Installation of Under Sleeper Pads on Ballasted Railway Track: An economic analysis of their potential implementation

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Abstract

This study examines the economic impact of installing Under Sleeper Pads (USPs) in two different routes in the UK: the London-Portsmouth line and a section of the East Coast Main Line (ECML). The Portsmouth line is a typical suburban route with a high proportion of commuters whereas the ECML is a higher speed line with less users and more distance between stations. The cost implications of this intervention are assessed through a stochastic application of Cost Benefit Analysis underpinned with a Sensitivity Analysis. Using an industry-specific model, VTISM (Vehicle Track Interaction Strategic Model), as well as the results of laboratory experiments conducted at the University of Southampton we are able to offer a set of conclusions. Increased reliability, improved ride quality and reduced vibration are important benefits for the users, higher in total terms on the Portsmouth line than on the ECML, but smaller when the comparison is made on a per capita basis. In other words, the investment brings a higher absolute efficiency gain for the Portsmouth line but a higher relative

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efficiency gain for the ECML. It is found that USPs can lead to substantial financial savings, these are higher for the ECML than the Portsmouth line. Finally, depending on assumptions concerning noise impacts, USPs are likely to have substantial wider social benefits, these are much higher for the Portsmouth line than the ECML. Although these conclusions are based on a UK case study, they could be applicable to any railway operation in a developed region facing high maintenance costs and growing demand.

Key words: Cost Benefit Analysis, Sensitivity Analysis, Stochastic Model, Maintenance Costs, Under Sleeper Pads.

1. Background and theoretical framework

Many railway networks in developed countries are facing the challenge of modernising their railway infrastructure and bringing it up to the standards required by 21st century railway operations. This is a particular problem in the UK, where 19th century infrastructure still carries the vast majority of intercity traffic. The UK rail network is made up of 20,800 miles of track (9,846 route miles) and renewal expenditure in 2009 was £2 billion higher than in 1996-7, with approximately £1.3 billion of this related to increased renewals volumes, and while costs have fallen from their peak following the Hatfield accident[1] (by 24% since 2004-5), efficiency improvements in track in particular have been difficult to achieve[2]. This is despite the fact that civil engineering costs in the UK are typically up to double those found in the rest of Europe, with international benchmarking from the Office of Rail Regulation (ORR) indicating that in 2008 there was an efficiency gap of 34-40% between Network Rail and top-performing European railways for maintenance and renewals spending[3]. Network Rail's maintenance costs are higher than those elsewhere in Europe, and while renewal levels have been increased in recent years to deal with a maintenance backlog, using a steady state analysis does not alter Britain's relative position[4]. 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 the predicted large increases in demand in future years. Powrie[5] therefore suggests targeting opportunistic and achievable improvements on the railway system that allow faster and heavier trains with less maintenance requirements.

Against this background, the University of Southampton have been leading the Track 21 project and its successor Track to the Future, funded by the Engineering and Physical Sciences Research Council. These projects are assessing how to make ballasted track systems more durable given higher traffic levels, and how to reduce the costs of maintenance and renewal. They have explored several innovative interventions which are intended to deliver better engineering, economic and environmental performance of railway track, of which this paper focusses on one, Under Sleeper Pads

(USPs). The main objective of this paper is to study the economic impact of installing Under Sleeper Pads (USPs) on two different routes in the UK: the London-Portsmouth line and the East Coast Main Line (ECML). The results shown in this paper are informed by laboratory tests. A future area of research is to have them validated by field trials. Taking together the laboratory tests and the economic analysis, they suggest that such field trials are promising. In fact, initial trials at Wooden Gates (on the ECML route studied in the paper) do indicate USPs reduce vertical deviation – although this is for S&C, not plain track[6].

