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Novel performance-based technique for predicting maintenance strategy of bitumen stabilised ballast

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Highlights

- Ballasted track-bed affected by settlement and contamination due to traffic and maintenance.
- Bitumen stabilised ballast (BSB) as solution to reduce track-bed maintenance burdens.
- Novel integrated track-bed degradation model to predict maintenance strategies.
- Increased intervals between minor and major maintenance operations due to the used of BSB.
- Sensitivity analysis to traffic and quality level set for the infrastructure.

Citation:

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Abstract

Despite being the most used worldwide, railway ballasted tracks presents high maintenance cost related to ballast settlement and particle degradation. With the aim of reducing life cycle costs, bitumen stabilised ballast (BSB) has been recently proposed as a relatively cheap alternative maintenance solution to be applied to existing tracks. This study aims at assessing the potential advantages of this technology, defining a novel maintenance strategy of traditional ballasted track-beds. A protocol for the application of the BSB technology and its associated maintenance strategy is defined. To estimate minor and major maintenance operations of BSB scenario in comparison to traditional ballasted track-bed, an integrated model, based on laboratory tests, combining the evolution of track irregularities and ballast contamination with traffic, was used. Results together with a sensitivity analysis related to main parameters adopted revealed that the application of BSB is expected to provide a significant increase of intervals between both minor and major maintenance activities.

Keywords: Bitumen stabilisation; Railway ballast; Maintenance; Degradation model; Tamping; Settlement; Life cycle approach

1. Introduction

1.1. Background

The railway plays a fundamental role in most transportation systems. It provides a fast mean of transportation by a durable and economical system. Ballasted track, which consists of track superstructure supported on a layer of granular material (ballast), represents the most used type of structure over other alternatives such as concrete slab (Michas 2012; UIC 2016). This type of track presents relatively low construction costs, high maintainability at a relatively low cost (for single operation), and the possibility of using indigenous material while providing relatively high damping capacity, noise absorption and high flexibility, self-adjusting properties (in the case of non-homogeneous subgrade) and high hydraulic conductivity (Selig & Waters 1994; Michas 2012; Sugrue 2013; Profillidis 2016).

However, the unbound nature of ballast layer, which helps to fulfil its main functions, is also related to the reduction of the geometric quality of the track, and therefore, its safety and ride comfort (Marsal 1967; Raymond 1985; Jeffs & Tew 1991; Salim 2004; Dahlberg 2004; Boler 2012). The passage of trains causes cyclic movements of the unbounded particles that result in permanent vertical and lateral deformations. For this track form, indeed, vertical settlement of granular layers and ballast particles degradation represent the major problems affecting frequency of maintenance and track durability. In particular, differential settlement, which is generally due to abrupt change in vertical stiffness, leads to increased dynamic loading, which can further increase permanent deformation, leading to a self-perpetuating mechanism (Read & Li 2006).

Ballast layer settlement, which participates with the highest contribution to the total track settlement (Selig & Waters 1994), is given by two major phases (Dahlberg 2004). The first one, faster, occurs when ballast is in a loose state (after tamping or renewals) and is the consequence of a first major consolidation (re-compaction). The second one is due to different mechanisms that occur under cyclic loading: densification, distortion and degradation. The densification is characterised by a progressive consolidation; the distortion is the mechanism where individual particles slide and roll; and the degradation represents the change in particle size determined by attrition and breakage (Sun et al. 2010).

Aside from contributing to permanent deformation, the degradation mechanism can also prevent the ballast layer to fulfil its main functions. Indeed, mineral contamination from particle breakage and wear due to traffic loading and maintenance represents the highest source (with more than 70%) of ballast layer fouling (Selig & Waters 1994; Pires & Dumont 2015). This phenomenon jeopardises the fast draining and elastic characteristics of ballast layer as well as its ability to be effectively maintained by tamping (Selig & Waters 1994; Calla 2003).

1.2. Track degradation and degradation models

Track geometry degradation is affected by several factors: traffic loads and speed, construction materials and methods, and maintenance history, among others (Audley & Andrews 2013). The track geometry is described by several parameters (BS EN 13848-5:2008+A1:2010 2010): vertical alignment (or longitudinal level), horizontal alignment, gauge, cant and twist (Figure 1).

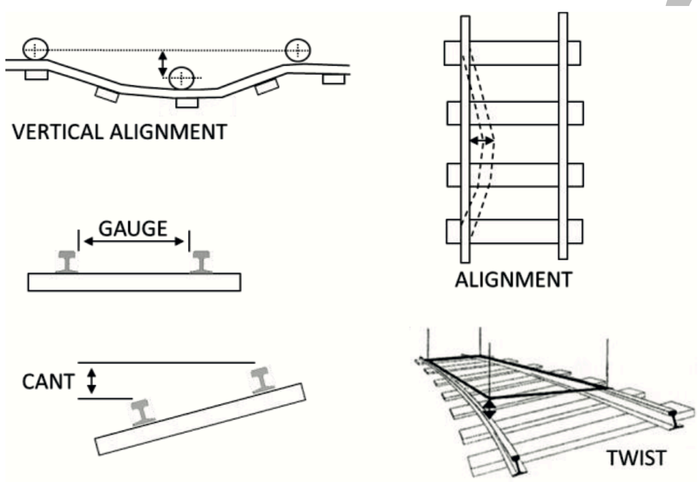


Figure 1 - Track quality parameters (Pires 2016).

