A Method for Assessing the Life Cycle Costs of Modifications to Ballasted Track Systems

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# **Abstract**

Tests can be carried out on elements of railway track in a laboratory to assess the potential for particular ballast and sleeper combinations to alter stiffness, reduce settlement, and improve the transfer of stresses between sleeper and ballast. For example, under sleeper pads (USPs) and random fibre reinforcements (RFRs) have been shown to reduce settlement in such tests. However, it is more problematic to apply test results to predict real world field rates of deterioration along the track geometry which is largely a function of differential settlement. This is important, because an understanding of reductions in real world rates of deterioration is necessary to predict life cycle costs (LCC) of such interventions and assess the economic case for altering current practice. This research examines the impact of installing USPs and RFRs on two different routes in the UK: the London-Portsmouth line and a section of the East Coast Main Line (ECML). A simple methodology, based on relative settlement is proposed to adapt the results of laboratory element tests into a suitable parameter for input into the track geometry degradation model, allowing estimation of LCC. The financial savings from installation were found to be slightly higher for the ECML than the Portsmouth line, and higher for USPs than for RFRs. Although these conclusions are based on a UK case study, they could be applicable to any ballasted railway track operation in a developed region facing high maintenance costs and growing demand.

**Keywords:** Differential settlement; Track stiffness; Ballast; Rail track; Under sleeper pads; Random fibre reinforcements; Life cycle costs; Laboratory tests; VTISM.

# **Introduction**

In the UK, almost 1.76 billion rail passenger journeys were made in the financial year 2018-2019, with rapid growth from 1.59 billion passenger journeys five years earlier [1]. However, there are concerns that rail could lose its principal advantages over other transport modes with respect to journey time reliability and environmental sustainability if it does not continually improve. For example, in the UK maintenance costs are higher than elsewhere in Europe [2]. Along with increasing fiscal constraints, this means that there is growing pressure on the UK rail industry to find ways to reduce its costs. There is also uncertainty over whether the railway system will be able to cope with predicted future demand [3] on a Network whose overall size in terms of mainline route length has remained essentially static for several decades [4]. To address these and other concerns [5] suggested targeting opportunistic and achievable improvements on the railway system that allow faster and heavier trains with less maintenance requirements.

The type of railway track system used on a given route will affect its maintenance costs. Broadly speaking there are two established types of railway track around the world: ballasted track and slab track [6]. In the first case, the rails distribute the load to the sleepers and the sleepers do the same to a bed of stones, called ballast, while in the second case the rails are supported by concrete slabs. In all cases maintenance activities are needed to extend the life of the rail infrastructure by maintaining an acceptable geometry for the safe operation of trains and tolerable passenger comfort. In the UK, the vast majority of railway routes use ballasted track. Whilst this type of track system offers great advantages, such as lower initial investment cost and the possibility to adjust and replace sections of track more easily than slab track [7], it also has more frequent maintenance needs, which could lead to higher life cycle costs (LCC) and may be less energy efficient over long timescales [8]. There has therefore been an ongoing body of research in recent years aimed at reducing maintenance requirements for ballasted track. However, while a number of potential interventions have been proposed and sometimes tested, it is often not clear whether the savings they generate outweigh the initial costs of installation.

This paper investigates these issues by focusing on two particular interventions which can help reduce the LCC of ballasted track: under sleeper pads (USPs) and random fibre reinforcements (RFRs). The main objectives of this paper are: Firstly, to propose a method for evaluating the relative benefits shown in single element laboratory test results to evaluating whole route performance; secondly, to study how track maintenance frequency would be affected by installing USPs or RFRs as standard at renewals on two different routes in the UK, the London-Portsmouth line and the East Coast Main Line (ECML); and, thirdly, to analyse the implications of those interventions for LCC. The remainder of this paper is organised as follows. Firstly, the relationship between settlement and geometry deterioration is discussed, and links with track degradation models are also made. Secondly, laboratory tests carried out with USPs and RFRs are described and a simplified method to adapt test results to predict rates of geometry deterioration is presented. Thirdly, test results are applied to two practical case studies. Finally, conclusions from the studies are presented. While these conclusions are based on two UK case studies, they could be applicable to any ballasted railway track in regions facing high maintenance costs and high demand.

# **Settlement and geometry deterioration**

Ballast provides a stable support to the track reacting against the vertical and horizontal forces applied by trains and providing a free draining medium. Ballast is often the main locus of track settlement although this depends on the local subsoils present [9]. Figure 1 shows the typical relative contributions of substructure layers to track settlement with a good subgrade soil foundation [10].

[Figure 1 app. Here]

Figure 1: Substructure contributions to settlement (after [10]).

If the track settled uniformly along its length according to Figure 1 this would not cause any difficulties for performance. However, non-uniform or differential settlement of the supporting substructure develops as a function of cyclic loading (axle passes). If left uncorrected, the track geometry will deteriorate as loading continues, affecting the ride quality and eventually the safety of train operation, and also resulting in higher train operating costs through increases in train maintenance and fuel consumption [11]. Therefore, it is necessary to periodically correct the track geometry. To return the track to its design line and level, ballast needs to be maintained, usually by mechanised tamping. Tamping is a process which consists of lifting the track and squeezing the ballast under the sleepers to fill the space generated. However, tamping causes ballast particle breakage with fines generation thus decreasing ballast performance over time.

The rate of track geometry deterioration can vary significantly from site to site depending on, for example: local geology, the track form, the frequency and variability in axle load and train speed, the age of track components and the number of prior maintenance tamps. Current industry practice is to measure the track geometry regularly, using specialized track recording vehicles that rely on either chord or inertial measurement systems. Recorded track geometries are converted to a relative offset from the idealized geometry over an appropriate wavelength (35 m, 70 m or 150 m). The standard deviation (SD) of the measured geometry for particular lengths of track (e.g. per 1/8 mile in the UK) gives a measure of the track quality. The measured geometry is evaluated against industry standards for maintenance requirements, both globally in the sense that a length of track may require maintenance or renewal if the SD reaches a certain level; and locally for geometry trigger exceedances that may require more urgent or even emergency remediation works. In such cases, speed restrictions or line closures are put in place, resulting in reactionary delays across the system.

Records of how the track quality (SD) changes over time or with cumulative tonnage allow empirical predictions of future maintenance needs to be made. Such predictions are usually based on an assumed linear or logarithmic deterioration of SD with time or cumulative tonnage, and may take account of the degree of ballast fouling and the increased frequency of maintenance needed as damage to the ballast accumulates.