The economic framework used in this research for assessing the socioeconomic impact of installing USPs is Cost Benefit Analysis, (CBA), chosen in this paper because it can calculate the efficiency, in economic terms, of a particular policy or investment. CBA consists of comparing the costs and benefits resulting from each of two scenarios, described in monetary terms, throughout the expected life of the proposed policy. The base scenario is also called the do-nothing or do-minimum scenario, while with-scheme (or do-something) analysis attempts to measure the impact if Network Rail were to install USPs on some railway tracks. Future benefits and costs are discounted to their current value through the social discount rate commonly used by governments to evaluate public policies[7]. If the discounted benefits and costs from the installation of USPs exceed the discounted costs and benefits of the base scenario, then the policy adopted is said to be economically profitable for society because a social welfare gain is expected. The difference between benefits and costs over the project lifespan is referred to as net present value (NPV), which is calculated as shown in equation (1):

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$$NPV = \sum_{t=0}^{n} (\frac{1}{1+r})^{t} \ x \ [TC_t^{dn} - TC_t^{USPs}] \quad (1)$$

where r is the social discount rate, t the period of time for the analysis, TC_t^{dn} the total cost in year t for the base scenario (do-nothing), TC_t^{USPs} the total cost in year t for the scenario with USPs. Every cost is calculated for both alternatives, do nothing and installation of USPs, during the period of time analysed. The result will show the socioeconomic gain (or loss) derived from the new policy. In our assumptions we have not considered any benefit from induced demand, since we assume demand growth will be identical for both scenarios. This is based on the fact that the installation of USPs is a minor intervention, otherwise the induced demand derived from the investment would have to be included in the NPV (that would be the case for instance of a new parallel railway track).

When applying CBA for current activities such as maintenance and renewals, cost modelling is a crucial issue because it helps to determine the value of cost to be used. This financial valuation might have an important effect on the outputs of the analysis[8]. The values adopted for parameters like noise or reliability could influence the result and profitability of track upgrades, with errors having the consequence of misperceptions of the return gained from investment. This uncertainty must be taken into account in any economic appraisal such as Life Cycle Cost[9]. Furthermore, before conducting these type of *ex-ante* economic studies some assumptions have to be taken; otherwise, the analysis would be simply unachievable (e.g. demand must be forecasted over a long period of time, which for its intrinsic nature has many uncertainties) (see De Rus[10] for guidance). Apart from this introduction, there are four sections more in this paper, which is divided as follows. Firstly, we provide a brief review of values of noise, vibration and ride quality, and reliability, which will be used in the economic modelling. A more detailed version of this review is provided in Ortega et al[11]. Secondly, we explain the main characteristics of the routes analysed, the Portsmouth line and ECML, and provide the minimum, middle and maximum values for all the variables studied latter. Thirdly we show the results of the stochastic approach of a Cost Benefit Analysis underpinned with a Sensitivity Analysis. Finally, derived from this research, we are able to offer a set of conclusions for policy makers. While these conclusions are based on a UK case study, they could be applicable to any railway operation in a developed region facing high maintenance costs and growing demand.

2. Literature Review

a. Noise

Rail passengers and people living or working in the vicinity of railway lines are all usually affected by changes in noise level, but the literature reviewed focused almost entirely on the noise impacts on people in areas around railway lines, with no valuations obtained for the effect of noise on rail passengers. Very few papers discussed on-board noise and those which exist are several decades old[12,13]. Noise cost estimates can be difficult to generalise due to their local nature and dependence on background noise levels[14]. Furthermore, the impact of a given noise level will depend on people's activities and their attitudes towards the railway, and as people become accustomed to a given level of noise exposure their annoyance level may decrease[15]. Three different methods were used in the studies reviewed to evaluate the cost of noise: stated preference (SP) surveys performed to obtain willingness to pay (WTP) and contingent valuation (CV), hedonic pricing (HP) (where the real market is used to obtain the economic value of one particular feature), and finally estimation of abatement costs[16]. Finally, it is worth noting that there was also little consistency between the formats in which the results were presented. Measures include Cost of Annoyance per Person, Property Value Depreciation, Marginal Cost of Additional Vehicles and Other Valuations. Following the suggestion found in the review by Ortega et al.[11], we have decided to use a value of £20 per dB of household affected per annum.

b. Values of Vibration, Ride Quality and Comfort

Despite an extensive search we found relatively few studies which assigned financial values to ride quality or vibration. A plausible explanation is that passenger comfort and perception of service quality are affected by several factors[17], such as time, country, culture or the physical condition of passengers, and when the subjective contribution from all aspects is approximately equal then the optimum level of comfort will be achieved[18], regardless of the relative contribution of different factors. However, Lee et al.[19] proved that the variables related to the seat such as shape (reclining seat), width and pitch were the most important in determining ride comfort for Korean high speed trains. Moreover, users have a higher sensitivity to vertical acceleration than to longitudinal or transversal acceleration[20].

