In the initial measurement, the gauge mean value is outside the service tolerance, thus making the mean value negative. Please also be advised that the negative in gauge mean value specifies the narrower distance between two rails than it should be. However, as the time passes by, the size of the track gauge is increasing and when the renewal action is conducted, the track is achieving a tremendous improvement in quality.

Furthermore, according to the analysis, the rate at which a railway track has degraded is not the same between period of time before and after renewal. The replacement of the broken parts and removal of irregularities in the renewal segments indicate a considerable improvement in quality and show bigger resistance to the nature of degradation of the track. The computation of degradation rate of J synthetic coefficient in Tables 6 and 7 are included in the samples which strengthen this argument.

Table 6 Degradation rate before renewal (Day 0-706)

Block	Days 0-706					
	Linear ($y = \alpha + \beta x$)			Exponential ($y=\alpha.e^{\beta x}$)		
	α	β	R^2	α	β	R^2
1	1.68	0.0003	0.83	1.68	0.0002	0.82
2	2.16	0.0005	0.91	2.17	0.0002	0.91
3	2.01	0.0006	0.80	2.02	0.0003	0.79
4	1.60	0.0005	0.99	1.61	0.0003	0.99
5	1.73	0.0007	0.99	1.74	0.0003	0.99
		Av. = 0.00052	Av=0.905		Av.= 0.00026	Av.=0.9

Table 7 Degradation rate after renewal (Day 1205 – 2632)

Block	Days 1205-2632					
	Linear ($y = \alpha + \beta x$)			Exponential ($y=\alpha.e^{\beta x}$)		
	α	β	R^2	α	β	R^2
1	0.27	0.00007	0.79	0.28	0.0002	0.79
2	0.26	0.00007	0.82	0.28	0.0002	0.82
3	0.11	0.0002	0.92	0.21	0.0004	0.89
4	0.28	0.00008	0.80	0.31	0.0002	0.79
5	0.26	0.0001	0.88	0.29	0.0002	0.86
		Av.= .000104	Av.=0.84		Av. = 0.00024	Av. =0.83

Tables 6 and 7 present the average values of degradation rate of J synthetic coefficient obtained for every 200 m long segment. The results show the rapid development of track degradation in the segments before renewal actions (av. β= 0.052 mm/100 days with linear regression), while in the renewal constructed line, the track indicates its resistance towards to the degradation process (av. β= 0.0104 mm/100 days with linear regression). Regarding the accuracy of prediction, the values of regression squared (R^2) for both intervals are more than 0.80. Although there is no absolute standard for what is a "good" R^2 value, the application of the regression square may optionally be used to evaluate the quality of prediction of track degradation. As the same logic applies, the rate of degradation is also computed for other methods of TQIs, which is summarized in Table 8.

It can be seen in the above table that the TGI degradation rate value is significantly higher than those obtained with other methods. However, please be reminded that this does not mean that the track quality calculated with TGI is much slower to arrive at a degraded state, since the way of measurements and the range of upper and lower values of the quality index are different for each one of the methods.

Furthermore, as a comparison for the three geometry parameters measured using European standards, gauge is demonstrated as having the highest variables of geometrical defect with degradation rate before renewal (β) approximately 0.319 and after renewal (β) approximately 0.084. This rate is considerably higher than the value of profile (before renewal, β = 0.102; after renewal, β=0.015), and alignment (before renewal, β = 0.024; after renewal, β=0.0083).

However, it might be interesting to know that globally, the percentage of quality index value of Gauge from the overall index value is sufficiently small (J synthetic coeff.: gauge (14,3%), profile (28,3%), alignment (28,5%); TGI: gauge (10%), profile (20%), alignment (60%)) (Talukdar et al., 2006).

