INFLUENCES OF TRACK STRUCTURE, GEOMETRY AND TRAFFIC PARAMETERS ON RAILWAY DETERIORATION

J. Sadeghi and H. Askarinejad*

Department of Railway Engineering, Iran University of Science and Technology
P.O. Box 18644, Tehran, Iran
javad_sadeghi@iust.ac.ir - h_askarinejad@rail.iust.ac.ir

*Corresponding Author

(**Received: April 30, 2006 – Accepted in Revised Form: November 22, 2007)**

Abstract The roles of the several parameters that influences railway track deterioration most, are examined in this research with a view to make railway track maintenance more effective and cost efficient. The results presented are based on a comprehensive study of railway track degradation on super structure, sub-structure and geometrical aspects. The changes in TQI (Track Quality Index), the track settelement and the average growth of track's irregularity are considered to be the main track deterioration criteria from the aspects of track geometry,on the tracks sub-structure and super structure, respectively. In this research the sensitivity of the closely related parameters between, ballast conditions, subgrade compaction, rail-pad stiffness, rail types, sleeper spacing, initial track quality, tonnage, train speed, axle loads, and load cycles are studied. It is shown how one can control the rate of track deterioration by the verification and modification of the track structure, geometry and traffic parameters.

Keywords Railway Track, Deterioration, Track Geometry

چکیده در این تحقیق، در جهت بهینه سازی هزینه ها و بالابردن کاریی عملیات نگهداری، زوال راه آهن با توجه به جنبه های مختلف روسازی، زیرسازی و هندسه مورد بررسی قرار گرفته و مهمترین پارامترهای موثر در زوال خطوط شناسایی شده است. در این راستا، میزان تغییرات شاخص کیفیت خط، نشست خط و مقدار میانگین بی نظمی های روسازی به ترتیب به عنوان معیار زوال از زوایای هندسی، زیر سازی و روسازی در نظر گرفته شده است. در این مقاله، میزان حساسیت زوال خطوط راه آهن نسبت به پارامترهای موثر در زوال خط شامل وضعیت بالاست و سابگرید، سختی پد، نوع ریل، فاصله تراورس، کیفیت اولیه خط، تناژ عبوری، سرعت قطار، بار محوری و تعداد سیکل های بارگذاری بحث و بررسی شده است. بر اساس نتاج حاصل شده، چگونگی کنترول و محدود نمودن میزان زوال خط بوسیله تغییر در پارامترهای سازه ای، هندسی، و ترافیکی راه آهن نشان داده شده است.

1. INTRODUCTION

Maintenance of railway tracks is both costly and difficult to manage effectively [1,2]. It is due to the fact that there are a large number of parameters influencing the rate of track degradation. However, railway industries are trying to improve the productivity of their maintenance teams through more effective control of track deterioration [3]. With this goal in mind we see the need to investigate the parameters that influence track deterioration. Although, some recent studies have been intended to investigate the rate of track degradation which have led to the development of several track degradation models, they have mostly concentrated on one particular aspect of the railway track system. Their results rely only on a limited number of parameters and in each study they considered only one of many aspects of the track deterioration and in turn, took into account those parameters directly related to this aspect. This method cannot provide a thorough indication of all influencing parameters and their role in the track degradation. To provide a cost effective and efficient railway track maintenance, a thorough appreciation of all the parameters and their influences is needed even if they are seen from different aspects. In other words, a need to conduct a comprehensive investigation into the influences of all track related structural, geometrical and traffic parameters exists. To better appreciate how these parameters influence the track deterioration they must be treated together, as a set. This research is a response in this direction.

According to the available literature there are three aspects to track deterioration [4].

