Railway Track Geometry Defects and Deterioration, a Literature Review

Chebaran Jonex, Sibomana Aime Aliphones, Zewdie Moges

Abstract- The assessment of track geometry defects is an important requirement for safe rail operation. Track geometry defects represents safety risk for the railway traffic and leads to a reduction of passenger ride comfort whereas a good track geometry quality provides good ride comfort for passengers and prevents the track from wearing too quickly. Hence the recognition of defects leading to essential vehicle responses is of crucial interest in track geometry assessment. The defects in track geometry are mostly used to characterize the quality of the track and to plan track maintenance. There have been many railway engineering related topics addressed through various studies in attempt to monitor and identify, measure and quantify, and propose appropriate remedial actions to track geometry defects. However, there has been inadequate study on the direct interactions concerning the degree of geometry defects and track deterioration together with corresponding maintenance activities. This paper conducts an examination and presents analysis of selected available research about railway track geometry defects, track deterioration and maintenance operations through embracing a systematic literature review (SLR) as the leading methodology. We start by giving a brief about track geometry, categorizing the track geometry parameters and track quality indicators, highlighting the effects of good track geometry and maintenance activities on the railway track performance. Track geometry defects are identified through critical examinations. The paper then investigates the cause-and-effect phenomena of track geometry defects and general track structural deterioration and an assessment of their remedial actions so as to minimize track deterioration and improve track serviceability.

Index terms: track geometry, geometry defects, deterioration, track quality, tamping, stoneblowing.

1. Introduction

Railways are a vital and effective means of mass transportation and play a vital role in modern transportation and social development. In an effort to achieve increased capacity in terms of both passengers and freight, the rail sector is moving towards higher train speeds, heavier axle loads and greater traffic density. This is due to the fact that railway transportation has high capacity, high efficiency, and low pollution compared to other transportation modes [1]. Railway track structures withstand severe conditions and numerous detrimental loading progressions in their life cycle [2].

During its life cycle, which usually lasts many decades, with train passing, the loads transmitted to the infrastructure, cause cyclic movements in the ballast particles, thereby causing deformation of the layer to take place, in which part of such strain is recovered, but a small deformation is permanent owing to ballast recompaction [3]. In addition, there is the accumulative deformation associated with ballast breakage and frictional wear, which serves to intensify the track degradation [4]. Railway track will settle as a result of permanent deformation in the ballast and underlying soil .The settlement is caused by the static and dynamic forces induced by traffic, which cause deviations from the designed geometry. Track geometry represents one of the key track condition parameters, also closely linked to several other degradation occurrences, and is regularly used for initiating the whole sort of track Maintenance and Renewal activities [5]. Track geometry can be defined as the three-dimensional geometry of the track [6] which includes: the sub-structural, the super-structural and the geometrical. As the track geometry begins to deteriorate, higher dynamic wheel-rail contact forces are being induced, resulting in wear on the various components of the track construction, plastic deformation and Rolling Contact Fatigue (RCF) of the rails [7]. The defects in track geometry are mostly used to characterize the quality of the track and to plan track maintenance. It is worth noting that, irregular track geometry can cause increased track loading that can lead to a high risk of derailment, and reduced component useful life [8].

The track geometry is affected by several factors including the condition of the superstructure elements (rails, fastening system, rail pads and sleepers), the condition of the substructure (ballast, sub-ballast and subgrade), traffic density, speed, axle load, environment and current maintenance strategies, among others [9]. According to [10] Studies that were made on how track geometry defects affect the development of rail defects, the outcomes revealed that there was a statistically substantial link between geometry defects and rail defects, when the geometry defect preceded the rail defect. Analysis showed that, if a track geometry defect is present, rail defect life is reduced by approximately 30% [11].

The sole purpose of this study is to conduct an examination about track geometry defects and deterioration also synonymous to track geometry degradation. The paper is focused on identifying and quantifying geometry defects, their corrective maintenance actions effectiveness on restoration of track geometry and contribution to track performance and durability. The overall objective therefore is ensuring safe track operation, reduce risk of derailment and lifecycle costs that are incurred on the track structure due to extreme degradation and frequent maintenance. Particularly this research study examines how researchers of selected literature viewed track geometry defects and general track structure deterioration.

2 Approach

This paper is purely based on the literature review since investigation about track geometry has been carried out by many researchers for the last fifty or more years. The findings reported in this paper are based on an analysis of literature and standards [12]. The reason for undertaking a systematic literature review (SLR) as the leading methodology for the study is to find an in-depth current state [13] of track geometry defects and degradation knowledge in the range of track infrastructure development and maintenance. Besides, SLR is largely considered to be genuine in terms of transparency as other researchers can further certainly validate the findings of the study by reproducing the research format [14].

We adopted a systematic literature review methodology of data selection, extraction, analysis and synthesis as shown in the figure1 below on the topical issue. The improvement of a systematic literature review is characterized by using an objective and rigorous research protocol aiming to minimize researcher bias [15]. This was through an organized, transparent and replicable procedure at each step of the process.

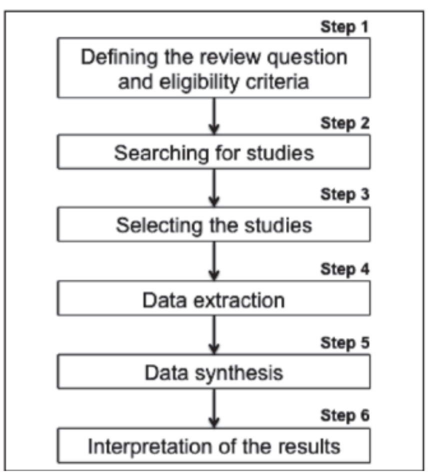


Figure 1: Steps in conducting a systematic review

To meet our research objectives, we chose to carry out a systematic literature review (SLR) focusing on the leading journals that publish railway and civil engineering research. To ensure suitably in-depth analysis of our research field, we undertook to aim our literature search to the subsequent journals: International Journal of Railway Research (IJRARE), International Journal of Rail Transportation (IJRT), Railway Engineering Science (RES), Rail Journal (RJ), International Journal of engineering research and technology (IJERT), Journal of advanced transportation (JoAT), International Journal of Railway technology (IJRT), Journal of Railway Engineering Society (JoRES), Journal of rail and rapid transit, and Journal of Geotechnical and Geoenvironmental Engineering. Our search for articles from these journals was aided by academic and social networks databases such as ResearchGate, ASCE, Springer, Science Direct, SAGE, JSTOR and some Publishers of quality peer-reviewed journals, Fully Open Access Journals specifically Hindawi, Taylor & Francis, Elsevier, Library, ice virtual library and ASCE library to retrieve the full research articles for our study. Overall, ResearchGate produced the most articles. Combined, these journals publish the majority of academic research focusing on railway engineering.