Because predictions are empirical, any relationships used must ‘lump together’ a number of local effects such as geology, hydrogeology, weather, ballast, sleeper type, earthworks and more. For example, the prediction method used by Network Rail (NR) includes a local track section factor (LTSF) [12], which scales the general form of the logarithmic track quality deterioration function to local historical records. The LTSF may also be used to forecast the effects of a given improvement (e.g. the provision of USPs at a renewal) by reducing the factor (see [13]). However, the evidence on which to base any such adjustment to the LTSF is often lacking, hence the need for more research and field trials. The effect of fouling may also be incorporated into such predictive tools to show its influence on increasing rates of geometry deterioration. However, functions to calculate the influence of fouling are difficult to implement accurately owing to the diversity of effects different fouling regimes can have on a range of ballasts [14,15]. Common sources of fouling are (1) fines generated from tamping (2) environmental fouling transferred into the ballast as a surface contaminant (e.g. spoil falling from open freight wagons) or (3) by migration into the ballast from a poor subgrade. In its worst case, this latter source leads to mud pumping [16]. Modern track construction and renewal methods aim to eliminate subgrade sources of fouling by suitable track bed thickness design that may include the provision of sand-blankets and geotextile filters and suitable drainage. Sources of environmental fouling are also less common in developed railways because freight wagons are more usually covered and spoil is not able to fall into the track bed.

More recently practitioners and researchers have postulated a link between track support stiffness and geometry deterioration [17–21]. The mechanism of track geometry deterioration implied by linking it with track bed support stiffness may be understood by considering what the train ‘sees’ of the track bed support stiffness. As far as a train is concerned, if the load remains uniform and the support stiffness does not change and is continuous beneath the rail, the wheel sits within the deflected profile of the rail and remains unaware of the support stiffness except when that stiffness changes or when the load changes. Varying track support stiffness therefore gives rise to dynamic increments of load which may in turn drive further differential settlement and apparent changes in support stiffness as support levels change along the track. Attempts have been made to evaluate the influence of varying support stiffness on changes in the load by the use of vehicle track interaction models (VTIs) and also sometimes to implement settlement rules using the modelled load outputs over many cycles to evaluate the effect of differential settlement in an iterative modelling procedure to predict geometry and maintenance needs into the future [22–24]. However, although these studies provide insights, they are hampered by both a lack of support stiffness measurements correlated to track geometry and the lack of a generally applicable settlement equation that allows for all the possible input variables [25].

Track support stiffness is made up of various parts including the effect of rail pads, ballast and sub-ballast, but it is often globally modelled as a simplified equivalent elastic spring per sleeper end or rail support or, if normalised per length of track as a modulus continuously supporting an infinite beam – the rail [26–28]. Based on these principles, the recently published Guide to Track Stiffness [29] sets out the mathematical framework and describes the various ways in which stiffness can be defined, how to allow for the effects of different components and how to convert between the different definitions.

# **Track degradation modelling**

Through the lens of asset management, track geometry degradation is commonly subdivided into the following phases: (1) the burn-in (characterised as relatively rapid and uncertain), which starts immediately after tamping, and is continuous up until the ballast reaches a consolidated state; (2) the useful life, starting at a relatively slower rate, with the deterioration path evolving almost linearly with time (or load); and finally, (3) the wear-out phase, where the deterioration rate starts increasing as a function of time, taking up, in due course an exponential-like form. It is in the interest of the infrastructure managers (IMs) to successfully analyse and understand such behaviour, to enable better decision-making, particularly on optimising their inspection intervals, evaluating the remaining useful life (RUL) of their assets, estimating the LCCs, and subsequently, making predictions on the times for renewal interventions to be scheduled [30]. To this end, the recent advances in real-time data acquisition and computational methods have generated an interest in the development of models to support more efficiently the railway track asset management process. Considering this [31] presented a detailed overview of the track degradation models in the academic literature, proposing a top-down hierarchical classification with the criteria for a subsequent shortlisting being made dependent on the desired level of detail, and functionality (see Figure 2).

Such models, at least in the context of railway infrastructure, can be roughly partitioned into deterioration and restoration modules, the former being their backbone, having the role of approximating the ageing process in condition, or in reliability, and the latter building upon a set of rules to regulate the optimal times for different interventions [31]. Towards the mid-levels of hierarchy, deterioration models can be further disaggregated into the classes of mechanistic, empirical, and hybrid models, which are conglomerates of different modelling approaches (Figure 2).

[Figure 2 app. Here]

Figure 2: Hierarchical classification of railway track degradation models [31] – based on an elaboration of [32].

Mechanistic models (see [33,34]) form their basis on *a priori* physical information. In essence, attempting to establish the underlying mechanical properties of the track components, by means of theory or by testing [34]. To this end, their solid engineering background is their biggest advantage; however, they do suffer from their inability to cope with the intrinsic uncertainty of the degradation path due to the existence of multiple heterogeneous factors along a track’s length.

Against this background, empirical models (see [35–37]) have been developed to be able to capture such uncertainty, by employing concepts from the theory of statistics, including for example, stochastic process modelling, and probability theory. This coupled with the fact that their roots are in actual observations, gives them the advantage of deriving absolute estimates of the track deterioration profile [38]. However, their lack of mechanical background of any sort is their most important downside [37], meaning that a lack of engineering understanding may result in invalid models. In essence, empirical models are structured from a given set of inputs and outputs, formulating relationships between them by utilising large amounts of data, which is another potential disadvantage, particularly when data is scarce. They nonetheless constitute a particularly powerful class of models, given their ability to account for a large number of descriptive factors that have an influence on the track’s degradation profile.

More recently, hybrid models (see [38,39]) have been developed in an attempt to get the best elements from both mechanistic and empirical approaches. Fundamentally, this class of models is based on an understanding of the behaviour of the system’s components, coupled with direct observations, measurements, and extensive data records. Prior to constructing these models, track segmentation centred on building segments with homogeneous properties (e.g. influencing factors, and maintenance history, etc.) is necessary [40]. From then on, existing engineering knowledge on different covariates affecting the degradation profile is used to explain empirical track measurement data, and more often than not, employing statistical regression over average values of different parameters for each of the partitioned section groups so as to construct appropriate predictive relationships. One such ‘hybrid-like’ model is described in Section 5, where the segmentation process (see Figure 3) could in theory be carried out through the LTSF, although a better technical understanding of what constitutes this factor would be necessary before this process takes place.

[Figure 3 app. Here]

Figure 3: Illustration of the LTSF-based segmentation for a double track stretch at Wooden Gates level crossing between Acklington and Alnmouth part of the ECML running from London King’s Cross to Edinburgh.

# **Life Cycle Cost modelling**

Short-term cost savings may not necessarily save money in the long run, and in order to be sure that a cost-minimising strategy is being pursued it is therefore necessary to undertake whole-life cost modelling, a form of project appraisal. This is undertaken using life cycle cost analysis (LCCA), sometimes also referred to as life cycle costing (LCC) and whole life cycle costing (WLCC), which is a method for calculating the total cost of a system or product over its lifespan. There is sometimes confusion over the definition of these terms, and while they are often used interchangeably the latter two methods are not necessarily synonymous as, unlike some applications of LCC, WLCC (for which no international standard exists) is a dynamic approach which provides up to date cost and performance forecasts throughout the entire life of the infrastructure, in contrast with the static forecasts over a specified (and sometimes arbitrary) project life provided by LCC at the start of the project [41]. ISO 15686 defines LCC as being “*a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs*”. As is usual for appraisal procedures, all costs are discounted based on a single reference date, and the results of the LCCA will therefore be affected by the specified project length and discount rate [42].