Standards prescribe minimum and maximum allowable values for these parameters based on the type of railway line. BS EN 13848 (BS EN 13848-5:2008+A1:2010 2010) states the existence of three indicators of track quality: extreme values for isolated defects, standard deviation (SD) in a typical length (200 m), and mean value. Depending on the type of line and the speed, there are three main limits for these indicators above which different actions need to be undertaken (BS EN 13848-5:2008+A1:2010 2010): Immediate Action Limit (IAL), which, if exceeded, requires taking measures to reduce the risk of derailment to an acceptable level; Intervention Limit (IL), which, if exceeded, requires corrective maintenance in order that the immediate action limit shall not be reached before the next inspection; and Alert Limit (AL), which, if exceeded, requires that the track geometry condition is analysed and considered in the regularly planned maintenance operations.

In order to plan and/or predict maintenance interventions, rail authorities and practitioners often use the standard deviation as a convenient measure of quantifying geometry quality of a track section (Chrismer & Selig 1991). In this regard, Table 1 shows the alert limits for the longitudinal level SD according to European Standards (BS EN 13848-5:2008+A1:2010 2010).

Table 1 – Longitudinal level AL standard deviation according to BS EN 13848 (adapted from BS EN 13848-5:2008+A1:2010 2010).

Speed (in km/h)	**Standard deviation (SD) (in mm) AL**	
	Minimum	**Maximum**
V ≤ 80	2.3	3
80 < V ≤ 120	1.8	2.7
120 < V ≤ 160	1.4	2.4
160 < V ≤ 230	1.2	1.9
230 < V ≤ 300	1	1.5

When quality indexes exceed these limits, maintenance is needed to restore quality of the track.

Predicting future degradation of infrastructure components is an essential element in maintenance planning. In this regards, the loss of track quality is due to a combination of many factors, being the major the repetitive passage of trains (Pires 2016). Experience shows that track quality degradation is a function of load amplitude and repetitions (Million Gross Tons, MGT) (Hausgaard 2013). By periodic inspection of the track this relationship can be determined for each specific section. However, according to Veit (Veit 2007), variations are observed in the deterioration rate: the same loading level, indeed, due to the heterogeneity and anisotropy of all granular layers, can cause different local settlements.

Esveld (Esveld 2001) reports deterioration rates of SD of track irregularities (vertical alignment) varying from 0.007 to 0.02 mm/MGT. Similar results (0.005 to 0.025 mm/MGT) were reported by Khouy (Khouy 2011) for a Swedish line with mixed passenger and freight traffic. Slightly lower values, varying between 0.00217 to 0.0119 mm/MGT, were presented by Hawari and Murray (Hawari & Murray 2008) for three heavy haul lines in Australia.

Over the past 30 years, several efforts have been employed to develop analytic models to predict degradation of railway tracks. An extensive literature review (Audley & Andrews 2013; Pires 2016) revealed that field data of track geometry degradation (SD of track irregularities) are best fitted by linear empirical laws as in Equation (1):

$$SD(MGT) = A + C \cdot MGT \tag{1}$$

where $SD(MGT)$ is the standard deviation corresponding to the amount of MGT; A is the initial value of standard deviation; and C is the coefficient which relates the standard deviation to the cumulated traffic after the initial degradation phase (A).

Nevertheless, most of the models consider track settlement (or track vertical strain) as main controlling factor in track degradation (Shenton 1985; Chrismer & Selig 1991; Shimatake 1997). This convenient parameter can be simulated through field trails and laboratory tests and can be used for comparing different design and maintenance technologies/strategies especially at the early stage of the development process.

However, in order to relate settlement to maintenance requirements, there is a need to establish a link between track irregularities, which vary along the track, and track average settlement. Selig and Waters (Selig & Waters 1994) and Berggren (Berggren 2009) reported studies showing that, excluding the initial settlement just after maintenance, SD of track irregularities grows almost proportionally to track settlement over at least a moderate range of ballast life (Figure 2).

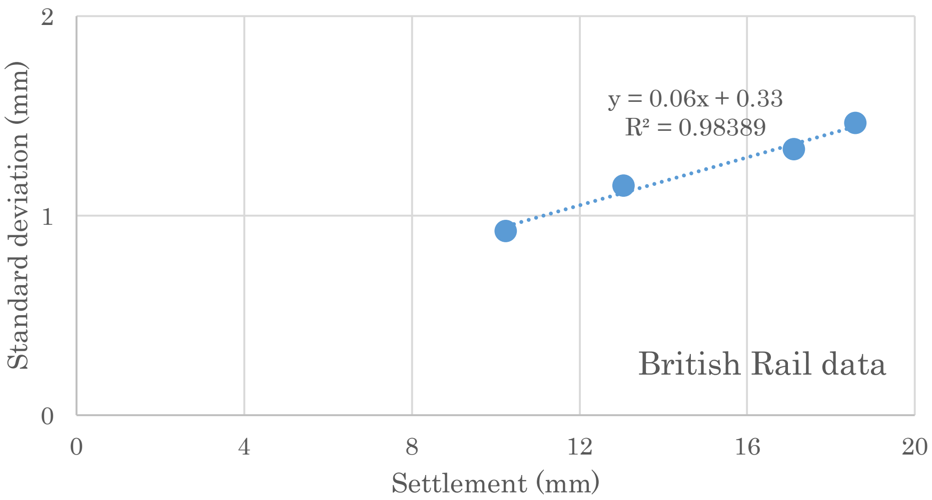


Figure 2 - Relationship between the standard deviation of track irregularities and average track settlement (adapted from Selig & Waters 1994).

1.3. Ballast maintenance

In order to guarantee adequate levels of safety and ride comfort, when the above-mentioned quality indexes exceed prescribed limits, maintenance is needed to restore quality of the track.