- The sub-structural aspect (i.e., degradation of the track sub-structure)
- The super-structural aspect (i.e., degradation of the track super-structure)
- The track geometrical aspect (i.e., degradation of the track geometry)

In order to determine the contribution of the different parameters to track deterioration, the influence of each parameter on the track degradation from these three aspects should be evaluated. In this research track degradation is therefore studied in three ways: investigation of ballast and track sub-layers settlement (track sub-structure), investigation of track irregularity (track super-structure), and investigation of the track quality index (track geometry). The track deterioration sensitivity from the three aspects of track structure, geometry and traffic parameters is investigated. Track structural parameters include ballast type, pad stiffness and rail type. Track geometrical parameters are sleeper spacing, drainage condition and initial track quality indices. Traffic parameters consist of tonnage, train speed, axle loads and load cycle [5]. The contributions of these parameters to the change in TQI, track settlement, and the growth of tracks irregularity are investigated graphically. This paper presents the results of these parametric analyses of track degradation models and identifies the parameters that have the most influence on railway deterioration.

2. TRACK DETERIORATION

According to the literature, track deterioration studies have been made using regression techniques to estimate a condition state as a function of a number of independent variables such as maintenance performed, traffic, track structure and track geometry [6]. A prerequisite for such investigation is a comprehensive historical database with the above factors included. In these studies, a functional form is specified on engineering principles and statistical techniques are used to estimate coefficients of the function. A review of the available literature indicates that the most effective empirical or mechanistic-empirical degradation studies from three different aspects (i.e., track sub-structure, track super-structure and track geometry) are those developed by Sato [7], Shenton [8] and Bing-Gross [9]. They each have developed track degradation models using the results of field inspections from a certain aspect. In this research, these models are considered as the most suitable deterioration models based on the number of parameters taken into consideration, their empirical mechanistic base, and cost of data acquisition. These models are briefly discussed as follows.

2.1. Track Degradation From the Super Structural Aspect

Sato studied the track degradation from track super-structural perspective. The degradation model developed by Sato is based on the growth of track super-structures conditions [7]. The expression given for the deterioration is related to the passed tonnage, average velocity, structure factor, jointed or type CWR (Continuously Welded Rail) and quality of subgrade as follows.

$$S = 2.04 \times 10^{-3} T^{0.31} V^{0.98} M^{1.10} L^{0.21} P^{0.26} \qquad (1)$$

Where S is the average growth in section (mm/100days) as the main criterion of the track super structure condition, T is the passed tonnage (million tons/ year), V is the average running speed (Km/h), M is the structure factor, L is the influence factor for jointed rail or CWR (1 for CWR and 10 for jointed) and P is the influence factor for subgrade (1 for good and 10 for bad). The structure factor M can be obtained from:

$$M = \frac{P_b \sqrt{k_1}}{\sqrt{mEI\,K}} \qquad (2)$$

Where P_b is the maximum sleeper pressure due to a wheel load, k_1 is the rail pad stiffness, m is the intermediate mass consisting of the effective mass of sleeper, ballast and subgrade, EI is the flexural rigidity of the rail and K is the car factor and is expressed as:

$$K = \frac{1}{1 - \xi\eta} \qquad (3)$$

Where, ξ is a constant which expresses the suspension characteristic, 0.5 in freight car and 0.9 for an excellent electric car and $\eta = \frac{M}{m}$ in which M is the unsprung mass and m is the sprung mass of the car.

2.2. Track Degradation From The Sub Structural Aspect

Shenton considered track settlement as the main controlling factor of track degradation from the sub structural aspect. The causal parameters which influence this settlement are sleeper type and size, ballast type, ballast and subgrade condition, the lift given by the tamping machine, equivalent axle load, and load cycles [8]. The general equation which quantifies the track settlement is as follows:

$$S = K_s \frac{Ae}{20}((0.64 + 0.028\,L)\,N^{0.2} + 2.7 \times 10^{-6}\,N) \qquad (4)$$

Where A_e is the equivalent axle load, N is the total number of passed axles, L is the lift given by the tamping machine and K_s is a factor which is a function of sleeper type and size, ballast type and of the subgrade.

2.3. Track Degradation From the Geometry Aspect

Bing and Gross [9] report on US trials to estimate track degradation. Fifteen important causal factors are identified and a multiple regression model, based on 460 observations from a test track, are estimated. An overall track geometrical quality index (TQI) is used as the main track degradation criterion from the geometry aspect. The final model includes the current geometry conditions of the track, speed, age of rails, ballast index, and the time since the last maintenance activity.