LCCA models integrate six sequential stages in the life of a product or facility, which can be summarised as follows [41]:

1. Justification for investment and client’s requirements. This involves the development of a robust business case analysis, based on the reasons and requirements for investment in a particular product or facility, the perceived benefits, and the objectives which must be fulfilled to meet these requirements and generate the benefits [41].
2. Conceptual development. This stage involves the translation of the project requirements and objectives into a conceptual plan for infrastructure which will fulfil them, and will thus require more specific costing data.
3. Design. Alternative means of implementing the conceptual plan are compared, with the best option selected based on strict criteria which take account of WLCC, benefits and risk levels.
4. Construction. This involves the selection of methods which will enable the preferred design to be built with maximum possible efficiency.
5. Operation and maintenance. This involves the determination of the most efficient and cost-effective means of operation of the infrastructure, while enabling it to meet the original project objectives. In the case of WLCC, this will be a dynamic process, as the optimal means of operation may change over time.
6. End of economic life. At this stage efforts are made to maximise the return from the facility at the end of its planned life.

In addition to this disaggregation of lifecycle stages, the product itself will also be disaggregated into a range of elements, which means that LCCA models effectively comprise a three-dimensional matrix. A significant element of the total costs will be fixed before the installation phase and, as this will often be the area where the greatest scope for savings exists, it is important that LCCA is undertaken alongside the earliest stages of project development [42]. These costs may also be the easiest to estimate, as for example disposal costs will be much more uncertain than construction costs, requiring estimation of the residual value of the infrastructure at the end of the specified project life [42]. There may also be uncertainty over how use of the infrastructure will vary over time, and it may be necessary to make allowances in the costing for potential system improvements to enable the infrastructure to continue to fulfil its intended role.

Many studies have been undertaken of LCCA for rail infrastructure, with perhaps the most exhaustive carried out as part of the EU Innotrack project [42], which aimed to develop a standardised procedure for carrying out such analysis among different target groups from the top management – responsible for strategic decisions – to the specialists – responsible for technical decisions [43]. More recently, the costs of introducing new technologies to the railway industry at the macro-scale have been modelled, looking at the interactions between different elements of the rail system and the process changes involved in the introduction of such technology [44]. Aside of traditional LCC, there is a large body of literature focussing on methods of optimised maintenance planning. For example, a mixed integer linear programming (MILP) optimization model has been developed that integrates three individual degradation models for the rails, sleepers, and ballast [45]. In this study, maintenance/replacement regimes were scheduled opportunistically in a condition-based manner for adjacent track segments to minimize LCC at the line level. A later study by the same authors extended the utility of the model to the network level [46], with the additional capability of studying the effects on LCC from reusing track components on secondary routes. A cost model has also been proposed to identify cost effective maintenance limits for track geometry [47]. This model accounts for the degradation rates of different track sections alongside costs for inspections, tamping, accident risks, and delay time penalties. It was found that at higher intervention limits, tamping is not cost effective due to capacity loss penalties from regulatory speed restrictions, energy consumption, and ride comfort. Another study adopted stochastic RAMS (Reliability, Availability, Maintainability and Safety) approaches to model the failure process of rails so that their maintenance procedure can be performed effectively [48]. A methodology based on Monte Carlo Simulation (MCS) has been proposed [49], including the design of an experiment for identifying uncertainties related to the estimation of LCC attributed to the statistical characteristics of reliability and maintainability parameters within a developed track maintenance cost model. More recently, a WLCC approach to evaluate a range of different investment strategies in railway track maintenance has been proposed [11]. The applicability of the model was demonstrated through an illustrative case study of three different route types in the UK. A linear regression model calibrated on historical track geometry observations was used to model track degradation. To address the uncertainties within their costing and input parameters, the authors conducted a sensitivity analysis of variations in these factors using MCS.

Modelling infrastructure costs is also crucial for the IMs, as these form the basis of the methodology for determining variable track access charges, to ensure that the ‘right’ vehicles are run on the network. A review of the literature broadly shows three approaches for estimating the incremental costs of traffic: (i) bottom-up engineering, (ii) top-down econometric, and (iii) cost allocation methods. It is worth noting, that each of these approaches has its limitations, for example, econometric methods may fail to capture the complexity of elements that affect the relationship between traffic and cost, particularly differentiating between passenger and freight vehicles. Then again, their strength lies on the use of actual cost data, whereas, bottom-up approaches can quantify the relative damage from different vehicles but may fail to translate this into cost. To address these issues, a two-stage methodology has been proposed that combines engineering simulation models with top-down econometric methods to evaluate the relative (short-run incremental or marginal) costs of different damage mechanisms (i.e. settlement, wear, and RCF) [50]. Such an approach is particularly useful for deriving cost information to be used to produce vehicle-differentiated track access charges (at the route section level).

# **Methods and laboratory results**

## **VTISM**

The economic analysis carried out for this paper uses a UK rail industry-specific software tool, Vehicle Track Interaction Strategic Model (VTISM) [51], which predicts and models maintenance needs and the effects of different maintenance strategies on costs using an equation relating geometry deterioration and ballast maintenance as follows:

|  |  |
| --- | --- |
|  | Equation 1 |

Where:

1. *G(t)* is the vertical short wave centred 35m rolling average filter SD at time *t* (*t* can also be substituted for cumulative tonnage and the constants *a* and *b* adjusted accordingly). This can be determined from measurements using a track geometry recording vehicle.
2. *Exp(atb)* is an empirical relationship for geometry at cumulative time (or tonnage) *t* based on the track and traffic characteristics – the parameters *a* and *b* may relate to average or typical train type, weight, speed, frequency, etc.
3. *LTSF* is the local track section factor, essentially a lumped factor to account for local track variation from the idealised deterioration rate, as determined from historical matching.
4. *BCF* is the ballast condition factor, a nonlinear relationship based on the fraction of the ballast voids filled with fines at any one time. The relationship allows for the introduction of fines due to traffic, environment, and dust from wagons and tamping maintenance.

A disadvantage of both the LTSF and BCF is that they coarsely lump together a variety of mechanisms of track deterioration, making it difficult to isolate the effects of any one of these, although the LTSF has in particular been linked with track stiffness (discussed later in this section).

Equation 1 can be applied for planned usage and projected into the future for different maintenance scenarios. It was originally developed for T‐SPA (Track – Strategic Planning Application), which is a decision support tool for strategic asset management developed by SERCO for NR, and has been incorporated in VTISM. T-SPA starts by taking a complete list of the assets and their condition at a particular time. This is obtained from a number of existing NR databases of infrastructure conditions and traffic levels. This data is then projected forward in time, to predict which track assets will need replacing when and what this will cost. This prediction is done taking into account their initial condition and traffic usage. A number of time steps are taken, each equivalent to one month. At each time step, T-SPA takes the initial asset register at the beginning of the time step and calculates how much deterioration will occur based on the existing condition and the traffic volumes. Models are used to relate the traffic levels to changes in vertical geometry and the predicted number of vertical defects in rails and hence the likelihood of a rail break. Also, damage resulting from rolling contact fatigue (RCF) and rail wear are included. This is the ageing process for the assets. The trigger level for a maintenance intervention is determined based on the speed of use of the line. A reduced time period between interventions (e.g. tamps) is achieved by applying a “damage” step to the BCF. An overview of how VTISM works is given in Section 6.