In this regard, from 1960s to date automatic tamping is the most used machine to correct track geometry defects. The vibrating action of its tines, indeed, allows for re-arranging particles' position restoring, thus, the original position of the track. However, this operation is accompanied by some detrimental effects: vibrating tines disturb and dilate the densely packed ballast layer, deteriorating particles and reducing track stability (Indraratna et al. 2011; Calla 2003). In this regard, tamping may not produce a durable track geometry, and track profile may quickly revert back to its original position, a phenomenon known as ballast memory (Selig & Waters 1994). Another issue related to tamping is the production of a high amount of fines (Calla 2003; Lim 2004; Aursudkij 2007; Sol-Sánchez et al. 2016). A typical 'tamp', due to the vibrating action, can produce up to 4 kg of fines/sleeper/tamp (Fair 2003), increasing progressively the contamination (fouling) of ballast layer. For these reasons, this operation typically reduces its efficiency after every application (Pires 2016).

Under the tonnage accumulation, ballast layer is progressively contaminated. In this regard, ballast layer resistance to permanent deformation, the efficiency of tamping, and more in general the ability of ballast to fulfil its main functions depend primarily on the content of fine-grained (fouling) material (Nurmikolu 2005). The highest contribution to contamination is given by particle breakage and wear due to traffic loading and maintenance (Selig & Waters 1994; Pires & Dumont 2015). When contamination level reaches critical limits, ballast layer needs to be renewed.

Overall, ballasted track-bed requires frequent and costly maintenance activities. Nonetheless, because of its widespread, interest is growing for alternative solutions which can reduce its maintenance costs. In addition, the progressive reduction of raw material with adequate properties requires immediate solutions to decelerate the degradation of the in-service ballast in tracks (increasing therefore its durability and reducing the need for renewal) as well as solutions to allow for the use of aggregates that are disqualified, according to the current Standards, because of their mechanical properties.

In this context, in recent decades ballasted tracks have been object of diverse researches focused on decelerating the loss in geometrical quality associated to ballast settlement and its progressive degradation. The most common techniques aim at ballast stabilisation using different gluing materials, such as polyurethane, resins or biodegradable polymers (Kennedy et al. 2013; Lakušic et al. 2010; Momoya et al. 2016).

1.4. Bitumen Stabilised Ballast (BSB) as solution to reduce track-bed maintenance costs

Among other stabilisation techniques developed over past few years, Bitumen Stabilised Ballast (BSB) represents an innovative solution designed to be used for new track-beds as well as to reinforce existing ones. It consists in use of bitumen emulsion (BE), which is blown at ambient temperature onto the ballast. This technology is being developed through small-scale and full-scale laboratory tests simulative of field conditions, optimising the main factors affecting the stabilised ballast behaviour (D'Angelo et al. 2016b; D'Angelo et al. 2016a; D'Angelo, Sol-Sánchez, Thom, et al. 2017; D'Angelo, Thom, et al. 2017; D'Angelo, Sol-Sánchez, Moreno-Navarro, et al. 2017).

The initial concept behind this technology was to reduce maintenance of existing ballasted tracks with a relatively economic solution to extend ballast service life which is also relatively easy to apply. In this regard, in order to minimise the traffic disruption, the bitumen stabilisation would be ideally applied during a routine maintenance operation to correct track geometry such as tamping or stoneblowing. The calculated amount of BE is assumed to be blown over the ballast surface by a system analogous to that used by stoneblower when sleeper is raised-up during the maintenance process, as illustrated in Figure 3(a). For instance, an optimum dosage for clean ballast it was found to be equal to 1.44% by weight of ballast (underlying the sleeper/ballast contact area) (D'Angelo, Sol-Sánchez, Moreno-Navarro, et al. 2017).

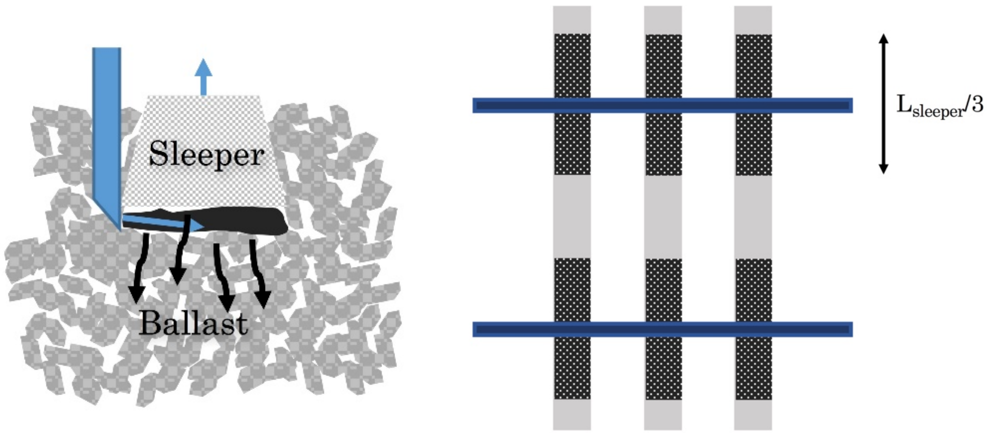


Figure 3 - Schematic illustration of (a) ballast stabilisation process with bitumen emulsion and (b) area of ballast interested by the stabilisation process with bitumen emulsion.

To carry out this operation, the ordinary tamping and stoneblowing machines would need to include an additional railcar storing the bitumen emulsion and a system to blow the optimum dosage of material for each specific section.