3. Methodology

In our study, we used the systematic literature review methodology of data selection, extraction, analysis and synthesis [16]. The data selection involved a systematic periodic search for articles related to railway track geometry and defects. We used Google Scholar as a search engine and although there is a debate within the scientific community on the use of Google Scholar as an academic database, it is also considered to provide "unique options" [17] to the academic community, We had to follow the recommendation that "researchers should consult Google Scholar especially for a relatively recent article, author or subject area" [18]. In this study, we considered articles published in the last 30 years to be recent and the total of 120 articles from all the downloaded articles were selected for the study. As search strings, we used the terms 'Track geometry defects' or 'Track geometry deterioration' simultaneously with 'railway track degradation'. We repeated the search with the intersection of track defects or deterioration.

3.1. Describing the review question and eligibility criteria.

We began by analysing the thematic area of track geometry defects and deterioration and geometry correction (maintenance) techniques to develop relevant objectives of the research study. From these objectives, research questions were formulated. A general research question corresponding to the main purpose as well as specific questions from the specific objectives were developed. Since the track geometry defects are interrelated to the other track degradation aspects of substructure and superstructure as well as excitation force; the wheel rail interaction, four specific objectives were considered appropriate

3.2 Selecting the studies (research articles)

We followed the recommendation of [19] which suggests that the selection of the studies should be conducted by more than one reviewer as this process is quite subjective. To avoid the risk of bias, we all read through the articles that seemed most relevant to study and that closely answers our study objectives. More focus was attached to the year of publication and content quality to guide in upholding the quality of the study.

3.3 Data extraction

Franco & Mario, 2009 [19] asserts that Data extraction must be accurate and unbiased and therefore, to reduce possible errors. This was done by more than two people. We mainly focused on the research paper study characteristics that include aims of the study, and techniques used. We also aimed at removal intervention and setting, outcome data, study results together with identifying the study gaps and suggestion for future studies.

3.4 Analysis and presentation of the results (data synthesis)

We combined our extracted data, analysed it and pulled it into the next chapter in a narrative approach. We also used Mendeley desktop, one of the referencing tool to reference the research study.

4. Review of Articles on Geometrical Track Quality

Track geometry refers to the position of each rail or the track centreline in three-dimensional space According to EN 13848-1 (2008), track geometry quality is defined as the "assessment of deviations from the mean or designed geometrical characteristics of specified parameters in the vertical and lateral planes which give rise to safety concerns or have a correlation with ride quality" [20].

4.1 Track geometry parameters

These are broadly used to characterize the track state and to plan maintenance activities [21]. Track geometry is characterized by five geometrical parameters; longitudinal level, alignment, gauge, cross level, and twist. Figure below show the definitions of the deviations of those five parameters [22]. The assessment of geometrical track quality can be conducted by analyzing these five geometrical indicators separately as proposed by the European Standard EN 13848-5 or by track quality indexes (TQIs) that might combine the track irregularities in two or more dimensions [23].

I. Longitudinal level

Longitudinal level is the geometry of the track centreline projected onto the longitudinal vertical plane. This parameter is defined as the vertical deviation (zp') of consecutive running table levels on the top of the left or right rail from the mean vertical position (the reference line)

II. Alignment

Alignment is the geometry of the track centreline projected onto the longitudinal horizontal plane. This parameter is defined as the horizontal deviation (yp) of consecutive positions of point P (see Figure 2 below) on the left or the right rail from the mean horizontal position (the reference line)

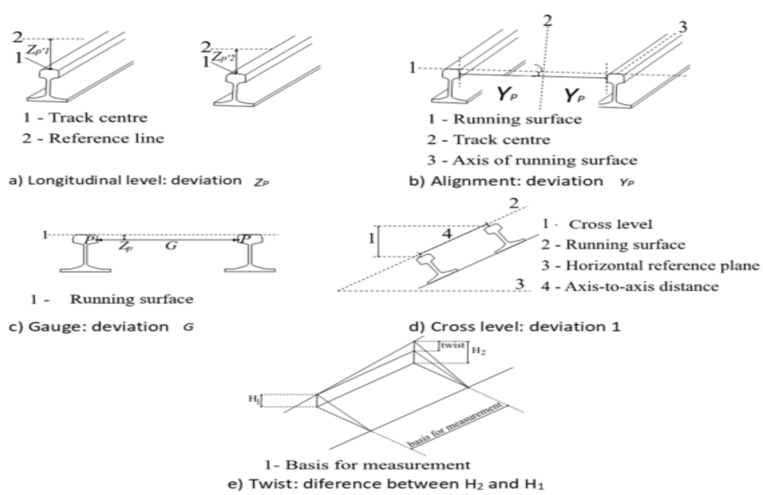


Figure 2: Track geometry parameters

III. Gauge

Gauge specifies the inner distance between two rails measured at 16 mm below the top surface of the railhead [24].

IV. Cant

The cant or cross-level is the difference in height between the adjacent running tables computed from the angle between the running surface and a horizontal reference plane.

V. **Twist**

Twist is the algebraic difference between two cross-levels taken at a defined distance apart, usually expressed as the gradient between the two points of measurement [6]

4.2 Assessment of track geometry quality

Assessments of railway track quality conditions constitute the basis of track maintenance management systems by which decisions on maintenance and repair strategy are often made. The main limitation in the current assessments technique is the lack of information on track structural defects, which are the main causes of track irregularities [25] .