## **Laboratory Tests**

The Southampton Railway Testing Facility (SRTF) was used to investigate the response of different combinations of sleepers and ballast to cyclic loading, over millions of load cycles representative of axle loads in Europe and elsewhere. The detailed test results are reported in [52–54] and only a brief description of the tests and selected outputs of the tests relevant to the current study are included in this paper. The SRTF is a test bay comprising one concrete mono-block sleeper on a 300 mm ballast bed underlain by rubber matting to represent a subgrade. The side walls are held at a fixed distance of 0.65 m apart, corresponding to a typical UK sleeper spacing to maintain conditions as close to plane strain as possible. The test is carried out on a strong floor and an overhead loading frame and actuator arrangement imposes a sinusoidal cyclic loading at 3 Hz through a spreader beam on top of short rail sections mounted on the sleeper in the usual rail fixing locations.

Figure 4 shows a cross section of the key features of the test set-up. At the base of the ballast bed a 12 mm thick rubber mat represents a slightly compressible subgrade. Its thickness was chosen so that the cyclic deflection of the sleeper reached realistic values (up to 1 mm) during testing.

[Figure 4 app. Here]

Figure 4: Test cross-section through a typical test set-up [53].

After carefully controlled preparation to maintain repeatability the test set up is loaded to at least 3 million cycles of an equivalent 20 tonne axle load representing approximately two years of use on a busy line. The detailed testing procedure and results are described in [25,52], but a summary of the testing carried out on the performance of USPs and RFRs is provided below.

### 5.2.1 Under Sleeper Pads

USPs (or performance pads as they are sometimes known) are thin rubber like sheets fixed to the underside of sleepers. These introduce an added compliance to the system such that under a given load some additional deflectionmay be present. Field trials and numerical studies of the effect of USPs have shown that they have potential to improve track performance. However, the evidence is sometimes contradictory [55–58] and consideration should be given to the particular characteristics of potential deployment sites. For example, for a site where stiffness is already low or changes abruptly, the underlying poor characteristics of the site may still dominate the final behaviour and could even be made worse by the addition of USPs. However, in principle, if a variation in stiffness is present along a length of track then by introducing USPs the proportion of controlled deflection is increased and hence the potential variation in support stiffness decreases proportionately.

Two types of USPs were tested supplied by the company Tiflex and their key properties are given in Table 1. Although these USPs were supplied by a particular company, they are typical of the USPs available and may be categorised respectively as stiff and soft pads [59].

[Table 1 app. Here]

Table 1: USP data.

### 5.2.2 Random Fibre Reinforcements

RFRs reinforce ballast by randomly mixing ballast with fibres of selected properties and dimensions. [60–62] used small scale triaxial tests on scaled ballast fibres and sand fibre mixtures to show that there are potential benefits to mixing fibres randomly into a granular mixture provided that the fibre dimensions are appropriately sized in relation to the grain sizes present. To demonstrate the feasibility of using polyethylene fibres in a real application, a test was carried out in the modified SRTF apparatus using the current standard NR ballast grading and fibres with the intention of improving the ballast settlement performance.

Initially the SRTF was used with a batch of ballast sourced from Cliffe Hill quarry, Leicestershire, UK to evaluate the improvement by reinforcing the ballast by fibres that were 300 mm long, 100 mm wide, and 0.5 mm thick polyethylene strips. In this initial test there was approximately 0.2% polyethylene fibre content by weight [63]. Later tests using a second batch of ballast from the same quarry showed that better results could be obtained from 300 mm long, 25 mm wide and 0.5 mm thick fibres at a 0.2% polyethylene fibre content by weight [64]. In the SRFT tests the two batches of Cliffe Hill ballasts conformed to NR specification. However, although the source quarry was the same, slight differences in gradation and possibly source within the quarry meant they performed slightly differently. For this reason the two RFR ballast tests have their own baseline tests in which the same batch of Cliffe Hill quarry ballast was used for comparison.

The test preparation, procedure, setting-up, and instrumentation was the same for all tests with the exception that additional procedures were required to blend the polyethylene fibres with the ballast prior to placing it into the SRTF. To ensure a uniform blend of ballast and polyethylene fibres, mixing was carried out in small batches of a known mass of polyethylene fibres and ballast.

Placing of the ballast-fibre mixture into the modified SRTF apparatus was carried out with great care to avoid segregation occurring and to produce a uniform distribution of fibres within the ballast. For a more detailed overview of the optimised fibres tests see [64].

### 5.2.3 Results from SRTF using USPs and RFR ballast

Key outputs of the tests on USPs and the best performing RFR ballast are presented in Figure 5 and Figure 6.

[Figure 5 app. Here]

Figure 5: Settlement for USP and RFR ballast modifications compared with baseline case for Cliffe Hill first ballast tests.

Figure 5 shows that both types of interventions have been successful in reducing the settlement throughout the cycles of each test over the base-case for the tests using the first batch of Cliffe Hill ballast. The use of the soft USPs shows the greatest improvement, next the stiff USPs and finally the provision of RFR ballast.

[Figure 6 app. Here]

Figure 6: Spring stiffness compared with settlement for ballast modifications and more novel USP and RFR modifications compared with baseline case.

Figure 6 shows the permanent settlement at 3 million cycles plotted against the spring stiffness. No strong trends are evident. However, further evaluation of stiffness Vs. settlement data by [52,53] considering other ballast and sleeper interventions showed that there was an inverse link between settlement and stiffness when the ballast type/gradation alone was the variable. In these tests however, non ballast materials have been introduced both into the ballast and onto the sleeper interface and this has altered the mechanisms of load transfer and stiffness behaviour. Thus, it may be concluded that the improvement in reducing settlement is not directly linked to the change in stiffness.

#### 5.2.3.1 Discussion of test results

The lack of a clear link between stiffness and settlement in these tests precludes use of relative stiffness as a performance indicator. Therefore it is proposed to use the overall settlement as an indicator of differential settlement potential along an operating length of well performing railway track in which fouling is not a dominant factor. This proposed link requires further field study to fully validate. However, in the case of evaluating potential novel modifications where such field data does not yet readily exist (or where studies have been carried out they are not generalizable [56]), laboratory results can provide a basis for an approximation. The use of the average settlement to predict differential settlement has previously been observed to be reliable in other applications. [65] reported settlement measurements for a large number of structures built on different types of soil, finding a correlation between the maximum settlement () and the angular distortion (), where is the relative settlement and the distance between two consecutive points (Figure 7). Similarly, in railway engineering, the irregularities in the track geometry are expected to be proportional to the average settlement.