Table 8 Summarize of degradation rate

Type of Measurements	Track before Renewal		Track after Renewal	
	Linear	Exponential	Linear	Exponential
	β [mm/ 100 days]	β [mm/ 100 days]	β [mm/ 100 days]	β [mm/ 100 days]
J synthetic Coefficient	0.052	0.026	0.0104	0.0240
Track Geometry Index (TGI)	1.560	0.016	0.9700	0.0054
Profile	0.102	0.500	0.0150	0.0580
Alignment	0.024	0.025	0.0083	0.0330
Gauge	0.319	n.a.	0.0840	0.0250

5. CONCLUSION

In this paper, several methods to evaluate the track conditions have been introduced and the applications of each method in the assessment of railway quality were studied. From the results obtained in this research, the following conclusions are drawn.

The analyses of results in two different periods have indicated a better quality levels obtained by the track after renewal. This improvement of performance indicators, thus, can be used as a parameter to assess the appropriateness of the implemented works to obtain the established objective of renewal strategy.

As discussed before, the rate of degradation of the track segment will be different according to the use of various measurement methods. TGI, for instance, has been accounted as the highest degradation rates with $\beta = 1.56$ mm/100days. However, the result was not surprising since the range of interval quality between upper and lower value in TGI is wider than others. The use of TGI also has imposed the necessity to adjust the tolerance value for maintenance in the case for high speed implementation. Concerning with European Standard EN 13848-5, the three geometrical parameters have shown different rate values leading to degradation as well as the amount of time needed to reach the critical conditions for maintenance. Since the maintenance will be perceived ineffective if it is just solely based on the irregularity of one particular parameter, therefore, it might be necessary to have more comprehensive analysis by combining all the different parameters to construct a uniform index that could facilitate the assessment of the overall fitness of the track segments. The applications of TGI and J synthetic have allowed this objective by using various geometry indicators in the track evaluation with different weighted values for each of them.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Bing, A. J. & Gross, A., 1983. Development of railway track degradation models. *Transportation Research Record* 939, pp.27-31.

CEN, 2005. *Railway applications -Track- Track geometry quality - Part 5: Geometric quality assessment*; German version prEN 13848-5:2005

El-Sibaie, M. & Zhang, Y., 2004. Objective Track Quality Indices. *Proceedings of 83rd TRB Annual Meeting*, Washington, D.C.

Ferreira, L. & Murray, M., 1997. Modelling rail track deterioration and maintenance current practices and future needs. *Transport Reviews*, 17, pp.207-221.

Fortunato, E., Pinelo, A., Lobo Costa, J., Gonçalves, D. & Pratas, A., 2007. Some results of performance indicators of a railway track obtained during its renewal process. *4th International SIIV Congress-Palermo*, Italy.

Iran Ministry of Roads and Transportation (IMRT), 2005. Railway track superstructure general technical specification Standard no. 301. *Iran: IMRT Ministry Publication Service*.

Jianmin, Z., 2007. Modelling and optimizing track maintenance and renewal. *Phd Thesis*, Civil Engineering Department, University of Birmingham.

Madejski, J. & Grabczyk, J., 2002. Continuous geometry measurement for diagnostics of tracks and switches. *Proceedings of the International Conference on Switches Delft University of Technology*, Delft, The Netherlands.

Sadeghi, J. & Askarinejad, H., 2007. Influences of track structure, geometry and traffic parameters on railway deterioration. *International Journal of Engineering*, Volume 20, No. 3.

Sadeghi, J. & Askarinejad, H., 2008. Development of Improved Railway Track Degradation Models. *International Journal of Structure and infrastructure Engineering*, Vol.3, Issue 4.

Sadeghi, J. & Askarinejad, H., 2009. Investigation on effect of track structural conditions on railway track geometry deviations. *Proceeding of the institution of mechanical engineers, Part F*, Journal of rail and rapid transit.

Sato, Y., 1995. Japanese studies on deterioration of ballasted track. *Vehicle System Dynamic*, vol.24, pp.197-208.

Talukdar, K., Arulmozhi, U., Prabhakar, K. & Satyanarayan, 2006. Project Presentation Improvement of TGI Value by Computer Analysis. *Ministry of Railways Indian Railways Institute of Civil Engineering*, India.

Zhang, J., Murray, H. & Ferreira, L., 1999. An Integrated Model for Track Degradation Prediction. World Transport Research: *Selected Proceedings of the 8th World Conference on Transport Research*, vol.3, pp.527-539.