The overall roadbed condition was quantified by a ballast index derived from an aggregate index of the ballast material, modified by factors for ballast and drainage condition. The aggregate index is determined from the results of the Los Angeles Abrasion and Mill Abrasion tests. Ballast index BI is given by the following formula.

$$BI = AI\,(BC + 1)^{1/3} + DF \qquad (5)$$

Where AI is the aggregate index (typically 40 for granite and 65 for limestone), BC is the ballast condition on a scale of zero for excellent to 3 for poor conditions, DF is the drainage factor (10 for good and 20 for bad conditions). Ballast index values range from 40 for excellent to 120 for very poor. An indication of causal parameter influence on track degradation for the Youngstown division test zone is presented in Equation 6 [9].

$$TQI_2 / TQI_1 = 1.25(TQI_1 / TQI_1^*)^{-0.58}(V_E / V_E^*)^{-0.18} \times (RA / RA^*)^{-0.11}(BI / BI^*)^{1.04} \times (1 + FS)^{-0.44} \qquad (6)$$

In which TQI_1 is the initial track quality index for the time period (in inches), TQI_2 is the final track quality index for the time period (in, inches), V_E is the equivalent train speed (mph), R_A is the rail age (years), BI is the ballast index; FS is the fraction of segment surfaced. V_E^* and RA^* are arbitrary fixed reference values of each parameter.

3. INFLUENCES OF PARAMETERS ON TRACK DETERIORATION

In order to investigate the influence of the track's structure, geometry and traffic parameters on the railway track deterioration, sensitivity analyses of the degradation models are conducted by comparing the changes to TQI, track settlement and track super structural conditions due to changes in the influencing parameters. The effect of different parameters on track deterioration is evaluated by plotting different parameters against TQI, track settlement and growth of track super-structure irregularities. For this purpose, other parameters are considered to be constant. Using sensitivity analysis, the following parameters are investigated:

- Track structural parameters: ballast index, pad stiffness, rail type, rail age and subgrade condition
- Track geometrical parameters: sleeper spacing, the lift by tamping machine and initial track quality indices,
- Traffic parameters: tonnage, train speed, axle loads and load cycles.

To determine the contribution of different parameters to the track deterioration from geometry aspect, the influence of each parameter on track degradation from this aspect should be evaluated. In this research track degradation is studied in three ways: ballast and track sub-layers settlement (sub-structure based), track irregularity (super-structure based), and track quality index (geometry based). In this paper, the track deterioration sensitivity from these three aspects to the changes in track structure, geometry and traffic parameters is investigated.

3.1. Analysis of Track Parameters From Geometry Aspect

The effect of different parameters on TQI is evaluated by plotting the parameters in the Bing-Gross model against TQI_2/TQI_1. Referenced values, considered for the parameters in this model are based on Table 1.The sensitivity of future TQI to initial track condition is illustrated in Figure 1. It indicates that the effect of initial track condition on future TQI is significant. Based on the results presented in this figure, any increase in the initial track quality index from 0.04 to 0.5 results in a 77 % change to TQI_2/TQI_1. Also it is demonstrated that the sensitivity of the track quality index with respect to change in initial TQI for small values of TQI is larger than that for high values. For example an increase of initial TQI from 0.04 to 0.2 results in a 60 % change to TQI_2/TQI_1 while it's increase from 0.2 to 0.5 results in a 41 % change to TQI_2/TQI_1.

The effect of Ballast Index on the change in TQI is plotted in Figure 2. This figure indicates that there is a 66 % change in TQI_2/TQI_1 when increasing the aggregate index from 40 (for granite) to 65 (for lime stone). In other words, by reduction of the ballast type (from granite to lime stone), the track condition is substantially reduced. That is, track quality conditions are considerably influenced by the condition of the ballast.

Figure 3 indicates the influence of train speed on TQI_2/TQI_1. It is shown that the effect of train speed on future TQI is not as significant as other parameters. Based on the results an increase in train speed from 20 to 120 (mph) results in 27 % change in TQI_2/TQI_1.