[Figure 7 app. Here]

Figure 7: Correlation between the maximum settlement (ρmax) and the angular distortion (δρ/L) for structures on different foundation soil [65].

The angular distortion used by [65] indicates differential settlement. Figure 7 indicates a reasonably linear relationship exists between the maximum settlement and the angular distortion for a number of case studies and the classification of foundations by soil type also indicates that in general sand foundations are better performing than clay (as may have been expected).

## **Use of laboratory tests to modify the LTSF**

To relate the overall settlement shown for the tests in Figure 5 it is proposed to modify the LTSF (Equation 1) based on the relative proportions of settlement (Equation 2) while retaining the BCF as an unvaried effect (which could nevertheless be evaluated for influence in future work). For this study a linear correlation with a 1:1 constant of proportionality will be applied. To allow for a contribution from the subgrade to the differential settlement a further weighting is also applied allowing 80% to be due to the ballast and a further 20% for the subgrade (based on Figure 1 for a well performing subgrade). LTSF modifier values from this approach are shown in Table 2.

|  |  |
| --- | --- |
|  | **Equation 2** |

[Table 2 app. Here]

Table 2: LTSF modifiers based on settlement at 3 million cycles.

Table 2 applies an 80% weighting to the ballast settlement. However, where the subgrade is of poorer quality and/or has poor drainage this proportion could reduce to allow for increasing differential settlement from the subgrade soils present and further modifications to the approach could be needed should fouling be significant. The LTSF calculation for the RFR ballast uses a different baseline value compared to the baseline value for USPs because of the different ballasts used.

# **Financial cost implications and geometry deterioration**

In this section the cost implications and track performance are analysed after installing USPs or RFRs during renewals on two different routes in the UK: the London Waterloo to Portsmouth (Direct) line and a section of the ECML between Newcastle and Edinburgh. Both routes were developed in the 19th century, with the Newcastle-Edinburgh route used mainly by trains operating at high speed with an average equivalent million gross tonnage per annum (EMGTPA) of approximately 16. Speeds are generally lower on the London-Portsmouth route, with a high density of commuter traffic, high service frequencies, and significant freight flows on some sections having an EMGTPA of approximately 22.

The track maintenance and renewals costs were obtained using VTISM for both routes under three scenarios, covering a base case and the separate installation of USPs and RFRs. The LTSF modifier was set to 0.75 for the USPs scenario and 0.81 for RFRs (based on Table 2), with the standard value of 1 used in the base-case. Analysis was carried out over a 60-year project life using 2009 prices and a discount rate of 3.5%. Figure 8 provides a flow diagram for the VTISM analysis, including the input of the LTSF modifier, and VTISM outputs giving the volume and cost of all interventions over the project life. The LTSF modifier is included at each track renewal (shown at the bottom of Figure 8).

[Figure 8 app. Here]

Figure 8: VTISM modelling framework.

The analysis described here focuses on the impact of these interventions on maintenance and renewals volumes, costs, and track quality (see [13] for a Cost Benefit Analysis (CBA) of USPs, including all social costs and externalities, and [66] for the carbon footprint of this upgrade). The main benefits were expected to arise from an increased service life of the track and a reduced maintenance and renewal volume [67], which would lead to less disruptions. A renewal with traxcavation (i.e. ballast replacement using heavy excavation machinery) in the first year of 13% of the London-Portsmouth route is assumed by VTISM and the rails would be replaced for around 5 miles. The corresponding figures for the ECML would be 6% of the route and around 10 miles respectively. About 1-1.5% of each route would be traxcavated and renewed in each of the remaining years of the period. The replacement and maintenance regimes are not identical due to different scheduled interventions, which are given by actions from NR’s renewal and maintenance budgets. Some parts of the track would for example only need rail renewals because ballast would be in an acceptable state, whilst other stretches would require a full renewal with traxcavation. The cost of installing USPs or RFRs in each successive renewal was added in USPs/RFRs scenarios to the costs calculated by VTISM. That is done in the cost boxes of Figure 8. The cost of each renewal activity that implies removing ballast and lifting the track will be increased by £74,280/mile of double track in the USPs scenario and £49,148/mile of double track in the RFRs scenario. This will only apply to complete renewal and traxcavation, re-sleeper ballast and traxcavation and finally, switches and crossings (S&Cs) renewals. For instance, in the first year the cost of installing RFRs on the Portsmouth line would be almost £475,000 while the corresponding cost of installing USPs would be £720,000.

After installing USP or RFRs at renewals the LTSF is modified and this is reflected in the subsequent maintenance and renewal volumes. Figure 9 and Figure 10 show the renewal and maintenance volumes under all three scenarios (USP, RFRs and base-case) for both study routes over the project life. It can be anticipated that the main cost savings from the new policy arise from changes in the renewal and maintenance needs. Inspection volumes are identical in both scenarios so are not shown in these figures and therefore will have no influence on the savings. Finally, according to VTISM, on the Newcastle-Edinburgh route there would be a small volume of renewal of steel sleepers, but because the volumes involved are negligible and identical for both scenarios these have been omitted from the analysis.

[Figure 9 app. Here]

Figure 9: Renewal volumes per track mile for a 60 year period.

[Figure 10 app. Here]

Figure 10: Maintenance volumes per track mile for a 60 year period.

Several conclusions can be drawn from Figures 9 and 10. Firstly, when installing USPs or RFRs at renewals the maintenance and renewal frequencies are decreased. In other words, using USPs or RFRs at renewal is a good strategy to reduce material and energy needs and therefore costs. The installation of USPs (lower LTSF modifier) reduced these needs more than the installation of RFRs (with a slightly higher LTSF modifier). Secondly, the main benefit arises from the complete renewal with traxcavation, whereas the main disbenefit comes from more rail renewal needs and therefore higher cost. Thirdly, with respect to maintenance the main benefit comes from the reduction of stoneblowing needs, but tamping and rail grinding and repair needs might be increased. Finally, the maintenance and renewal difference between both routes is mainly explained by traffic conditions; on the London – Portsmouth route there is more traffic than on the ECML and therefore all components degrade faster.

Table 3 shows the aggregated discounted costs over the 60 year period per type of intervention over the whole route. Although this table replicates the results shown in Figures 9 and 10, some additional points can be highlighted.

[Table 3 app. Here]

Table 3. Total Discounted Cost per work Description.

First, with respect to the aggregate figures, costs are reduced with USP and RFR for both routes. The total savings are around 8%. In detail, these IM savings represent 8.69% (USPs) or 8.41% (RFRs) of the total costs for the Newcastle-Edinburgh route and 8.56% (USPs) or 8.10% (RFRs) of the total costs for the Portsmouth line. Therefore, the IM should choose between renewals over the basis of additional expected benefits of each intervention, since cost savings are quite similar for both, USPs and RFRs. Second, as expected, the installation of USPs brings higher financial benefits to the IM than RFRs. However, the cost reduction is lower than the renewal and maintenance needs reductions and this lies in the fact that the installation of USPs is about 50% more expensive than RFRs. Third, for the London-Portsmouth route the two main differences lie in the complete renewal and traxcavation, re-sleeper ballast traxcavation, and in stoneblowing. For the ECML the majority of the savings are in S&C renewals.