Three indicators can define the track geometric quality; Extreme values of isolated defects, Standard deviation over a defined length (typically 200 m) and Mean value. Thought should be given to progressions of isolated defects since they could produce resonance effects, and to combinations of defects in several parameters at the same location. Three main levels shall be considered [26], [27]

- Immediate Action Limit (IAL): denotes to the value which, if exceeded, necessitates taking measures to reduce the risk of derailment to an acceptable level.
- Intervention Limit (IL): denotes to the value which, if exceeded, necessitates remedial maintenance so that the immediate action limit shall not be reached before the following inspection
- Alert Limit (AL): refers to the value which, if exceeded, necessitates that the track geometry condition is investigated and considered in the often prearranged maintenance actions.

4.3 Analysis of Track Parameters from Geometry Aspect

Track Quality Index (TQI) is defined as a numerical value that represents the relative condition of the track surface geometries [24]. TQI is distinguished into two dependent variables; Track Geometry Index (TGI), which is defined as a function of one or more of the core geometry parameters such as profile, alignment, gauge, cant, and twist. 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. TQI is a statistical summary of a track geometry parameter measured within a suggested length of track and effectively summarized a large number of quantities of each parameter for a given track segment [28], [29].

Bing-Gross model evaluated the effect of different parameters on Initial Track Quality Index (TQI) against TQI_2/TQI (future track quality index) as follows;

- It was indicated that, the effect of initial track condition on future TQI is significant. Based on the results, it was found that an increase in the initial track quality index from 0.04 to 0.5 resulted in a 77 % change on TQI_2/TQI_1. Also it was demonstrated that the sensitivity of the track quality index with respect to change in initial TQI for small values of TQI is higher than for big values as increase in initial TQI from 0.04 to 0.2 resulted 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 [30].

- The effect of Ballast Index on the change in TQI indicated 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 [31].

- The influence of train speed on TQI_2/TQI_1 was shown that, 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.
- Rail gauge is less effective on the geometry conditions of the track [32].

To represent the track quality condition various researchers applied different TQIs. Mainly, the three indicators, i.e. mean value, standard deviation over a specific length, and extreme values of track geometry parameters are used to define TQIs. [33], [34].

5. Review of articles on effects of railway track design on expected degradation

Mehran Sadri, Michael Steenbergen * [35] conducted a study on the effects of railway track design on expected degradation assuming a geometrically faultless and straight track along with spatial invariability, except for the presence of discrete sleepers. The susceptibility of the track to degradation was quantitatively computed by means of calculating the mechanical energy dissipated in the substructure under a moving train axle for variations of diverse track parameters. Results show that, apart from the operational train speed, the ballast/substructure stiffness is the major parameter inducing energy dissipation. Largely, the deterioration of the track varies with the train speed and the stiffness of substructures.

Michaël J.M.M. Steenbergen [36] studied the role of varying dynamic stiffness on railroad degradation; and argue that, spatially invariant and straight track assumption of analyzing effects of track stiffness on degradation is no longer true because geometrical and/or constitutive track properties are non-uniform over the length. Such discontinuities appear on many scales; the sleeper bay is an example with a periodical character, whereas examples with a related character are level crossings, bridges, tunnels, abutments, culverts but also switch panels and ballast and foundation stiffness variations. So, these irregularities are also responsible for influencing expected track degradation due stiffness variation created by nonuniformity along the track.

6. Review of Articles on track geometry maintenance activities

Measurement of track geometry irregularities is the most used automated condition monitoring technique in railway infrastructure maintenance. Most problems with the track (at least the ones concerning the ballast and substructure) are unveiled as track geometry irregularities [37].

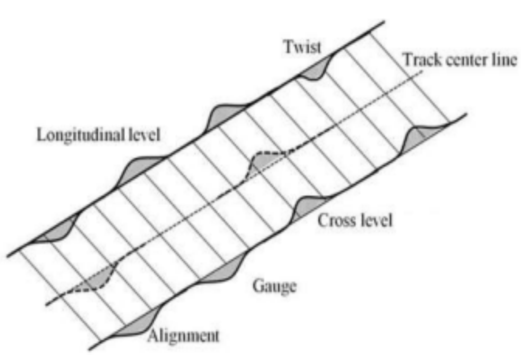


Figure 3: Track irregularities

A track defect is a section of the endless track geometry indication of deviations from the design shape which can provoke important dynamic vehicle reactions [38].

With the increasing demand for higher train speeds and capacities (passengers and freights), substructure is experiencing more extreme shock and vibration causing swift deterioration of the ballast bed [39]–[41]. Accordingly, it is crucial to reinstate ballast bed performance through implementation of corrective actions. To restore track geometry, there are two main maintenance actions that can be performed, stone blowing procedure and tamping procedure [8], [42]

6.1 Ballast Tamping

To align the track geometry, tamping is the most widely used means of filling ballast sleeper gaps and homogenizing ballast beds [43] as a maintenance activity and it is necessarily performed for newly built railway lines. In addition, it improves the ballasted track geometry by lifting up and shifting the rail and sleeper. The main objective of tamping operation is to compact the stone ballasts under sleepers supporting the railway, squeezing and vibrations. The degree of ballast compactness is used as a measure to assess the quality of tamping action. Currently the tamping machine has substituted manual tamping in rapid, highly mechanized and automatic directions.

6.1.1 Tamping process

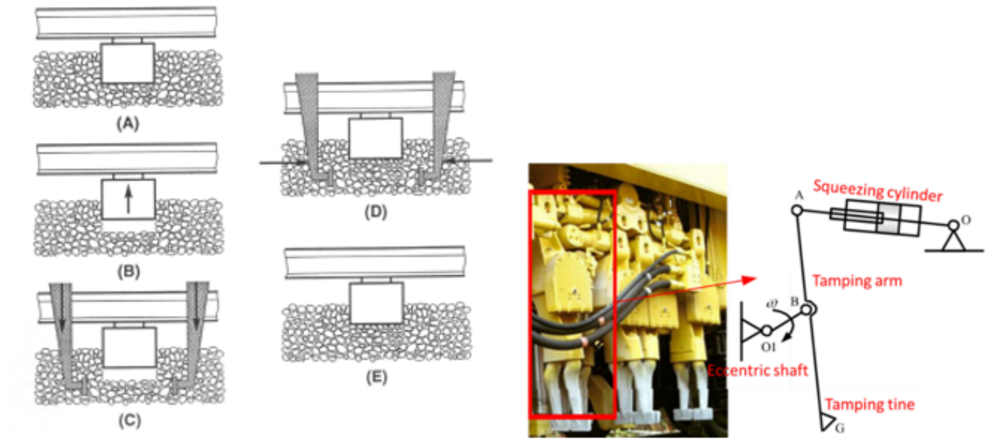
Non-synchronous uniform pressure tamping causes the ballast to be compacted under the sleepers due to the effect of vibration and pressure-controlled squeeze force, taking not the paths of the tamping tines as a criterion but their effective tamping forces [44].