As presented in Figure 4, rail age is less effective on the geometry conditions of the track. Based on this figure, the influence of a change in rail age from 0.5 to 5 years on TQI_2/TQI_1 is only 22 %.

3.2. Analysis of Track Parameters from super-Structural Aspect

The effect of different parameters on the degradation of the track superstructure is evaluated by plotting the parameters in the Sato model against growth of track super-structure irregularity. The referenced values considered in this study are: axle load 20 ton, train speed 100 km/h, annual tonnage 15 million ton, rail modulus of elasticity 2.1×10^5, rail moment of inertia 3055 cm^4, car unsprung mass 43 kg, car sprung mass 460 kg, sleeper spacing 600mm, coefficient of subgrade reaction 100 KN/mm^3, railpad stiffness 500 KN/mm, ballast depth 300 mm, ballast type granite, ballast and drainage condition moderate, and rail type CWR.

The influence of rail type on the growth of track irregularity is presented in Figure 5. In this figure a comparison is made between the annual passed tonnage and the average growth of track

TABLE 1. Referenced Values Considered for Bing and Gross Model.

Effective Parameter	TQI_1	TQI_1^*	V_E	V_E^*	RA	RA^*	BI	BI^*	FS
Referenced Value	0.04	0.04	100	100	1	1	80	80	0

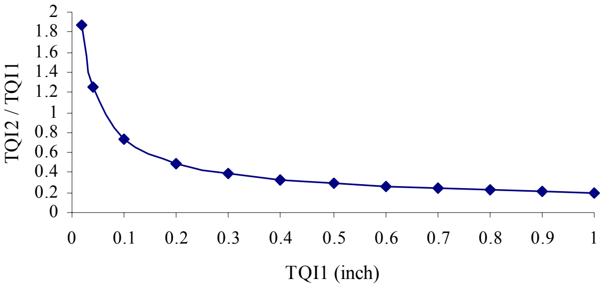

Figure 1. The influence of initial TQI on the future track quality index.

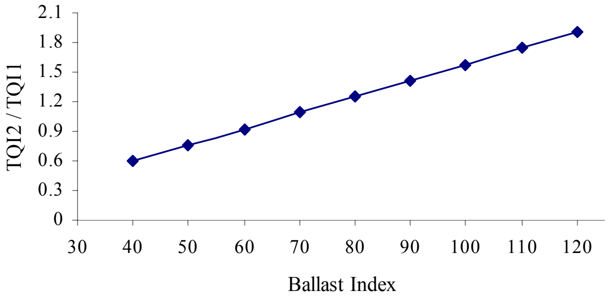

Figure 2. Ballast type against track quality index.

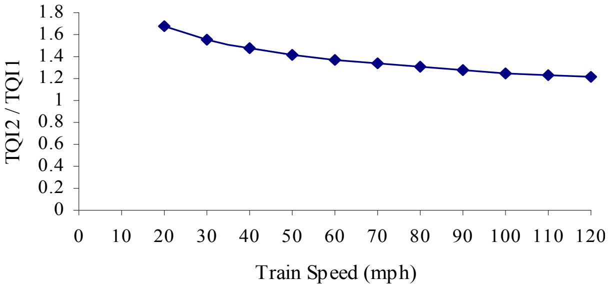

Figure 3. The influence of Train speed on the future track quality index.

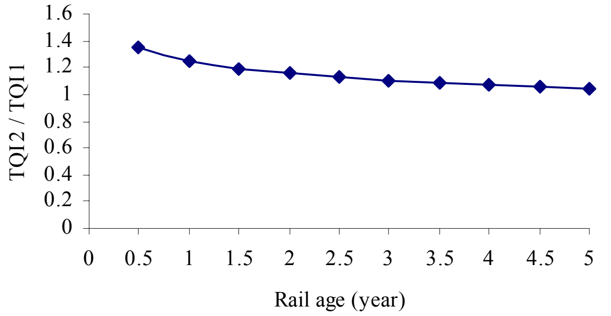

Figure 4. The influence of Rail age on the future track quality index.

irregularity for jointed and welded rails. Based on the results, it can be deduced that, for the same values of track irregularity in jointed and welded rails, the allowable tonnage for a continuous welded track is five times more than that for jointed tracks. It is shown that for an annual tonnage of 15 million tons per year, a rail type change from CWR to jointed rail results in an 80 % increase in the average growth of track super-structure irregularity.