Research has provided financial valuations of ride quality seating comfort, ambience, ride quality, seating layout, ventilation and noise[21]. The first three aspects were found to be the most important aspects with a valuation ranging from 3.41% to 5.22% of the single fare for seating comfort, 1.88% to 3.05% for ambience and 1.89% to 3.06% for ride quality. Paulley et al.[22] found that refurbishment which changed train characteristics from those associated with old 'slam door' stock to new air-conditioned stock in South East England was worth around 2.5% of the fare paid, with most train refurbishments worth somewhat less than this (~1.5%). The Passenger Demand Forecasting Handbook (PDFH)[23] measured improvements in ride quality in terms of a decrease in in-vehicle time (IVT). Going from an extremely bumpy ride to a very smooth ride would lead to a benefit equivalent to 3.3% of IVT (commuting) to 3.7% (business/leisure), whilst going from an extremely bumpy ride to a train with a lot of movement would have benefits of 2.4% and 2.6% of IVT. According to our calculations, the highest change in IVT (3.7%) could be equivalent to around 10% of ticket price for the Portsmouth line. So, considering the proportion of this possible improvement in comfort which could be attributed to the installation of USPs, we have estimated their average value as only 1% of the ticket price.

c. Values of Reliability

Values of reliability may vary significantly between passengers and even between trips for the same passenger, since the shape of the schedule utility function (the value placed on different degrees of punctuality) will be strongly affected by individual passengers and their journey purpose, and they may also place different subjective valuations on particular delays. As a consequence the same degree of unreliability might cause different travellers to make very different travel decisions[24]. Frequency of travel might influence perceptions of reliability, with regular passengers likely to have a clear idea of reliability levels on their usual services, while infrequent travellers are more likely to be influenced by their most recent journey (however atypical) or by press reports and hearsay[23]. Bates et al.[25] suggested that a multiplication factor of 2.5 for delay minutes was a reasonable measure of the direct disutility of delays, but also pointed out that this was an average value based on passengers having full knowledge of random delay distributions, and concealing a range between 1 and 5 depending on journey length and purpose. Apart from overvaluation of lateness, there are other reasons which can help to explain these results such as the possibility that despite poor service performance rail travellers are unwilling or unable to reduce their rail travel. Preston et al.[26] hypothesised that users may have got used to a certain level of delay or be more tolerant to delays due to a high degree of delay associated with road travel. Rail OR[27], looked at three significant runs of poor performance on the London-Northampton line using TRUST and CAPRI data, deriving implied multiplication factors which were around the generally accepted figure of 2.5. Therefore, we will also use this figure in our economic appraisal including some differences between commuters and non-commuters.

3. Case Study

3.1. Overview

In this section we describe the main characteristics of the two case study routes used in this research, and explain how the minimum and maximum values for the main variables have been selected. The ECML is an electrified railway route of almost 400 miles between London and Edinburgh via Newcastle. It is an intercity route which was built in the 19th century, trains operate at high speed and have a high average tonnage. We will focus here on the stretch from Newcastle to Edinburgh. The London Waterloo to Portsmouth line links London with the south coast of England. It was also built in the 19th century and includes some of the busiest sections of railway in the UK. London has a major influence on the route and is the origin or destination of the majority of journeys, trains operate at medium to high speeds, and there are important flows of freight and commuter traffic. The London-Portsmouth route is a typical suburban route with a lot of commuters and a high service frequency whereas the ECML is a high-speed line with less users and more distance between stations. Table 1 depicts the main features of both lines:

Table 1. Main characteristics of the London-Portsmouth line and the ECML

	London-Portsmouth line ("Urban Line")	ECML ("Inter-Urban line")
Total travellers (Millions)	21.5	1.8
Average equivalent million gross tonnage per year (EMGTPA)	22	16
Commuters	12.3	0.53
Houses within 80m	30,500	9,250
Houses within 300m	108,500	41,500
Route length (miles)	74	122

The effect stemming from the installation of USPs can be split into installation costs, changes to track maintenance and renewals, and impacts on noise, comfort/ride quality and reliability. The methodology carried out to calculate the cost of each impact is explained in the following section.