- The ballast bed is made homogeneous through the knocking of ballast particles to relocate to most stable positions by tamping tine oscillations
- The crib ballast particles are forced to move to the position below the sleeper, by which the sleepers have better support from the ballast bed by the squeezing action of the tamping tines.
- Due to lifting the track, the track geometry irregularity is corrected, including the surface (longitudinal level or vertical alignment), alignment (horizontal alignment), cross level (cant), and warp (twist) [16]

The entire tamping process is as follows [45];

(A) The track and sleeper are in an arbitrary position before tamping begins.

(B) The track and sleeper are raised by the machine to the target level. As a result, a gap is created under the sleeper.
(C) The tamping tines are inserted into the ballast on both sides of the sleeper. This step can cause ballast damage.
(D) The tamping tines squeeze the ballast into the gap under the sleeper. Therefore, the right position of the rail and sleeper is recovered. This might also cause ballast breakage.
(E) The tamping tines are lifted from the ballast. They will then move on to tamp around the next sleeper.



(a)Tamping sequence [46] (b)Tamping unit produced by Matisa [47]

Figure 4: Tamping unit and tamping sequence

6.1.2 Tamping principle

The most widespread tamping principle worldwide is using tamping tines that are penetrated in the ballast layer in zone near the rails [48]. The physical process of tamping is briefly described as follows.

- First the tamping tines are inserted into ballast beds with vibration. The vibration is a transverse wave that makes the ballast bed loose, for which the tamping tines easily penetrate [49].
- After the tamping tines have penetrated the ballast bed, longitudinal wave vibrations are applied. Ballast particles currently have two kinds of motions [45].

Main tamping technologies aim at achieving the following [43]; high-alignment, high-homogeneity and high-uniformity.

6.1.3 Effects of tamping on ballast performance

The ballast is one component of the track that undertakes important purposes: retaining track position, transmitting exertions to the underlying materials and providing drainage for rainwater. Moreover, the ballast can be rearranged during maintenance to restore the track geometry [50]. For this reason, railway tracks require periodic profile corrections, the most common technique being the tamping of the ballast [44] .However, the action of tamping is associated with several effects and can lead to additional subsequent track settlement from the disturbances caused by the tamping tools [46], [51]. The mechanical properties of ballast bed largely increase at first, and then decrease with the increase of tamping frequency and tamping depth [52]. In view of these problems associated with tamping, recent decades have seen the development of several alternative solutions aimed at improving the quality of the track, while simultaneously improving the durability of the ballast layer. One particular alternative is the maintenance process known as stone blowing.

6.2 Stoneblowing and effects on ballast performance

Stone blowing process was motivated by the observation that after tamping ballast tends to go back to the condition that was there before tamping [8]. This process consists of the insertion of stones between the sleeper and the surface of the ballast layer, filling the empty space created by lifting and, therefore, recovering the original position of the railway track.

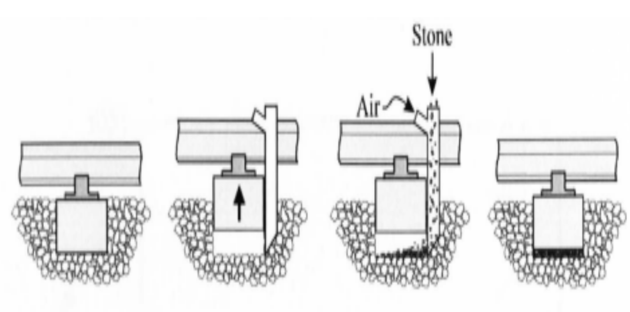


Figure 5: Stoneblowing sequence

6.3 Effect on Tamping and Stoneblowing on ballast settlement

It was observed that ballast tamping was the least efficient task, as it was extra difficult to reinstate the total deformation (after the tamping process, the settlement was still higher than 0 mm), and a higher number of maintenance interventions were needed to avoid settlements greater than 15 mm. This fact can be attributed to the ballast memory that is observed after the tamping process, which only enlarges the granular layer, and therefore, it quickly returns to its pre-maintenance position. In addition, the efficiency of ballast tamping was gradually reduced, because fewer loading cycles were applied after each intervention to obtain a deformation higher than 15 mm. In contrast, the process of stoneblowing allowed for the restoration of the total settlement of the track, and this process even allowed for a slight over-lifting in order to improve the durability of the track geometry [52], [53]. The results indicated that, the effectiveness of stoneblowing is more than four times higher than that of tamping, an observation which is more marked when the number of tamping tasks is increased, thereby reducing its effectiveness. Nonetheless, it should be noted that, after the application of stoneblowing, rapid settlement took place (although it was two times lower than the recompaction of ballast after tamping) as a result of the compaction of the small-sized stones that were added [4].

6.4 Influence of Tamping and stoneblowing on track behaviour

With regard to the impact of the maintenance tasks on track behaviour, and comparing the effect of the ballast tamping and stoneblowing processes on the evolution of track stiffness as well as values of density of dissipated energy, it was noted that in both cases, there is a progressive increase in track stiffness and reduction in its capacity to dissipate energy, which could be related to the continuous compaction of the ballast layer under the impact of passing trains. This process could lead to the development of a zone where there are changes in stiffness in reference to adjacent sections where no maintenance tasks are carried out. Consequently, acceleration in track degradation could take place due to the possible existence of higher dynamic overloads [54], while the track has a lower capacity to damp the loads transmitted by trains.