The affect of tonnage on the irregularity of welded track also can be deduced from Figure 5. This figure indicates that the growth of track super-structure irregularities is approximately proportional to the third root of the passed tonnage. As indicated, there are considerable changes in irregularity growth when increasing the tonnage from 1.5 to 15 million tons per year. However, for tonnage more than 15 million tones, tonnage does not significantly influence the analysis results. Using this figure, the allowable passed tonnage of a jointed track can be predicted. For example, if the growth of track irregularity is being scheduled for 0.27 mm per 100 days, the allowable passed tonnage should be 15 million tons per year. This figure indicates an increase in tonnage from 5 to 15 results in a 62.5 % increase in the average growth of track super-structure irregularity.The results of the analyses of the model for different speeds are presented in Figure 6. According to this figure, there is a considerable change in track super-structure irregularity when the speed increases. This figure indicates that the influence of speed on growth of track irregularity is 3 times more than that of changes in tonnage. For a tonnage of 15 the increase of train speed from 80 to 200 (km/h) results in about a 150 % increase in the average growth of track irregularity.To investigate the sensitivity of the track irregularity to the subgrade condition, a comparison between the allowable annual tonnage for a track in poor, moderate and good subgrade conditions is made. According to

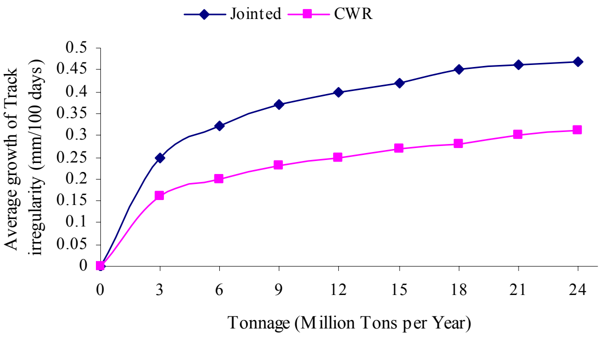

Figure 5. The influence of rail type on the average growth of track irregularity.

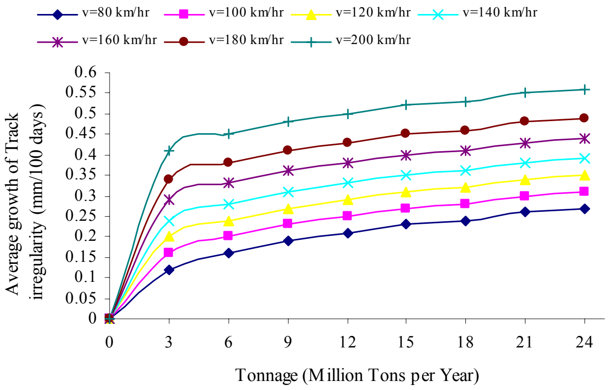

Figure 6. The influence of speed on the average growth of track irregularity.

Figure 7, the results indicate that the allowable annual tonnage for track with a subgrade in good conditions is 4 times more than that for a poor subgrade condition**.** It is shown that for the annual tonnage of 15 (million tons per year), if the subgrade condition changes from good to poor, it results in a 140 % increase in the average growth of track super-structure irregularity. To determine the effect of rail pad stiffness on the average growth of track super-structure irregularity, the coefficient of track deterioration versus pad stiffness is obtained and the results are presented in Figure 8. It indicates that there is a considerable increase in the growth of track irregularity when increasing the pad stiffness, but any increase after 600 KN/mm does not significantly change the track super-structure irregularity. As shown, the increase of rail-pad stiffness from 100 to 600 (kN/mm) results in about a 60 % increase in average growth of track irregularity. The reduction of irregularity for less stiff pads is probably due to reduced vibration transmission to the sleepers. Figure 9 indicates a linear correlation between the average growth of track super-structure irregularity and the increase of sleeper spacing. There is a 47 % increase in track irregularity when increasing sleeper spacing from 500 mm to 750 mm. The reduction of sleeper spacing to less than 500 mm is not practical, since it reduces the possibility of full tamping.