3.2. *Investment*

This is the cost of installing USPs. In these illustrative calculations we assume that in the initial year, 2009, all track is renewed in both the base case and the USPs scenario. This is required in order to reset the Local Track Section Factor (LTSF), which takes into account the local track variation from the ideal deterioration rate, for the entire route and to be able to compare benefits and costs for the entire route rather than particular track sections. Moreover, after this assumption, the effect of installing USP can be isolated and properly analysed since the initial year in both scenarios would be the same. By multiplying the number of sleepers by the unit cost of each sleeper, the investment is obtained. There are 91 sleepers per 55.21 metres of single track[28]. Taking also into account switches, and crossings and stations we assume that 400,000 USPs will be installed on the Portsmouth line and

650,000 on the ECML[2]. Data obtained from manufacturers as part of this research project suggests that the unit cost per USP is £15 (2009 prices) so the investment in both routes can be easily calculated.

3.3. Track maintenance & renewal

In this paper we have modified the LTSF in proportion to the reduction in settlement by the adoption of a particular modification over the unmodified case achieved at 3 million load cycles in laboratory tests on elements of track (Abadi, et al.[29, 30], & Abadi[31]) and assuming that 80% of the settlement was due to the interaction with the ballast layer (inferred from Selig and Waters[32]). Adopting this methodology, the LTSF was predicted to reduce by 25% in the case of using a stiff 4 mm thick USP where the word stiff applies to the category of pad used (Auer et al.[33]) and can be inferred from the manufacturers technical information (for stiff USPs: 0.25 N/mm3 ⩽ CStat ⩽ 0.35 N/mm3). In the case of soft USPs (0.079 N/mm3 ⩽ CStat ⩽ 0.105 N/mm3), the laboratory test found out that the LTSF was reduced by 27%, so it was a quite similar reduction compared to stiff USPs[30]. The main benefit would arise from an increased service life of the track and a reduced maintenance and renewal volume[34], which would lead to less disruptions. The combination of USP and stoneblowing (i.e. a form of track maintenance) reduces the need for track maintenance whilst maintaining railway track geometry[35].The Life Cycle Cost (LCC) of track maintenance and successive renewals is given by the Vehicle Track Interaction Strategic Model, VTISM, which is an industry specific model of track behaviour and associated costs[36]. VTISM calculates this cost for the whole of the London-Portsmouth line and the Newcastle-Edinburgh section of the ECML. VTISM assumes a renewal with traxacavation (i.e. the removal of ballast with heavy excavation machinery) in the base year of around 13% of the total length of the Portsmouth line and the rails would be renewed for around 5 miles, with the corresponding figures for the ECML only 6% and around 10 miles respectively. In subsequent years, around 1 – 1.5% of each route would be traxcavated and renewed each year. Some stretches would

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[2] We have rounded the numbers to the nearest 10,000.