Introduction of under sleeper pads (USP) was adopted as a measure to mitigate problems of track stiffening and loss in dissipated energy capacity [55]. In both cases (tamping and stone blowing), the use of USPs permitted for a significant reduction in track stiffness along with an increase in its capacity to dissipate energy, an effect that was more noticeable with the use of soft pads. Thus, a reduction of 50% in the stiffness of the pad (from stiff to soft) led to an increase of more than 30% in the flexibility of the track and around 100% in its capacity to dampen loads, mainly related with higher elastic deformations [4].

6.5 Influence of Tamping and stoneblowing on ballast degradation

A high destruction and several tamping leads to a need of cost expensive ballast cleaning. The cause of the high destruction is a high contact pressure on ballast stones by squeezing operation and the tines penetration [48], [56]. Stone blowing allows for an important reduction in ballast breakage, because tampers are not used to vibrate ballast. The breakage indices obtained for the case of stone blowing were even lower than those measured when USPs were used in combination with tamping. The use of USPs could considerably improve the effectiveness of tamping and stone-blowing processes, particularly when using softer elastic pads [57]**.** The use of Under Sleeper Pads (USPs) and a process known as stoneblowing can be conceived as alternative maintenance solutions that aim to reduce the railway track degradation [58].

7. Discussion

In some cases, the track can deteriorate without any traffic (e.g. the soil may settle due to the weight of the embankment, especially in the early years after construction) but in most cases passing traffic is the driving force of deterioration [59]. The track geometry quality is related to the irregularities of the track structure and act as aid of excitation of the wheel rail force. As soon as the track geometry starts to deteriorate, the variations of the wheel/rail interaction forces will increase, and the track deterioration rate increases [54]. The track irregularity is of the character that, it grows under the train load and is rectified by tamping with multiple tie-tampers or by manual surfacing with beaters or tie-tampers [60] and stoneblowing. The lower the irregularities, the higher the track quality. Track gauge, twist, longitudinal and cross-level, alignment are examples of quantities that are used to assess the quality of a track. The analysis of track condition for consequent maintenance allows for identification of the extent of defects or deviations in five geometrical quantities.

The cause effect phenomenon in track degradation in a newly constructed or maintained track is a cycle in which the train loads (traffic parameters) causes permanent settlement of the track substructure (ballast/subgrade) which then triggers track geometry defects. The geometry defects initiates and exacerbates the development of super-structural defects which in turn causes considerable increase in wheel rail interaction forces [29], [61]. The wheel rail increased forces amplifies the railway traffic force and a corresponding effect is transferred to track substructure. Therefore, general track irregularities growth and severe degradation occurs gradually if timely intervention in terms of maintenance is not undertaken to distort the cycle as elaborated in Fig 6 below.

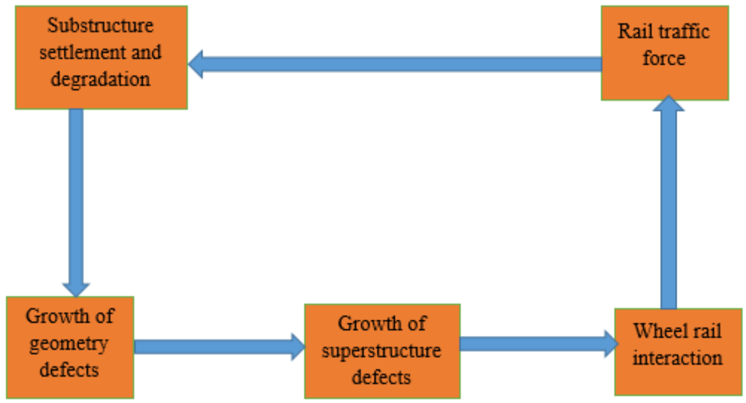


Figure 6: Cycle of cause effect track structure degradation

From the above figure of interaction of the three aspects of track deterioration (Sub-structural or degradation of the track substructure, Super-structural or degradation of the track superstructure and Geometry or degradation of the track geometry) [30], it is concluded that, track geometrical defects exacerbates the global track deterioration. Since substructure settlement due to train loading causes the growth of geometrical defects, it is therefore crucial that, the railway track design work and maintenance activities should be geared towards ensuring substructure stiffness of commendable mechanical performance and durability. This is especially attained by the levels of initial track quality index (TQI) and quality of the ballast material chosen for new construction.

When routine track inspections and monitoring reveals that, geometrical defects have grown to and beyond allowable established limits by standards, the most common track geometry correction mechanisms which has been highlighted in this paper is tamping and stoneblowing as the dominant maintenance activities. It was however noted that tamping operations cannot recover total deformation of the track and the settlement was greater than zero (0) mm. Additionally, the track was still susceptible to settlement within a short period of train passing due to the dilatant behavior of ballast during tamping which makes the ballast to quickly return to its pre-maintenance position. Stoneblowing however ensures total recovery of track deformation but, with the drawback of rapid settlement that takes place on the onset of train passing after maintenance which could trigger rapid geometry defects immediately after maintenance.

The use of under sleeper pads (USPs) in both cases of tamping and stoneblowing allowed for an important reduction in track stiffness along with an increase in its capacity to dissipate energy hence minimization of geometry defects growth rate after maintenance operations.

Based on the results obtained from laboratory study [4], it was noted, that the application of stoneblowing, instead of tamping, could considerably improve the mechanical performance and durability of railway tracks, which would lead to an important reduction in service and maintenance costs. In addition, the findings indicated that, its effectiveness could be even be higher than that obtained when USPs are employed (which also requires a notable increase in investment) together with tamping.