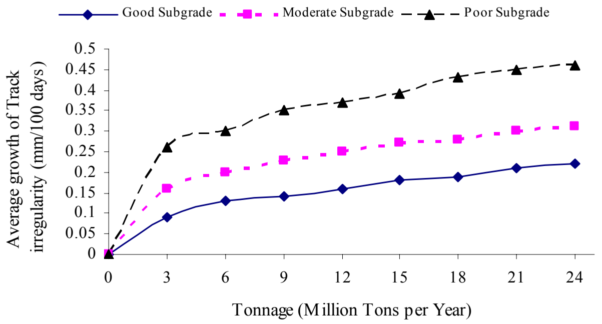

Figure 7. The influence of subgrade condition on the average growth of track irregularity.

3.3. Analysis of Track Parameters From Sub-Structural Aspect

To investigate the effect of different parameters on the track degradation from the sub-structure perspective, the parameters in the Shenton model are analyzed. Referenced values, considered for parameters in this study are as presented in Table 2. Considering the track ballast settlement as the main track degradation criterion from the sub-structure aspect, the sensitivity of the track settlement to increase in the axle load, load cycle and lift by tamping machine is studied here, using the results obtained from the Shenton deterioration model. Results demonstrate that an incremental increase in axle load and load cycle accelerates the rate of deterioration. The results, presented in Figure 10, indicate an almost linear relationship between the axle load and track settlement. That is, a 1.5 mm increase of track settlement is made by a 2 ton increase in axle load. The study of the changes to

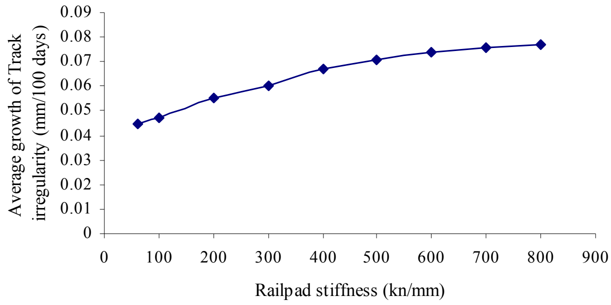

Figure 8. Rail pad stiffness versus the Average growth of track irregularity.

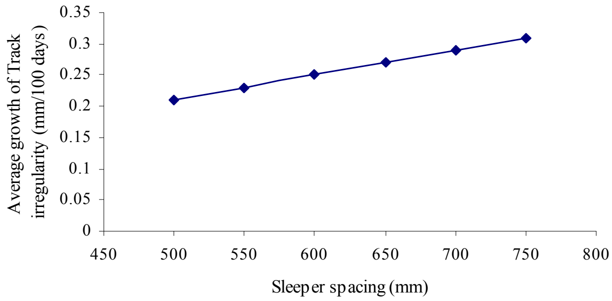

Figure 9. The influence of sleeper spacing on Average growth of track irregularity.

TABLE 2. Referenced Values Considered for Shentom Model.

Effective parameters	A_e (ton)	N (axle)	L (mm)	K_s
Referenced value	20	1000	20	1

the track settlement due to the number of load cycles indicates that the rate of the track settlement over the load cycle increases as the axle load increases and that the track degradation is more sensitive to the change in load cycle for high values of axle loads. Based on Figure 10, an increase in the number of load cycles from 100 to 10000 results in about a 166 % increase in track settlement. Also change of axle load from 16 to 22 ton results in 77 % increase in track settlement. As indicated in Figure 11, there is a linear relationship between the lift by tamping machine and track settlement. This figure demonstrates that an increase of lift by tamping machine from 4 to 40 mm results in about a 133 % increase in the track settlement.