The main benefits therefore lie in the reduction of the use of materials which are comprised mainly of steel and concrete on the one hand, and less use of maintenance machines on the other. To achieve greater financial benefits, interventions that reduce the use of new material should be incentivised over interventions that reduce maintenance needs. Finally, when these figures are calculated per track mile the result would favour the London-Portsmouth route.

To have a clear picture of the differences between RFRs, USPs, and base-case scenarios over the whole period, Figure 11 represents the accumulated difference each year in maintenance and renewal activities over time. Figure 11 shows that the cash flow compared with base-case scenario is worse for the first few years but as the costs/benefits are discounted and accumulated the situation quickly reverses. For the London-Portsmouth route the break-even point is achieved in year 3 with RFRs and 6 with USPs. For the Newcastle-Edinburgh route the maintenance and renewals impact would be positive after 6 years with RFR or 8 years with USPs. Consequently, under all scenarios the payback period is relatively short. One impact not considered in the appraisal is that RFRs and USPs might make rail travel cheaper with the consequent increase in demand potentially having an important indirect effect on maintenance and renewal costs.

[Figure 11 app. Here]

Figure 11. Maintenance and Renewal Accumulated Benefits. USP and RFR vs Base-Case.

In order to check the consistency and plausibility of these results, the LTSF modifier has been modified by +/- 10% compared to the mean value, which is 0.75 for USPs and 0.81 for RFRs. For the sake of the sensitivity analysis, VTISM was also tested with a LTSF modifier of 0.95. This sensitivity analysis is shown below, in Figure 12. The benefits included in the figure only represent the effect of changing the LTSF modifier, but not the investment made (i.e. the cost from VTISM has not been increased by £74,280/mile of double track in the USPs scenario, or by £49,148/mile of double track in the RFRs scenario). Therefore, it only shows what happens *ceteris paribus* if stiffness is modified at renewals. Two main findings can be obtained from this figure. First, the lower the LTSF modifier, the higher the benefit. Second, there seems to be a limit in which a lower LTSF does not necessarily bring higher benefits. In fact, the lower the LTSF modifier the lower the elasticity of base costs with respect to LTSF modifier. For instance, reducing LTSF from 1 to 0.95 indicates an elasticity of costs higher than 1 (i.e. elastic curve), whereas below that figure the elasticity is lower than 1 (i.e. inelastic curve) and this elasticity decreases along with LTSF modifier. So, in the range studied, costs are not very sensitive.

[Figure 12 app. Here]

Figure 12. Sensitivity analysis.

In order to look at the effects of USP and RFR on track quality, Figure 13 displays the mean SD of vertical track geometry for track category 1 (track with the highest quality) over the whole period for both routes. Some lessons can be obtained from this figure. First, the expected SD for the Base-Case is worse than for the USPs or RFRs. That is, overall SD is reduced when LTSF is reduced as well. Second, only a few years (from 5 to 10) after the initial renewals of the track with lower LTSF, the track quality is clearly improved. Third, as expected, the USPs scenario displays marginally higher track quality in comparison with RFRs. In fact, by conducting a series of t-tests, the track geometry differences are found to be statistically significant with a confidence interval of 95% when comparing any of the two interventions with the base-case [68]. Nevertheless, no statistical difference was found between USPs and RFRs [68]. Finally, track quality on the ECML is better than on the London–Portsmouth route, which as noted before can perhaps be explained by lighter traffic but also historically better track conditions.

[Figure 13 app. Here]

Figure 13. Mean vertical SD (in mm). USP and RFR vs Base-Case.

# **Conclusions**

This paper presents a study of how track performance and LCC can be measured and improved by installing USPs or RFRs at renewals on two different routes in the UK. The research modelling shows the potential for relatively modest changes in practice to result in substantial LCC savings. The key findings are summarised as follows:

* A methodology was proposed to predict the potential for differential settlement potential along an operating length of track using settlement measurements from laboratory tests on a single sleeper bay. The relative improvement in overall settlement in the laboratory testing was implemented into an economic model to assess the LCC implications. Although the proposed methodology has proven useful for measuring the relative benefits shown in laboratory test results, more data from laboratory testing and field trials is needed to validate and/or modify the approach if the evidence shows it necessary.
* It was shown that the inclusion of novel interventions at renewals brings important benefits in terms of reduced maintenance and renewal needs, and therefore less material and energy being used on the track. However, VTISM indicates that rail renewal and rail grinding may be required more frequently, although these are modelled results that need empirical verification. Moreover, track quality is also improved and therefore better ride quality can be expected. Rail travel could be cheaper with the consequent increase in demand potentially having an important indirect effect on maintenance and renewal costs.
* The analysis suggests that installing USPs at renewals provides higher LCC savings than installing RFRs. However, the payback period of USPs is on average two to three years longer than RFRs. In other words, the breakeven point from installing USPs is approximately reached after six to eight years, while for the RFRs scenario it is roughly reached after three to five years.

Finally, the methodology presented could be applied to investigate other novel track modifications. Further analysis may incorporate elements of the wider social cost, for example the impact of track interventions on the environment in the form of lifecycle Greenhouse Gas (GHG) emissions, or any potential impacts on air-borne and ground-borne noise. Further improvements of the methodology could consider the impact of interventions at renewals on different ballast shapes and ballast fouling. Another potential area for further research is to investigate how track stiffness/quality may influence train operating costs, and how novel interventions, such as USPs, may reduce dynamic impact loading and in turn the maintenance requirements of rolling stock.

# **Declarations of interest**

None.

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# **References**

[1] ORR, Office of rail and road station usage database, Off. Rail Road. (2019). http://dataportal.orr.gov.uk/ (accessed July 18, 2019).

[2] R. McNulty, Realising the Potential of GB Rail, in: Final Indep. Rep. Rail Value Money Study, Department for Transport & Office of Rail Regulation, London, United Kingdom, 2011: p. 320. https://orr.gov.uk/rail/publications/reports/rail-value-for-money-study.

[3] S. Ison, M. Frost, R. Watson, UK rail transport: a review of demand and supply, Proc. Inst. Civ. Eng. - Transp. 165 (2012) 225–234. https://doi.org/10.1680/tran.10.00028.

[4] ORR, Rail infrastructure and assets, Off. Rail Road. (2019). http://dataportal.orr.gov.uk/ (accessed July 9, 2020).

[5] W. Powrie, On track: the future for rail infrastructure systems, Proc. Inst. Civ. Eng. - Civ. Eng. 167 (2014) 177–185. https://doi.org/10.1680/cien.14.00014.

[6] A.M. Remennikov, S. Kaewunruen, A review of loading conditions for railway track structures due to train and track vertical interaction, Struct. Control Heal. Monit. 15 (2008) 207–234. https://doi.org/10.1002/stc.227.