8. Conclusion

The great indicator of track degradation in most cases is the appearance of track geometrical defects. In order to properly analyse the extent of track degradation, continuous research into improving the accuracy and simplicity of identifying track geometry defects should be aimed at. Future work is suggested to fully develop a cost benefit analysis on the use of under sleeper pads (USPs) throughout the track length which could reduce on the frequency of tamping and long term corresponding maintenance costs. Further research is also encouraged to expand the understanding of train loadings to minimize track substructure deformation and degradation for an optimum design in attempt to control track geometry defects. Because tamping operation, as the most common maintenance operation is associated with ballast breakage and creation of fines that accelerates fouling problem, technology aspect of tamping is an issue for further study in an effort to limit its negative impacts while achieving the desired objective. This is justified by the fact that, there are limited companies controlling the core technologies for tamping machines and thus, the number of published studies on the same is limited [43].

Finally, we hope that this systematic literature review study can raise the desire of other engineering researchers to shape on and examine more about track geometry defects, overall track degradation phenomena and associated correction techniques.

9. Recommendations

- Accurate forecast and effective simulation of the growth of track geometry condition is essential for planning effective railway track maintenance.
- Train loads and speeds should be limited to design values for which an optimum design can safely withstand without excessive deformation and defect growth. Where it is deemed vital, track use can be restricted till unacceptable defect is resolved.
- Whereas the operational train speed and the ballast/substructure stiffness are the most significant parameters influencing energy dissipation and therefore track deterioration basing on the assumption of a geometrically perfect and straight track with spatial invariability[35], but logically there exist discontinuities (ie culverts, transition to bridges, hanging sleeper etc) causing nonuniformity and stiffness variation along the track [62] . This phenomena could as well have considerable influence to track behavior that could supersede the former (operation speed and ballast stiffness)
- Initial track quality index (TQI) influences the expected track degradation overtime and acceptable minimum should be achieved both for new constructions and during maintenance operations.

Declaration of Conflicting Interests

The authors declare that there are no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgment

The authors want to thank the World Bank (WB) for financing the railway engineering studies at the African railway center of excellence (ARCE) Addis Ababa. The authors would like to thank ARCE management for allowing us to be part of this scholarly journey as well as the anonymous reviewers for their comments that improved the paper and acknowledge the inclusion of some of their ideas.

References

[1] I. N. C. With, "The Future of Rail - Opportunities for energy and the environment," 2019, doi: https://doi.org/10.1787/9789264312821-en.

[2] M. Sauni, H. Luomala, P. Kolisoja, and E. Turunen, "Investigating Root Causes of Railway Track Geometry Deterioration – A Data Mining Approach," *Front. Built Environ.*, vol. 6, no. August, pp. 1–11, 2020, doi: 10.3389/fbuil.2020.00122.

[3] T. Dahlberg, "Some railroad settlement models - A critical review," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 215, no. 4, pp. 289–300, 2001, doi: 10.1243/0954409011531585.

[4] M. Sol-Sánchez, F. Moreno-Navarro, and M. C. Rubio-Gámez, "Analysis of ballast tamping and stone-blowing processes on railway track behaviour: The influence of using USPs," *Geotechnique*, vol. 66, no. 6, pp. 481–489, 2016, doi: 10.1680/jgeot.15.P.129.

[5] S. Jovanovic, "Railway track quality assessment and related decision making," *Conf. Proc. - IEEE Int. Conf. Syst. Man Cybern.*, vol. 6, pp. 5038–5043, 2004, doi: 10.1109/ICSMC.2004.1400992.

[6] I. Soleimanmeigouni, A. Ahmadi, A. Nissen, and X. Xiao, "Prediction of railway track geometry defects: a case study," *Struct. Infrastruct. Eng.*, vol. 16, no. 7, pp. 987–1001, 2020, doi: 10.1080/15732479.2019.1679193.

[7] A. F. Vikesland, "Track geometry degradation cause identification and trend analysis," no. May, 2019.

[8] M. S. Muinde, "Railway track geometry inspection optimization," p. 61, 2018, [Online]. Available: http://ltu.diva-portal.org/smash/get/diva2:1257286/FULLTEXT01.pdf

[9] P. Fair and S. W. F. Anderson, "The geotechnical behaviour for ballast materials of track maintenance railway," *Univ. Sheff.*, no. July 2003, 2003.

[10] A. M. Zarembski, N. Attoh-Okine, D. Einbinder, H. Thompson, and T. Sussman, "How track geometry defects affect the development of rail defects," *Proc. 2016 Annu. Conf. Expo.*, pp. 1081–1096, 2016.

[11] A. M. Zarembski, D. Einbinder, and N. Attoh-Okine, "Using multiple adaptive regression to address the impact of track geometry on development of rail defects," *Constr. Build. Mater.*, vol. 127, no. November, pp. 546–555, 2016, doi: 10.1016/j.conbuildmat.2016.10.012.

[12] A. J. G. Silvius and R. P. J. Schipper, "Sustainability in project management: A literature review and impact analysis," *Soc. Bus.*, vol. 4, no. 1, pp. 63–96, 2014, doi: 10.1362/204440814x13948909253866.

[13] A. Amiril, A. H. Nawawi, R. Takim, and S. N. F. Ab-Latif, "The importance and implementation of sustainability factors in Malaysian railway projects," *Proc. 30th Annu. Assoc. Res. Constr. Manag. Conf. ARCOM 2014*, no. August 2016, pp. 73–82, 2014.

[14] W. Aarseth, T. Ahola, K. Aaltonen, A. Økland, and B. Andersen, "Project sustainability strategies: A systematic literature review," *Int. J. Proj. Manag.*, vol. 35, no. 6, pp. 1071–1083, 2017, doi: 10.1016/j.ijproman.2016.11.006.

[15] L. Patrício and M. Franco, "A Systematic Literature Review about Team Diversity and Team Performance: Future Lines of Investigation," *Adm. Sci.*, vol. 12, no. 1, 2022, doi: 10.3390/admsci12010031.

[16] D. Tranfield, D. Denyer, and P. Smart, "British J of Management - 2003 - Tranfield - Towards a Methodology for Developing Evidence‐Informed Management Knowledge by.pdf," *British Journal of Management*, vol. 14. pp. 207–222, 2003.

[17] M. E. Falagas, E. I. Pitsouni, G. A. Malietzis, and G. Pappas, "Comparison of PubMed, Scopus, Web of Science, and Google Scholar: strengths and weaknesses," *FASEB J.*, vol. 22, no. 2, pp. 338–342, 2008, doi: 10.1096/fj.07-9492lsf.