In order to stabilise only the ballast subjected to the highest contact pressure (Shenton 1975; Pires 2016) one third of the sleeper length per each side extended for all the sleeper width is assumed to be interested by this operation, as illustrated in Figure 3(b). This procedure, which was simulated by D'Angelo et al. (D'Angelo, Sol-Sánchez, Thom, et al. 2017) using full-scale ballast box tests, represents at the same time a convenient way to use the same machine to perform geometry correction and ballast stabilisation with bitumen.

Despite having shown in previous studies the potential reduction of need of minor and major maintenance activities, bitumen stabilised ballast track-bed will require maintenance to restore track geometry as well as to be renewed at the end of life. Indeed, based on the initial concept, the stabilised layer would be ideally maintained by stoneblowing in order to not alter the cohesive bridges between particles given by bitumen application. This operation, simulated in the full-scale ballast box (D'Angelo, Sol-Sánchez, Moreno-Navarro, et al. 2017), not modifying the BSB structure represents an optimum way to restore track geometry while preserving improvements brought by BE application. However, this maintenance process is available only in few countries, being tamping the most common maintenance process used for geometry correction worldwide. Differently from stoneblowing, tamping operation may damage BSB structure due to the vibrating action of tines. In this regard, in analogy with other stabilisation techniques (Lakušic et al. 2010; Kennedy et al. 2013; Laurans et al. 2016), BSB can be considered to have a built-in safety to the extent that the loss of cohesion would result in the ballast reverting back to an unbound state. Nevertheless, until further studies on BSB maintainability are conducted, it can be conservative to consider an additional BE application when tamping is used to correct track geometry.

For the same principle, at this stage of the technology development, especially when using lifecycle thinking approaches to assess the economic feasibility and the environmental impacts of this new technology, it is conservative to consider the total replacement of old BSB during renewals. In this respect, future studies should focus on the maintainability of BSB through methods which can optimise the reuse of bitumen which is coating aggregate but is not acting as a bonding agent between particles (for example because of tamping action). This would allow recycling BSB during renewal operations increasing savings in a lifecycle approach.

1.5. Aim of the study and research steps

The aim of this study is to evaluate the potential advantages of the application of BSB for defining a new maintenance strategy of traditional ballasted track-beds. Indeed, the main objective of this work is to propose a protocol for the application of the BSB technology as a new construction and maintenance procedure and timing based on its performance evaluation and the traffic volume. An integrated model is used to estimate minor and major interventions for both traditional ballast (unbound) and stabilised ballast BSB (bound). The integrated model developed in this paper combines the evolution of SD with traffic and the level of contamination of ballast allowing calculating the timing for a correct maintenance activity. To understand how variations of a set of parameters and assumptions affect the robustness of the model and the results a sensitivity analysis is carries out. Indeed, the schedules for tamping and renewal operations over the life cycle of the entire infrastructure are calculated for different traffic volumes and SD limit required.

2. Development of an integrated track deterioration model

To schedule maintenance activities over a period of analysis, track degradation models, evaluating the evolution of track quality indicators, need to be used. Two indicators were considered for the evaluation of maintenance strategies of both BSB and reference (unbound) ballast: the standard deviation of track irregularities and the ballast contamination level. The minor and major maintenance operations here considered (tamping and renewal) scheduled after critical levels of track geometry (SD) and ballast layer contamination are reached.

2.1. Standard deviation of track irregularities

The evolution of standard deviation of track irregularities with traffic for both reference ballast and BSB was calculated using Equation 1.

For this equation, the coefficient A, which is the initial value of standard deviation, was assumed to be equal to 0.33 mm (Shimatake 1997; Pires 2016). This was assumed to be the same for both materials because it represents the initial condition of the track after construction or major renewals.

To evaluate the coefficient C, which indicates the evolution of degradation with the traffic, it was used the value of settlement rate per loading cycle (SRLC) from full-scale laboratory tests on BSB and reference ballast carried out using a ballast box (Figure 4) (D'Angelo, Sol-Sánchez, Thom, et al. 2017).

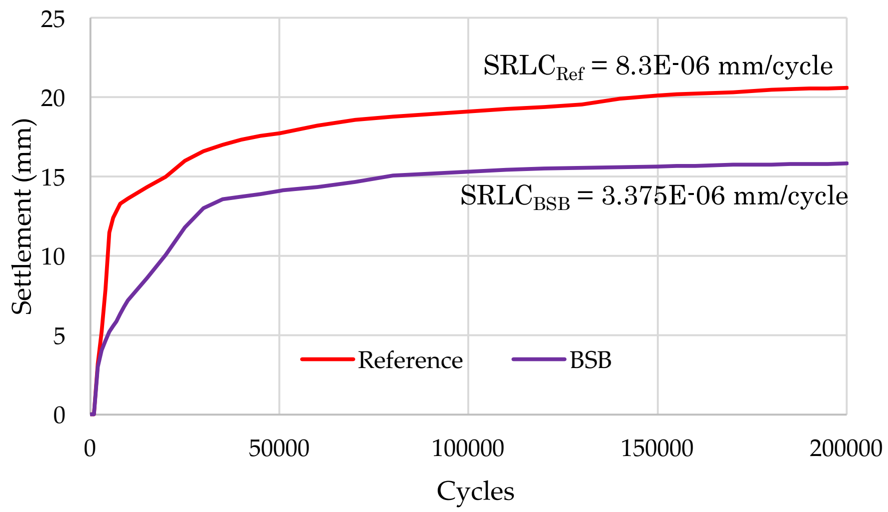


Figure 4 – Evolution of settlement with loading cycles for BSB and reference ballast during over full-scale ballast box dynamic tests (adapted from D'Angelo, Sol-Sánchez, Thom, et al. 2017).