4. CONCLUSION

Efficient and cost effective railway track maintenance can be achieved by controlling track deterioration. In this paper railway track and its traffic parameters influencing degradation of those track were introduced and the roles of each parameter in its deterioration were studied. The results presented here are based on the comprehensive study of railway track degradation

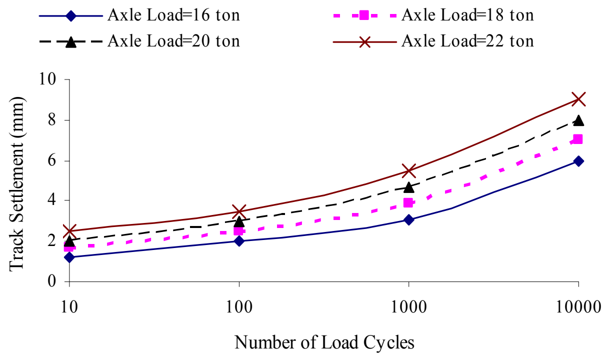

Figure 10. The influence of axle load and number of load cycles on the track settlement.

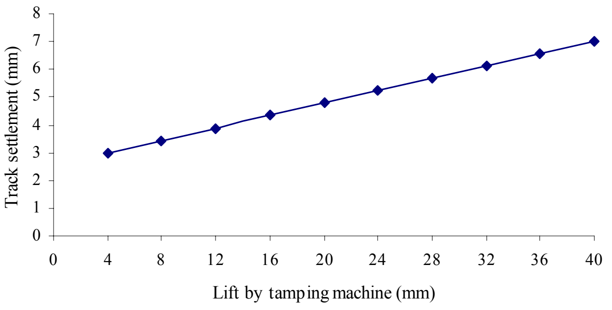

Figure 11. influence of the lift by tamping machine on the track settlement.

from the aspects of super-structure, sub-structure and geometry. The changes in TQI (Track Quality Index), the track settlement, and the average growth of track irregularities were considered as the track's main deterioration criteria for the track's super-structure, sub-structure and geometry aspects, respectively. In this research the sensitivity of the track deterioration to the most relevant parameters of ballast conditions, subgrade compaction, rail-pad stiffness, rail types, sleeper spacing, initial track quality, tonnage, train speed, axle loads, and load cycles were studied. From the results obtained in this research the following conclusions are drawn.The allowable annual tonnage for a track with a good quality subgrade is 4 times more than that of one with poor subgrade quality. It is shown that jointed rails causes a lower quality track in comparison with the continuously welded rail (CWR). Based on the results, it can be deduced that for the same values of track irregularity for jointed or welded rails, the allowable tonnage on a continuous welded track (CWR) can be five times more than that of jointed tracks.The results indicates that the growth of track's super-structure irregularities is approximately proportional to the third root of the passed tonnage. It is shown that there is a considerable change in track's irregularity when the speed increases. A comparison between the results indicates that the speed's influence on the irregularity growth of track's super-structure is 3 times more than that of the changes in tonnage. It also shows that the rate of settlement versus the load cycle develops as the axle load increases which is to say, track settlement is more sensitive to change in load cycle for higher values of axle loads. A short summary of the results is presented in Table 3. Including, the influences of the track's structural parameters (ballast index, pad stiffness, rail type, rail age and subgrade condition), track's geometrical parameters (sleeper spacing, the lift by tamping machine and initial track quality indices), and traffic parameters on the track degradation are rated in Table 3. In this table, each parameter is assigned an influence factor indicating the amount (importance) of influences of the parameters on the track's degradation. The factor for the parameter with the least effect on the degradation is considered to be one. The factor for the other parameters is obtained by dividing the quantified influences of the parameter on the degradation by that of the least influencing parameter. For example the influence of train speed on the super structural degradation is 3.19 times more than that of the sleeper spacing.

It is known that the expenditure during the planning and construction phase of a railway system is relatively small compared to the total cost. This means that decisions made to reduce the costs during construction, e.g., the selection of low quality track elements or lack of provision of adequate drainage, may reduce construction costs but will result in higher maintenance cost and train delay times which in turn, consumes these savings several times over. In other words, achieving an optimum efficiency in the track repair and maintenance during its life cycle may result in a significant reduction of the total cost of the railway. The results presented here highlights the role of each, the track and traffic parameters on the degradation of the tracks sub structure, super-structure and track geometry. These motivating research results inspire the implementation of efficient and cost effective maintenance plans and incorporate effective track deterioration controls.