[7] G. Michas, Slab Track Systems for High-Speed Railways, Stockholm, Sweden: Royal Institute of Technology (KTH), 2012.

[8] M. Kiani, T. Parry, H. Ceney, Environmental life-cycle assessment of railway track beds, Proc. Inst. Civ. Eng. - Eng. Sustain. 161 (2008) 135–142. https://doi.org/10.1680/ensu.2008.161.2.135.

[9] T.-S. Yoo, E.T. Selig, Field Observations of Ballast and Subgrade Deformations in Track, Transp. Res. Rec. 733 (1979) 6–12.

[10] E.T. Selig, J.M. Waters, Track geotechnology and substructure management, Thomas Telford Limited, London, United Kingdom, 1994.

[11] M. Sasidharan, M.P.N. Burrow, G.S. Ghataora, A whole life cycle approach under uncertainty for economically justifiable ballasted railway track maintenance, Res. Transp. Econ. 80 (2020). https://doi.org/10.1016/j.retrec.2020.100815.

[12] SERCO, Track Strategic Planning Application: Technical Basis, Warrington, Cheshire, United Kingdom, 2007.

[13] A. Ortega, S. Blainey, J. Preston, Installation of under sleeper pads on ballasted railway tracks: An economic analysis of their potential implementation, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 232 (2018) 1800–1813. https://doi.org/10.1177/0954409717748811.

[14] A.K. Rohrman, H.F. Kashani, C.L. Ho, Effects of natural abrasion on railroad ballast strength and deformation properties, Constr. Build. Mater. 247 (2020) 118315. https://doi.org/10.1016/j.conbuildmat.2020.118315.

[15] Federal Railroad Administration, Laboratory Study of the Failure Characteristics of Fouled Ballast: Phase II, Washington, DC, United States, 2020. https://railroads.dot.gov/sites/fra.dot.gov/files/2020-02/Laboratory Study of Failure Charcteristics.pdf.

[16] A. Hudson, G. Watson, L. Le Pen, W. Powrie, Remediation of Mud Pumping on a Ballasted Railway Track, Procedia Eng. 143 (2016) 1043–1050. https://doi.org/10.1016/j.proeng.2016.06.103.

[17] I. Grossoni, A.R. Andrade, Y. Bezin, S. Neves, The role of track stiffness and its spatial variability on long-term track quality deterioration, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 233 (2019) 16–32. https://doi.org/10.1177/0954409718777372.

[18] T.R. Sussman, W. Ebersöhn, E.T. Selig, Fundamental Nonlinear Track Load-Deflection Behavior for Condition Evaluation, Transp. Res. Rec. J. Transp. Res. Board. 1742 (2001) 61–67. https://doi.org/10.3141/1742-08.

[19] G.A. Hunt, EUROBALT optimises ballasted track, Railw. Gaz. Int. 156 (2000) 813–816.

[20] P.K. Woodward, J. Kennedy, O. Laghrouche, D.P. Connolly, G. Medero, Study of railway track stiffness modification by polyurethane reinforcement of the ballast, Transp. Geotech. 1 (2014) 214–224. https://doi.org/10.1016/j.trgeo.2014.06.005.

[21] L. Le Pen, D. Milne, G. Watson, J. Harkness, W. Powrie, A model for the stochastic prediction of track support stiffness, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 234 (2020) 468–481. https://doi.org/10.1177/0954409719841800.

[22] J. Oscarsson, Simulation of Train-Track Interaction with Stochastic Track Properties, Veh. Syst. Dyn. 37 (2002) 449–469. https://doi.org/10.1076/vesd.37.6.449.3521.

[23] J. Oscarsson, Dynamic Train-Track-Ballast Interaction with Unevenly Distributed Track Properties, Veh. Syst. Dyn. 37 (2002) 385–396. https://doi.org/10.1080/00423114.2002.11666248.

[24] K. Nguyen, D.I. Villalmanzo, J.M. Goicolea, F. Gabaldon, A computational procedure for prediction of ballasted track profile degradation under railway traffic loading, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 230 (2016) 1812–1827. https://doi.org/10.1177/0954409715615374.

[25] T. Abadi, L. Le Pen, A. Zervos, W. Powrie, A Review and Evaluation of Ballast Settlement Models using Results from the Southampton Railway Testing Facility (SRTF), in: Procedia Eng., 2016: pp. 999–1006. https://doi.org/10.1016/j.proeng.2016.06.089.

[26] S. Timoshenko, Method of analysis of statical and dynamical stresses in rail, in: Second Int. Congr. Appl. Mech., Zurich, Switzerland, 1927: pp. 407–418.

[27] G.P. Raymond, Analysis of Track Support and Determination of Track Modulus, Transp. Res. Rec. 1022 (1985) 80–90. http://onlinepubs.trb.org/Onlinepubs/trr/1985/1022/1022-011.pdf.

[28] C. Esveld, Modern Railway Track, 2nd ed., MRT-Productions, Zaltbommel, The Netherlands, 2001.

[29] TSWG, Cross Industry Track Stiffness Working Group - A Guide to Track Stiffness, 1st ed., University of Southampton, Department of Civil & Enviromental Engineering, Southampton, United Kingdom, 2016.

[30] N. Lyngby, P. Hokstad, J. Vatn, RAMS Management of Railway Tracks, in: K.B. Misra (Ed.), Handb. Performability Eng., First, Springer-Verlag London Ltd., London, United Kingdom, 2008: pp. 1123–1145. https://doi.org/10.1007/978-1-84800-131-2\_68.

[31] G. Rempelos, J. Preston, S. Blainey, A State of the Art Literature Review on Railway Track Degradation Models, Manuscr. Prep. (2020).

[32] L. Ferreira, M.H. Murray, Modelling rail track deterioration and maintenance: Current practices and future needs, Transp. Rev. 17 (1997) 207–221. https://doi.org/10.1080/01441649708716982.

[33] J. Öberg, E. Andersson, Determining the deterioration cost for railway tracks, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 223 (2009) 121–129. https://doi.org/10.1243/09544097JRRT222.

[34] Y.-J. Zhang, M. Murray, L. Ferreira, Modelling rail track performance: an integrated approach, Proc. Inst. Civ. Eng. - Transp. 141 (2000) 187–194. https://doi.org/10.1680/tran.2000.141.4.187.

[35] D. Prescott, J. Andrews, Investigating railway track asset management using a Markov analysis, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 229 (2015) 402–416. https://doi.org/10.1177/0954409713511965.

[36] D. Prescott, J. Andrews, A track ballast maintenance and inspection model for a rail network, Proc. Inst. Mech. Eng. Part O J. Risk Reliab. 227 (2013) 251–266. https://doi.org/10.1177/1748006X13482848.

[37] J. Andrews, A modelling approach to railway track asset management, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 227 (2013) 56–73. https://doi.org/10.1177/0954409712452235.