SRLC values were converted to SD using the correlation found by Selig and Waters (Selig & Waters 1994) for British Rail, as in Equations (2) and (3):

$$C_{Ref} = SRLC_{Ref} \cdot 40000 \cdot 0.06 = 0.02\, mm/MGT \tag{2}$$

$$C_{BSB} = SRLC_{BSB} \cdot 40000 \cdot 0.06 = 0.008\, mm/MGT \tag{3}$$

In these equations, the SRLC values were firstly converted from mm/cycle to mm/MGT (40000 factor – 25 t axle) and then to mm/MGT of SD (0.06 - Figure 2).

C_{Ref} value, calculated in this way, ties in with those reported by other authors using field measurements (Esveld 2001; Khouy 2011).

In order to take into account the progressive loss of effectiveness of maintenance (Audley & Andrews 2013), for tamping an efficiency of 95% in restoring the geometry from previous application was assumed (Shimatake 1997; Pires 2016; Caetano & Teixeira 2016).

2.2. Ballast contamination level

Another important parameter used to determine an appropriate timing for renewals is the ballast contamination level (Pires 2016). In this regard, to evaluate the timing when ballast layer needs to be renewed, railway infrastructure managers usually refer to predetermined values of MGT thresholds or other methodologies using as a criterion the level of ballast contamination. This indicator of degradation of the ballast layer must not exceed specific limits. Nevertheless, these values varies among the countries, (Bruzek et al. 2016) leading to an uncertain situation regarding common requirements and revealing a lack of consensus on grain-size diameter and fouling parameters used to define contamination levels. In European countries, for instance, a suggested limit is 30% for particle passing to 22.4 mm sieve (Nurmikolu 2005).

Several studies evaluated the ballast degradation in test arrangement simulating traffic loading. An extensive review of these studies is provided by (Nurmikolu 2005). Intention of this analysis is using laboratory results of ballast particle deterioration obtained by the authors in order to predict the level of void contamination of ballast. For this purpose, in agreement with European standards (BS EN 13450 2013; Nurmikolu 2005), ballast degradation $D(MGT)$ has been defined as the percentage of particle passing at 22.4 mm sieve. Two contributions are considered in the evaluation of ballast degradation: the mineral contamination due to the progressive abrasion and breakage under the cyclic loading and the contamination due to the maintenance operations (Audley & Andrews 2013), as in Equations 4 and 5:

$$D_{ref}(MGT) = D_{traffic,ref} \cdot MGT + D_{tamping} \cdot N_{tamping}(MGT) \tag{4}$$

$$D_{BSB}(MGT) = D_{traffic,BSB} \cdot MGT + (D_{tamping} + D_{BSB}) \cdot N_{tamping+BSB}(MGT) \tag{5}$$

where $D_{traffic,ref}$ and $D_{traffic,BSB}$ are the percentage of particle passing at 22.4 mm sieve per MGT for ballast reference and BSB, respectively, obtained from Figure 5 (internal data); $D_{tamping} = 0.5\%$ is the percentage of particle passing at 22.4 sieve generated per each tamp (Nurmikolu 2005); $D_{BSB} =$ 1.52% is the percentage of material passing at 22.4 sieve due to the addition of BE (calculated from the dosage used for clean ballast); $N_{tamping}$ and $N_{tamping+BSB}$ are the number of maintenance operations for ballast reference and BSB, respectively.

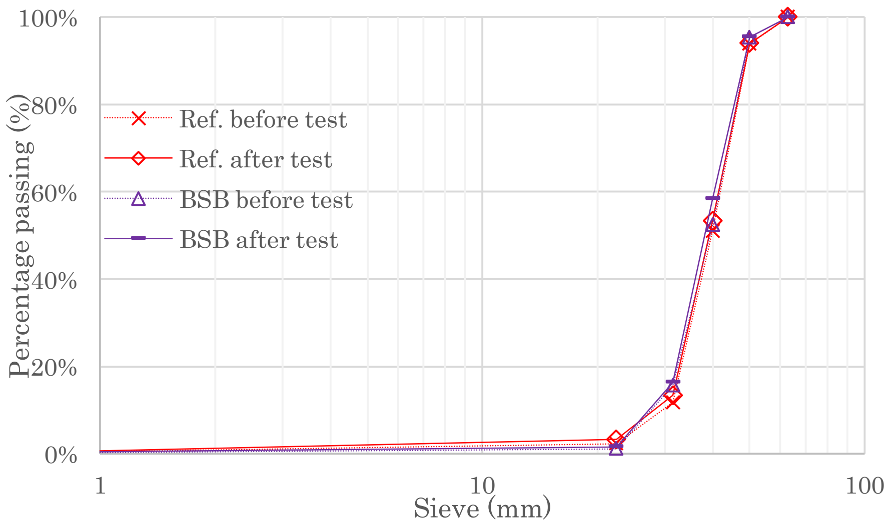


Figure 5 – Particle size distribution for BSB and reference ballast before and after full-scale Precision Unbound Material Analyser (PUMA) dynamic tests (internal data).

3. Results of simulations and sensitivity analysis

Having defined both models, it is possible to predict minor and major maintenance operations in function of MGT, as shown in Figure 6 and Figure 7, where the vertical spikes represent the tamping and renewals actions, respectively.

In this scenario maintenance strategies, are defined as function of traffic for both tamping (indicated as Reference) and tamping + BSB (indicated as BSB) considering a SD limit of 2 mm (BS EN 13848-5:2008+A1:2010 2010) and 30% limit of particle passing to 22.4 mm sieve (Nurmikolu 2005).