[18] N. Bakkalbasi, K. Bauer, J. Glover, and L. Wang, "Three options for citation tracking: Google Scholar, Scopus and Web of Science," *Biomed. Digit. Libr.*, vol. 3, no. 2003, pp. 1–8, 2006, doi: 10.1186/1742-5581-3-7.

[19] F. M. Impellizzeri and M. Bizzini, "Systematic review and meta-analysis: a primer.," *Int. J. Sports Phys. Ther.*, vol. 7, no. 5, pp. 493–503, 2012, [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/23091781%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3474302

[20] I. Soleimanmeigouni, *Predictive Models for Railway Track Geometry Degradation*. 2019. [Online]. Available: http://ltu.diva-portal.org/smash/get/diva2:1286681/FULLTEXT01.pdf

[21] I. Soleimanmeigouni, A. Ahmadi, H. Khajehei, and A. Nissen, "Investigation of the effect of the inspection intervals on the track geometry condition," *Struct. Infrastruct. Eng.*, vol. 16, no. 8, pp. 1138–1146, 2020, doi: 10.1080/15732479.2019.1687528.

[22] R. Licciardello, G. Malavasi, A. Tieri, and P. Vitali, "Reference Values for Railway Sidings Track Geometry," *Transp. Res. Procedia*, vol. 14, pp. 1996–2005, 2016, doi: 10.1016/j.trpro.2016.05.167.

[23] C. Vale and M. L. Simões, "Prediction of Railway Track Condition for Preventive Maintenance by Using a Data-Driven Approach," *Infrastructures*, vol. 7, no. 3, 2022, doi: 10.3390/infrastructures7030034.

[24] A. R. B. Berawi, R. Delgado, R. Calçada, and C. Vale, "Evaluating track geometrical quality through different methodologies," *Int. J. Technol.*, vol. 1, no. 1, pp. 38–47, 2010, doi: 10.14716/ijtech.v1i1.35.

[25] J. Sadeghi and H. Askarinejad, "Application of neural networks in evaluation of railway track quality condition," *J. Mech. Sci. Technol.*, vol. 26, no. 1, pp. 113–122, 2012, doi: 10.1007/s12206-011-1016-5.

[26] S. Standard, "SLOVENSKI STANDARD iTeh STANDARD PREVIEW iTeh STANDARD PREVIEW," 2017.

[27] B. Luber, "Railway track quality assessment method based on vehicle system identification," *Elektrotechnik und Informationstechnik*, vol. 126, no. 5, pp. 180–185, 2009, doi: 10.1007/s00502-009-0635-3.

[28] T. Phanyakit and T. Satiennam, "Track-quality index and degradation of railway track structure: The construction track doubling project of northeast line from thanon chira junction to khon kaen station, Thailand," *MATEC Web Conf.*, vol. 192, pp. 4–7, 2018, doi: 10.1051/matecconf/201819202022.

[29] A. M. Zarembski and C. S. Bonaventura, "Dynamic effects of track surface condition on vertical wheel/rail forces and energy consumption," *Proc. ASME Jt. Rail Conf. 2010, JRC2010*, vol. 2, pp. 1–6, 2010, doi: 10.1115/JRC2010-36002.

[30] J. Sadeghi and H. Askarinejad, "Influences of track structure, geometry and traffic parameters on railway deterioration," *Int. J. Eng. Trans. B Appl.*, vol. 20, no. 3, pp. 291–300, 2007.

[31] J. Sadeghi and H. Askarinejad, "An investigation into the effects of track structural conditions on railway track geometry deviations," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 223, no. 4, pp. 415–425, 2009, doi: 10.1243/09544097JRRT266.

[32] Pourahmadi, "Ar ch Ar ch یافته ها," *J. Clin. Psychol.*, vol. 2, no. 1, pp. 205–211, 2009.

[33] I. Soleimanmeigouni, A. Ahmadi, and U. Kumar, "Track geometry degradation and maintenance modelling: A review," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 232, no. 1, pp. 73–102, 2018, doi: 10.1177/0954409716657849.

[34] I. Soleimanmeigouni, X. Xiao, A. Ahmadi, M. Xie, A. Nissen, and U. Kumar, "Modelling the evolution of ballasted railway track geometry by a two-level piecewise model," *Struct. Infrastruct. Eng.*, vol. 14, no. 1, pp. 33–45, 2018, doi: 10.1080/15732479.2017.1326946.

[35] M. Sadri and M. Steenbergen, "Effects of railway track design on the expected degradation: Parametric study on energy dissipation," *J. Sound Vib.*, vol. 419, pp. 281–301, 2018, doi: 10.1016/j.jsv.2018.01.029.

[36] M. J. M. M. Steenbergen, "Physics of railroad degradation: The role of a varying dynamic stiffness and transition radiation processes," *Comput. Struct.*, vol. 124, pp. 102–111, 2013, doi: 10.1016/j.compstruc.2012.11.009.

[37] N. Lyngby, "Railway track degradation: Shape and influencing factors," *Int. J. Performability Eng.*, vol. 5, no. 2, pp. 177–186, 2009.

[38] S. Kraft, J. Causse, and F. Coudert, "An approach for the classification of track geometry defects," *Dyn. Veh. Roads Tracks - Proc. 24th Symp. Int. Assoc. Veh. Syst. Dyn. IAVSD 2015*, no. August, pp. 1135–1144, 2016, doi: 10.1201/b21185-121.

[39] B. Indraratna, N. T. Ngo, and C. Rujikiatkamjorn, "Behavior of geogrid-reinforced ballast under various levels of fouling," *Geotext. Geomembranes*, vol. 29, no. 3, pp. 313–322, 2011, doi: 10.1016/j.geotexmem.2011.01.015.

[40] Y. Guo, V. Markine, W. Qiang, H. Zhang, and G. Jing, "Effects of crumb rubber size and percentage on degradation reduction of railway ballast," *Constr. Build. Mater.*, vol. 212, pp. 210–224, 2019, doi: 10.1016/j.conbuildmat.2019.03.315.