5. ABBREVIATIONS

TQI	Track Quality Index
CWR	Continuous Welded Rail
BI	Ballast Index
AI	Aggregate Index
BC	Ballast Condition
DF	Drainage Factor
RA	Rail Age
FS	Fraction of Segment Surfaced
MGT	Million Gross Ton

6. NOMENCLATURE

L	Load factor and lift given by the tamping machine
M	Structure factor and unsprung mass

m	Sprung mass and intermediate mass
N	State factor and load cycle
K	Car factor
ξ	Constant of spring characteristics
P_b	Maximum sleeper pressure
k_1	Rail pad stiffness
EI	Flexural rigidity of rail
S	Average growth of track irregularity and ballast settlement
T	Annual passed tonnage
V	Running speed
P	Influence factor for subgrade
TQI_1	Initial track quality index
TQI_2	Final track quality index
V_E	Equivalent train speed
V_E^*	Arbitrary fixed reference values of equivalent train speed
RA^*	Arbitrary fixed reference values of rail age
A_e	Equivalent axle load
K_s	Factor of sleeper type and size, ballast and subgrade type

7. REFERENCES

1. Sadeghi, J., “Algorithm of Iranian TMMS”, Second Research Report No. F11/19016, Iran University of Science and Technology, Iran, Tehran, (2005), 14-23.
2. Sadeghi, J. and Akbari, B., “Field investigation on effects of railway track geometry parameters on rail wears”, ***International Journal of Zhejiang University, Science A***, Vol. 7, (2006), 1846-1855.
3. Chrismer, S. and Selig, E. T., “Computer model for ballast maintenance planning”, ***5th International Heavy Haul Railway Conference***, Beijing, (1993), 223-227.
4. AREMA., “Manual for Railway Engineering”, American Railway Engineering and Maintenance-of-Way Association Publishing Service, Washington DC,

TABLE 3. Rating of Parameters Influences on Track Deterioration from Different Aspects.

<table>
<tr><th>Item</th><th colspan="2">Traffic Parameters</th><th colspan="3">Structural Parameters</th><th>Geometrical Parameters</th></tr>
<tr><td rowspan="2">Track Sub Structural Degradation</td><td>Axle Load</td><td>Load Cycles</td><td colspan="3" rowspan="2">-</td><td>Lift by Tamping Machine</td></tr>
<tr><td>1</td><td>2.15</td><td>1.73</td></tr>
<tr><td rowspan="2">Track Super Structural Degradation</td><td>Tonnage</td><td>Train Speed</td><td>Rail Pad Stiffness</td><td>Rail Type</td><td>Subgrade Condition</td><td>Sleeper Spacing</td></tr>
<tr><td>1.33</td><td>3.19</td><td>1.27</td><td>1.7</td><td>2.98</td><td>1</td></tr>
<tr><td rowspan="2">Track Geometry Degradation</td><td colspan="2">Train Speed</td><td>Ballast Index</td><td colspan="2">Rail Age</td><td>Initial Track Quality Index</td></tr>
<tr><td colspan="2">1.22</td><td>3</td><td colspan="2">1</td><td>3.5</td></tr>
</table>

U.S.A., Vol. 4, (2006).

5. Uzarski, D. R., Brown, D. G., Harris, R. W. and Plotkin, D. E., "Maintenance Management of U.S. Army Railroad Networks-the RAILER System", Technical Report No. FM-94/01, USCERL, (1993), 120-240.
6. Mundrey, J. S., "Railway Track Engineering", McGrew-Hill, New Delhi, India, (2003).
7. Sato, Y., "Optimum track structure considering deterioration in ballasted track", ***6th International Heavy Haul Conference***, Capetown, (1997), 576-590.
8. Shenton, M. J., "Ballast deformation and track deterioration", ***Journal of Track Technology***, Organized by the Institute of Civil Engineers, University of Nottingham, Vol. 12, (1984), 253-264.
9. Bing, A. J. and Gross, A., "Development of railway track degradation models", ***Transportation Research Record*** **939**, (1983), 27-31.