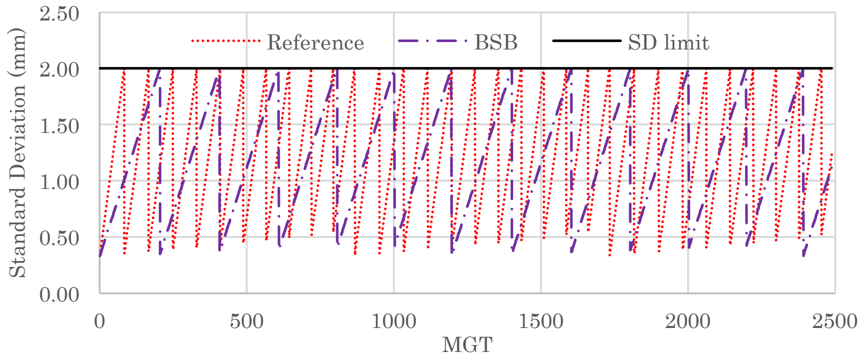


Figure 6 – Evolution of standard deviation of track irregularities with MGT for reference ballast and BSB for an SD limit of 2 mm.

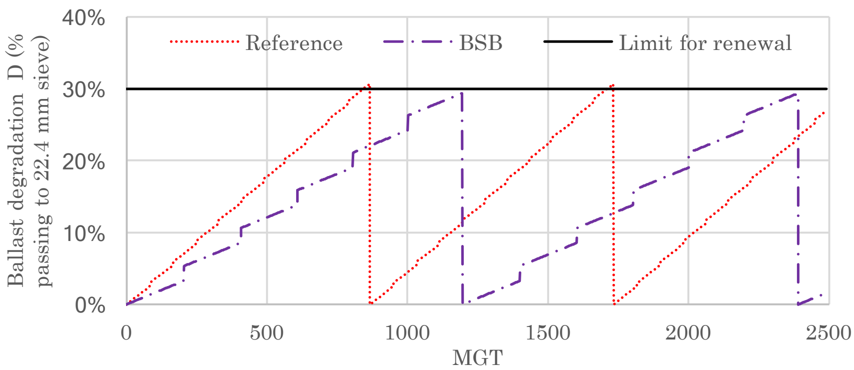


Figure 7 – Evolution ballast contamination due to MGT and tamping operations for reference ballast and BSB for a 30% limit of particle passing to 22.4 mm sieve.

It is possible to observe increased intervals between maintenance activities due to the use of BSB, which could result in important economic and environmental savings.

In the next sections a sensitivity analysis are computed to understand how variations of a set of parameters and assumptions affect the reported output of a model. Thus, the relative effects of different factors may be evaluated and compared. In this case the “One-(factor)-At-a-Time” (OAT) sensitivity analysis method was employed. This method allows for the detection of variations in the results produced varying one factor at a time while all the others are kept constant (Santos et al. 2017).

In this study, two parameters have been considered with different levels: SD limit and annual MGT.

3.1. Influence of traffic on maintenance strategies

Firstly, the effect of variation of traffic has been determined considering a constant SD limit equal to 2 mm. As for the baseline scenario, 30% limit of particle passing to 22.4 mm sieve (Nurmikolu 2005; Berggren 2009) is considered. Annual traffic equal to 20 MGT (medium traffic railway line) and 40 MGT (heavy traffic) (Hensley & Rose 2000) were analysed. The traffic growth rate is assumed to be equal to 0.5%, kept constant every year. In this study, which focuses only on the maintenance operation related to ballast layer, the period of analysis is assumed to be 60 years (MAINLINE Deliverable 5.4 2013; Pires 2016).

Based on these assumptions, the maintenance strategy for reference ballast and BSB, considering 20 MGT traffic volume, are reported in Figure 8.

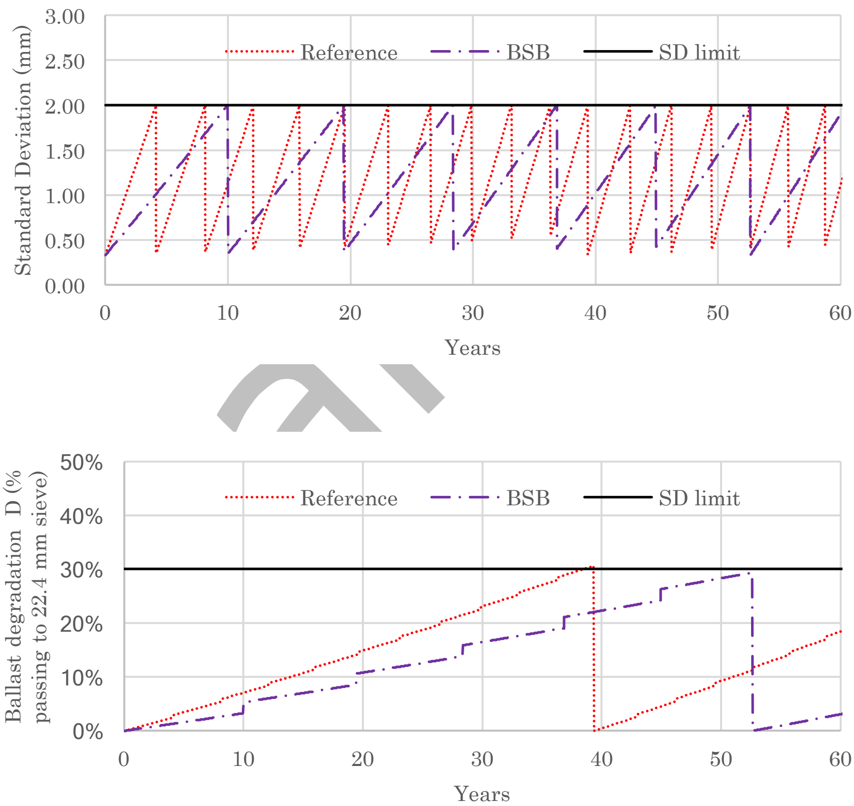
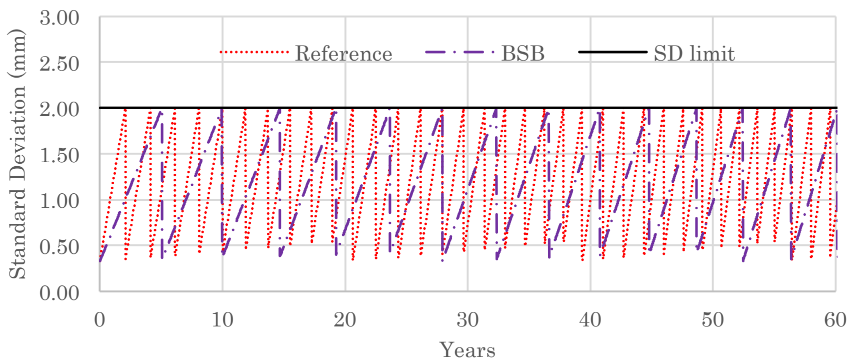