[41] H. Huang and E. Tutumluer, "Discrete Element Modeling for fouled railroad ballast," *Constr. Build. Mater.*, vol. 25, no. 8, pp. 3306–3312, 2011, doi: 10.1016/j.conbuildmat.2011.03.019.

[42] S. M. Famurewa, T. Xin, M. Rantatalo, and U. Kumar, "Optimisation of maintenance track possession time: A tamping case study," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 229, no. 1, pp. 12–22, 2015, doi: 10.1177/0954409713495667.

[43] Y. Guo, V. Markine, and G. Jing, "Review of ballast track tamping: Mechanism, challenges and solutions," *Constr. Build. Mater.*, vol. 300, p. 123940, 2021, doi: 10.1016/j.conbuildmat.2021.123940.

[44] B. Lichtberger, "Modern tamp ¡ ng technology," no. March, 2020.

[45] A. Bhanitiz, "A laboratory study of railway ballast behaviour under traffic loading and tamping maintenance," *Dr. Thesis. Univ. Nottingham, UK*, 2007.

[46] J. J. Kumara and K. Hayano, "Deformation characteristics of fresh and fouled ballasts subjected to tamping maintenance," *Soils Found.*, vol. 56, no. 4, pp. 652–663, 2016, doi: 10.1016/j.sandf.2016.07.006.

[47] Y. Liu, G. F. Gong, H. Yang, D. Han, and H. Wang, "Regulating Characteristics of New Tamping Device Exciter Controlled by

Rotary Valve," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 1, pp. 497–505, 2016, doi: 10.1109/TMECH.2015.2438095.

[48] M. Przybylowicz, M. Sysyn, V. Kovalchuk, O. Nabochenko, and B. Parneta, "Experimental and theoretical evaluation of side tamping method for ballasted railway track maintenance," *Transp. Probl.*, vol. 15, no. 3, pp. 93–106, 2020, doi: 10.21307/TP-2020-036.

[49] S. Aingaran, L. Le Pen, A. Zervos, and W. Powrie, "Modelling the effects of trafficking and tamping on scaled railway ballast in triaxial tests," *Transp. Geotech.*, vol. 15, pp. 84–90, 2018, doi: 10.1016/j.trgeo.2018.04.004.

[50] G. Saussine, E. Azéma, R. Perales, and F. Radjaï, "Compaction of Railway Ballast During Tamping Process : a Parametric Study DETECTION OF BALLAST DAMAGE BY IN-SITU VIBRATION MEASUREMENT OF SLEEPERS Compaction of Railway Ballast During Tamping Process : a Parametric Study," vol. 469, no. July 2009, 2010.

[51] B. Davies and J. Andrews, "Railway track availability modelling with opportunistic maintenance practice," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 236, no. 8, pp. 907–919, 2022, doi: 10.1177/09544097211047663.

[52] S. Shi, L. Gao, X. Cai, H. Yin, and X. Wang, "Effect of tamping operation on mechanical qualities of ballast bed based on DEM-MBD coupling method," *Comput. Geotech.*, vol. 124, no. January, p. 103574, 2020, doi: 10.1016/j.compgeo.2020.103574.

[53] H. Boler, D. Mishra, E. Tutumluer, S. Chrismer, and J. P. Hyslip, "Stone blowing as a remedial measure to mitigate differential movement problems at railroad bridge approaches," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 233, no. 1, pp. 63–72, 2019, doi: 10.1177/0954409718778654.

[54] T. Dahlberg, "Railway track stiffness variations - consequences and countermeasures," *Int. J. Civ. Eng.*, vol. 8, no. 1, pp. 1–12, 2010.

[55] C. Jayasuriya, B. Indraratna, and T. Ngoc Ngo, "Experimental study to examine the role of under sleeper pads for improved performance of ballast under cyclic loading," *Transp. Geotech.*, vol. 19, pp. 61–73, 2019, doi: 10.1016/j.trgeo.2019.01.005.

[56] G. D. Angelo, S. Bressi, M. Giunta, and D. Lo Presti, "Citation :," vol. 161, no. February, pp. 1–8, 2018.

[57] S. Kaewunruen and A. M. Remennikov, "Under sleeper pads: field investigation of their role in detrimental impact mitigation," *Proc. 13th Int. Railw. Eng. Conf.*, pp. 1–17, 2015.

[58] M. Sol-Sánchez, F. Moreno-Navarro, G. Martínez-Montes, and M. C. Rubio-Gámez, "An alternative sustainable railway maintenance technique based on the use of rubber particles," *J. Clean. Prod.*, vol. 142, pp. 3850–3858, 2017, doi: 10.1016/j.jclepro.2016.10.077.

[59] E. Berggren, *by*. 2009.

[60] Y. Sato, "Japanese Studies on Deterioration of Ballasted Track," *Veh. Syst. Dyn.*, vol. 24, no. sup1, pp. 197–208, 1995, doi: 10.1080/00423119508969625.

[61] S. Kraft, J. Causse, and F. Coudert, "An approach for the validation of railway vehicle models based on on-track measurements," *Veh. Syst. Dyn.*, vol. 53, no. 10, pp. 1480–1499, 2015, doi: 10.1080/00423114.2015.1054406.

[62] K. Muramoto, T. Nakamura, and T. Sakurai, "A study of the effect of track irregularity prevention methods for the transition zone between different track structures," *Q. Rep. RTRI (railw. Tech. Res. Institute)*, vol. 53, no. 4, pp. 211–215, 2012, doi: 10.2219/rtriqr.53.211.

Authors

I. Chebaran Jonex: Department: Civil Infrastructure, Addis Ababa Institute of Technology, African Railway Center of Excellence (ARCE), Addis Ababa University Addis Ababa, Ethiopia.

II. Sibomana Aime Aliphones: Department: Civil Infrastructure, Addis Ababa Institute of Technology, African Railway Center of Excellence (ARCE), Addis Ababa University Addis Ababa, Ethiopia.

III. Zewdie Moges, Director ARCE: Department; Civil Infrastructure, Addis Ababa Institute of Technology, African Railway Center of Excellence (ARCE), Addis Ababa University Addis Ababa, Ethiopia.