for example only need rails to be replaced because sleepers would be in a good condition, whereas other stretches would need a full renewal with traxcavation. The cost of installing USPs in each successive renewal was added in USP scenarios to the costs calculated by VTISM, which is roughly an increase of 3% of the costs for each renewal. Since in this case study both routes would have a hypothetical major renewal right at the beginning, the LCC from VTISM cannot be directly applied and it is necessary to determine a sensible adjustment for the benefit due to the reduction of track maintenance and renewal costs. A rough estimation of this benefit could be determined by applying a linear proportion to this cost. However, consultation with industry indicated that USPs could degrade faster than other track components, so it was decided to use an upper limit for the benefit from track maintenance and successive renewals. The lower limit for the LCC benefit was set as the direct result from VTISM. The upper limit for the LCC benefit was set as a factor which is a multiple of the lower limit. This factor is calculated using the discounted percentage of the route renewed in the whole life under the assumption that an hypothetical complete renewal is carried out right at the initial year divided by the discounted percentage of the route renewed given by VTISM. For the London – Portsmouth line, the percentage of route renewed in the whole life and discounted with a rate of 3.5% is 51.66% in the base case directly given by VTISM and 40.36% when USPs are installed during track renewal. When considering a whole track renewal right at the beginning (i.e. 100% in the first year instead around 13%) these corresponding figures are 138.57% and 127.27%. Therefore this factor is 2.91 for the London – Portsmouth route, which is the average of 2.68 (138.57 divided by 51.66) and 3.15 (127.27 divided by 40.36), whilst for the Edinburgh – Newcastle route the factor is 3.52. With these figures it is possible to estimate the benefit in term of reduced maintenance and renewal costs for the whole infrastructure life.

3.4. Noise

The buildings within 300 metres of the track were assumed to be affected by air-borne noise whereas the buildings within 80 metres of the track would be affected by ground-borne noise[37]. Moreover, the use of USPs could lead to a reduction of ground-borne noise[38] of up to 15 dB[39], but would slightly increase air-borne noise[40]. For those buildings within 80 metres the effect may be reduction in ground-borne noise whereas for those houses between 80 and 300 metres the increase in air-borne noise would be the dominant impact. Noise and vibration due to ground-borne noise is more annoying than just air borne noise (i.e. in the first case the house is affected by noise and vibration whilst in the latter case is only affected by noise), albeit taking into account there are no monetary values for ground-borne noise, we have to assume this has the same valuation as air-borne noise. We have made a cautious assumption of a minor reduction of 5 dB on average in ground-borne noise and an increase of 1dB in air-borne noise[40]. Following results from laboratory tests[40], soft USPs would have slightly more negative effects on the air-borne noise with the rolling noise increased by up to 2 dB compared to the former 1dB of stiff USPs, whereas the ground-borne noise might be reduced by up to 20 dB (5dB for stiff USPs) compared to the 15dB of USPs tested in the RIVAS project[39]. These differences relate to the different stiffness characteristics of the USPs tested and the different experimental set-ups. Moreover, these variations to some extent cancel out in terms of our economic analysis.

The annual rate of growth in the number of houses and in the values for noise have been taken from Nellthorp et al.[41]. In order to be conservative in the study, we selected these values because they are lower than the WebTAG (Transport analysis guidance in the UK) parameters. By multiplying the reduction of noise per house, the number of houses and the value of noise per house in each year we obtain the total figure for this externality.

3.5. Comfort/Ride Quality

USPs would also reduce noise inside the train and improve ride quality due to the reduction of vertical acceleration for conventional speed trains[42], but would have no impact on other attributes of comfort. In fact, Austrian experience with USPs has shown a track quality improvement as well as the aforementioned reductions of vibration and maintenance costs[43]. Following PDFH guidelines[23], the value of changing from a very uncomfortable to a very comfortable ride could be around 10% of the ticket price for the selected routes. Nevertheless, as we previously explained in the literature review, the value chosen for an increase in comfort as a result of installing USPs is 1% of the ticket price. We have differentiated between anytime or full, season, and off peak and cheapest tickets. We assume that commuters buy season tickets in a proportion of 85%/15% standard/first class which is the same proportion as of seats offered in the train, and use the season ticket 480 times each year. The same proportion of standard/first is applied to anytime users. However, we assume that holders of reduced tickets do not travel in first class and that 25% of travellers within this category have a railcard with an average discount of 33%. The proportion of each type of ticket sold (full, season or reduced) from each station is given in the Office of Rail and Road (ORR) station usage database. The proportion of passengers travelling from each station to other stations have been determined using official data from ORR and from a study conducted by Transport Scotland[44] regarding the rail market in the ECML corridor. Finally, by multiplying the number of users in each category by the percentage of their ticket price attributed to the improvement, the value of comfort/ride quality is known.