[38] J. Sadeghi, H. Askarinejad, Development of improved railway track degradation models, Struct. Infrastruct. Eng. 6 (2010) 675–688. https://doi.org/10.1080/15732470801902436.

[39] N. Rhayma, P. Bressolette, P. Breul, M. Fogli, G. Saussine, Reliability analysis of maintenance operations for railway tracks, Reliab. Eng. Syst. Saf. 114 (2013) 12–25. https://doi.org/10.1016/j.ress.2012.12.007.

[40] M. Ahac, S. Lakušić, Tram Track Maintenance -Planning by Gauge Degradation Modelling, TRANSPORT. 30 (2015) 430–436. https://doi.org/10.3846/16484142.2015.1116464.

[41] H.A. Boussabaine, R.J. Kirkham, Whole Life-Cycle Costing: Risk and Risk Responses, 1st ed., Blackwell, Oxford, UK, 2004.

[42] A. Ekberg, B. Paulsson, Innotrack: Concluding Technical Report, Paris, 2010.

[43] B. Ripke, W. Nawabi, A. Lamper, U. Juntti, J. Paragreen, Innotrack: Guideline for LCC and RAMS Analysis, Paris, 2009.

[44] K. Lovell, C. Bouch, A. Smith, C. Nash, C. Roberts, P. Wheat, C. Griffiths, R. Smith, Introducing new technology to the railway industry: System-wide incentives and impacts, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 225 (2011) 192–201. https://doi.org/10.1177/09544097JRRT383.

[45] L.F. Caetano, P.F. Teixeira, Optimisation model to schedule railway track renewal operations: a life-cycle cost approach, Struct. Infrastruct. Eng. 11 (2015) 1524–1536. https://doi.org/10.1080/15732479.2014.982133.

[46] L.F. Caetano, P.F. Teixeira, Strategic Model to Optimize Railway-Track Renewal Operations at a Network Level, J. Infrastruct. Syst. 22 (2016) 04016002. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000292.

[47] I. Arasteh Khouy, P.O. Larsson-Kråik, A. Nissen, U. Kumar, Cost-effective track geometry maintenance limits, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 230 (2016) 611–622. https://doi.org/10.1177/0954409714542859.

[48] S. Kumar, U. Espling, U. Kumar, Holistic procedure for rail maintenance in Sweden, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 222 (2008) 331–344. https://doi.org/10.1243/09544097JRRT177.

[49] A.P. Patra, P. Söderholm, U. Kumar, Uncertainty estimation in railway track life-cycle cost: A case study from Swedish National Rail Administration, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 223 (2009) 285–293. https://doi.org/10.1243/09544097JRRT235.

[50] A. Smith, S. Iwnicki, A. Kaushal, K. Odolinski, P. Wheat, Estimating the relative cost of track damage mechanisms: combining economic and engineering approaches, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 231 (2017) 620–636. https://doi.org/10.1177/0954409717698850.

[51] SERCO, VTISM Version 2.6.6 User Guide, Hook, United Kingdom, 2014.

[52] T. Abadi, L. Le Pen, A. Zervos, W. Powrie, Effect of Sleeper Interventions on Railway Track Performance, J. Geotech. Geoenvironmental Eng. 145 (2019) 04019009. https://doi.org/10.1061/(asce)gt.1943-5606.0002022.

[53] T. Abadi, L. Le Pen, A. Zervos, W. Powrie, Improving the performance of railway tracks through ballast interventions, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 232 (2018) 337–355. https://doi.org/10.1177/0954409716671545.

[54] E. Ferro, The Mechanical Behaviour of Fibre Reinforced Railway Ballast, Southampton, United Kingdom: University of Southampton, 2018.

[55] UIC, Project no. I/05/U/440. Under Sleeper Pads - Semelles sous traverses - Schwellenbesohlungen, in: UIC Summ. Rep., 3rd ed., Paris, France, 2009: p. 39.

[56] L. Le Pen, G. Watson, A. Hudson, W. Powrie, Behaviour of under sleeper pads at switches and crossings – Field measurements, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 232 (2018) 1049–1063. https://doi.org/10.1177/0954409717707400.

[57] A. Paixão, C. Alves Ribeiro, N. Pinto, E. Fortunato, R. Calçada, On the use of under sleeper pads in transition zones at railway underpasses: experimental field testing, Struct. Infrastruct. Eng. 11 (2015) 112–128. https://doi.org/10.1080/15732479.2013.850730.

[58] J. Ali Zakeri, M. Esmaeili, H. Heydari-Noghabi, A field investigation into the effect of under sleeper pads on the reduction of railway-induced ground-borne vibrations, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. 230 (2016) 999–1005. https://doi.org/10.1177/0954409714565499.

[59] M. Sol-Sánchez, F. Moreno-Navarro, M.C. Rubio-Gámez, The use of elastic elements in railway tracks: A state of the art review, Constr. Build. Mater. 75 (2015) 293–305. https://doi.org/10.1016/j.conbuildmat.2014.11.027.

[60] O. Ajayi, L. Le Pen, A. Zervos, W. Powrie, Feasibility study of random fibre reinforced railway ballast using image-based deformation measurements, in: XVI Eur. Conf. Soil Mech. Geotech. Eng., 2015: p. 5.

[61] O. Ajayi, L. Le Pen, A. Zervos, W. Powrie, A behavioural framework for fibre-reinforced gravel, Géotechnique. 67 (2017) 56–68. https://doi.org/10.1680/jgeot.16.p.023.

[62] O. Ajayi, L. Le Pen, A. Zervos, W. Powrie, Scaling relationships for strip fibre–reinforced aggregates, Can. Geotech. J. 54 (2016) 710–719. https://doi.org/10.1139/cgj-2016-0346.

[63] T. Abadi, Effect of sleeper and ballast interventions on rail track performance, Southampton, United Kingdom: University of Southampton, 2015.

[64] E. Ferro, O. Ajayi, L. Le Pen, A. Zervos, W. Powrie, Settlement response of fibre reinforced railway ballast, in: 11th World Congr. Railw. Res. (WCRR2016), 29 May - 2 June 2016, Stella Polare Congress Center, Fiera Milano, Milan, Italy, 2016: p. 6.

[65] G. Ricceri, M. Soranzo, An analysis on allowable settlements of structures, Riv. Ital. Di Geotec. 19 (1985) 177–188. http://www.associazionegeotecnica.it/sites/default/files/rig/RIG\_1985\_4\_177.pdf.

[66] A. Ortega, S. Blainey, J. Preston, Assessing Whole-Life Carbon Footprint of Under Sleeper Pad Installation for Ballasted Track, J. Transp. Eng. Part A Syst. 144 (2018) 04018073. https://doi.org/10.1061/jtepbs.0000192.

[67] S. Marschnig, Lowering Track Lifecycle Costs with Sleeper Pads, EURAILmag Bus. Technol. Mag. Eur. Rail Decis. Makers. (2011) 146–147.

[68] G. Rempelos, Random fibre reinforcements and rail track performance, Southampton, United Kingdom: University of Southampton, 2016.

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