Figure 8 – Evolution of standard deviation of track irregularities and ballast contamination with time for reference ballast and BSB for SD limit of 2 mm and 20 MGT of initial traffic.

It can be noted that, for the same configuration, the intervals between tamping operations progressively decreases due to the loss of efficiency of the operation itself and the forecasted increase of traffic.

As expected, since BSB presented a lower settlement rate, the number of tamping is reduced by almost 60% with respect to reference ballast. The effect of this reduction can be appreciated also looking at the ballast contamination: while for a single maintenance operation BSB has a higher contribution to particles lower than 22.4 mm (addition of BE), the reduced number of interventions together with a lower deterioration rate increased the interval between renewals by approximately 35% in comparison to reference ballast.

Figure 9 shows the evolution of track irregularities and ballast contamination over the period of analysis of 60 years for SD limit of 2 mm for a heavy traffic line (40 MGT).



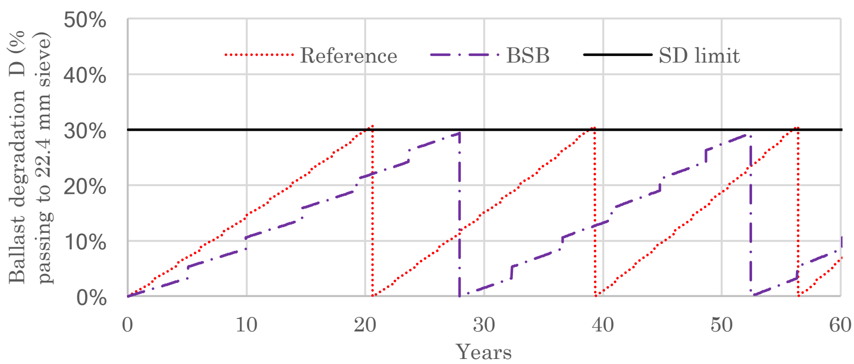


Figure 9 – Evolution of standard deviation of track irregularities and ballast contamination with time for reference ballast and BSB for SD limit of 2 mm and 40 MGT of initial traffic.

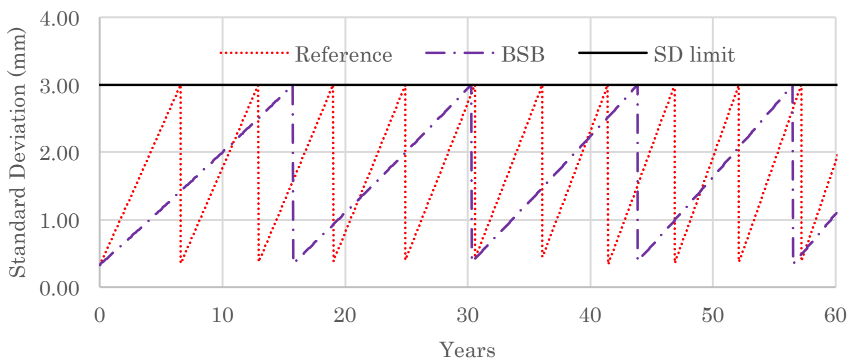
It can be observed that while in general the number of maintenance operations increased for both configurations, the improvement provided by BSB application remained constant (approximately 60% reduction in total number of tamping and approximately 35% extension of ballast service life). These results, which are direct consequence of models adopted, indicate that, standing the assumptions made, BSB would act positively in maintenance reduction independently from the traffic and the track quality level.

As regards the number of major renewals, their number was doubled as consequence of a double the initial traffic (from 20 MGT to 40 MGT) for both configurations, confirming that traffic is the most significant parameter affecting ballast deterioration.

3.2. Influence of SD limit on maintenance strategies

In order to assess the sensitivity of this analysis to the SD limit, maintenance strategies have been evaluated following the same method also for SD limits of 1.5 mm and 3 mm (BS EN 13848-5:2008+A1:2010 2010) while the initial traffic volume has been kept constant at 20 MGT.

Figure 10 and Figure 11 show the evolution of track irregularities and ballast contamination over the period of analysis of 60 years for SD limits of 3 mm and 1.5 mm, respectively.



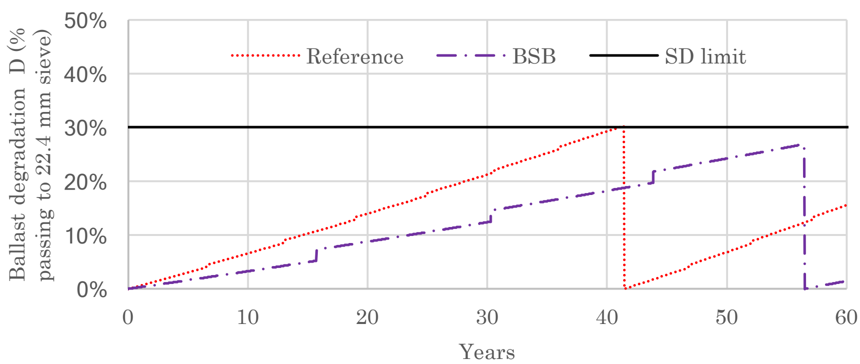
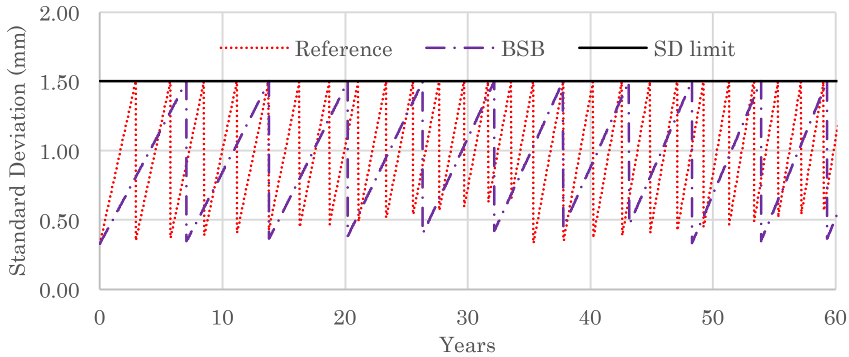


Figure 10 – Evolution of standard deviation of track irregularities and ballast contamination with time for reference ballast and BSB for SD limit of 3 mm and 20 MGT of initial traffic.



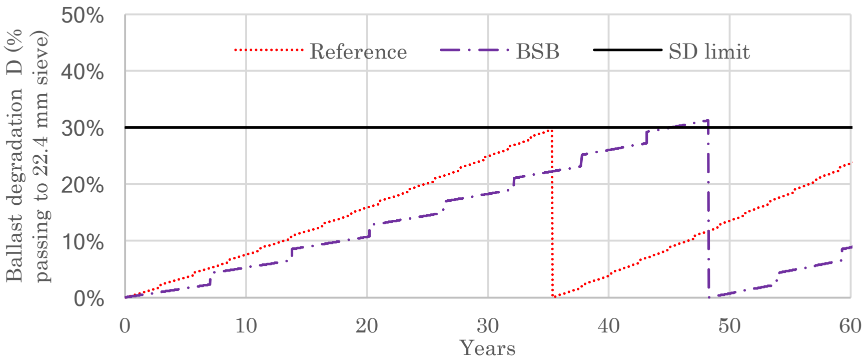


Figure 11 – Evolution of standard deviation of track irregularities and ballast contamination with time for reference ballast and BSB for SD limit of 1.5 mm and 20 MGT of initial traffic.

It can be observed that, as expected, the number of tamping applications is directly related to the assigned quality level of the infrastructure (SD limit): the lower the SD limit the higher the number of tamping during the period of analysis.

For both limits, the reduction in terms of number of tamping provided by BSB is again approximately 60% while the increase in interval between renewals is approximately 35%.

It is worth noting that the renewals timing are similar for all SD limits analysed: year 35-41 for reference ballast and year 48-56 for BSB. For ballast contamination, indeed, the number of tamping applications gives a lower contribution. It mostly depends on the traffic, parameter which was analysed in the previous section.

4. Summary and conclusions

This study aimed at evaluating the potential advantages of the application of BSB for defining a new maintenance strategy of traditional ballasted track-beds. A protocol for the application of the BSB technology and its future maintenance was defined. An integrated model, based on laboratory tests simulative of field conditions, was used to estimate minor and major interventions for both traditional ballast (unbound) and stabilised ballast BSB (bound). The integrated model developed in this paper, by combining the evolution of SD with traffic and the level of contamination of ballast, allowed to evaluate the timing for a correct maintenance activity. A sensitivity analysis to traffic volumes and SD limit was carried out in order to understand how variations of a set of parameters and assumptions affect the robustness of the model.

From results obtained it can be concluded that: (i) overall the use of BSB can increase intervals between both minor and major maintenance activities; (ii) the reduction in maintenance need due to the use of BSB is independent on the quality level on the infrastructure and the initial traffic; (iii) ballast service life depends mostly on the traffic and in a minor part on the maintenance history.

The lower number of maintenance operations expected when BSB is adopted, represents a fundamental step for the reduction of the use of non-renewable resources that are becoming scarce. Indeed, even if bitumen emulsion is used, the improvement of the ballast performance that increases the durability of its functions might be fundamental in terms of environmental burdens and economic impacts. Thus, in order to evaluate the feasibility and sustainability of BSB, future line on research will focus on life cycle cost analysis (LCCA) and life cycle assessment (LCA) of such technologies, based on the maintenance strategies obtained by this study.

Moreover, the integrated model proposed in this paper is a first deterministic version that can be updated introducing a probabilistic approach taking into account the variability of the different parameters.

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