3.6. Reliability

Around 30% of delays are due to track defects and network management[45] and according to VTISM these disruptions would be reduced by around 20% after the installation of USPs, which would lead to an overall improvement in reliability of 6%. Nevertheless some items of the railway infrastructure would be relatively unaffected by USPs and in order to be conservative we have decided to reduce the figure, giving a final improvement of 1.5% for both lines. Based on evidence from Network Rail[45], we have considered that 92% of trains would arrive on time, that is within 5 minutes of expected time, 5.6% would be delayed up to 30 minutes and 2.4% would be cancelled or significantly late for the Portsmouth line. These figures were set at 89%, 7% and 4% respectively for the ECML. The values of time have been chosen from WebTAG[46] and depends on the type of user: working, non-working commuting and non-working others. To conduct the appraisal, the kind of ticket was transformed into the type of user using the figures given by the PDFH[23]. So, we linked commuting users with non-working commuting users, business users with working travellers, and finally leisure travellers with non-working other users.

3.7. Other parameters

Finally, values for other relevant parameters such as demand, evolution of demand and Retail Price Index (RPI) have been obtained from the WebTAG and National Rail Trends (NRT) websites. Demand growth and Retail Price Index (RPI) are capped after 20 years, and their annual average values for the first 20 years are settled around 2.05% and 3.5% respectively. Following the WebTAG recommendations, RPI has been used to calculate tickets price in nominal terms, but converted afterwards into real terms through the GDP deflator.

3.8. Cost Benefit Analysis Variables

To conduct this economic analysis some hypotheses have been assumed, and it should be noted that risks are not easily taken into account in CBA assessment[47]. For instance, the renewals could be slightly different than those considered by VTISM because the industry model assumes the renewal of some stretches in the initial year instead of the renewal of the whole route, or the value of the ground–borne noise reduction or reliability improvement could also be different due to a different USP stiffness. So, in order to overcome the intrinsic weakness of the CBA methodology, we choose a stochastic approach rather than the deterministic one that is commonly used. This is done with a Monte Carlo Simulation underpinned by a sensitivity analysis aimed at determining the level of certainty and identifying the most important parameters for policy lessons. The goal of running a Monte Carlo Simulation is to assess risk more accurately, choosing randomly modifiable values in each iteration whereas the goal of sensitivity analysis is to know the most important parameters influencing the result.

Below, Table 2 summarizes the ranges of the 22 variables selected for these two analyses, and offers the minimum and maximum values we suggest should be used for both routes. The majority of the values have been compared to the mean value previously described, but for some of the variables it was assumed that they could only increase or decrease from those values. As seen in the previous section the valuation of these variables can vary among a wide range of values and they therefore need to be adjusted to the particular case study. This is the case for the growth of value of noise, which in order to reflect a forecast aligned with WebTAG can be up to 20%. This was also the case for the value of reliability for commuters and non-commuters, since their values are different and the first one can be higher than the second one. All the proportions of trains delayed and on time as well as type of users depend on the route and are not therefore shown in the table. Proportions of users travelling with full price tickets, season tickets and reduced tickets were adjusted to sum to 100%. The same was done with working users, leisure users and commuting users. We used Excel VBA and assumed a normal distribution with a standard deviation ensuring the variability between the minimum and the maximum values. Overall, 2,000 Monte Carlo simulation runs were conducted considering the mean, minimum, and maximum value of each parameter as well as the standard deviation.

Table 2. Selected CBA parameter values

Parameter Analysed	**Min Value**	**Max Value**	**% Change compared to mean**
Average Annual Demand Growth (%)	1.03	3.08	-50%/+50%
Average Annual RPI (%)	1.4	5.62	-60%/+60%
Average Annual Increase of Households (%)	0.28	0.33	-20%/+20%
Average Annual Growth of value of noise (%)	1.62	1.94	-20%/+20%
Value of Reliability for commuters. Minutes of average lateness (m.a.l.)	2.5	3	-10%/+20%
Value of Reliability for non-commuters (m.a.l.)	2	2.5	-10%/+10%
Average Annual growth of VOT working (£)	0.47	1.47	-20%/+20%
Average Annual growth of VOT non Working (£)	0.2	0.32	-20%/+20%
Proportion of Working Users (%)	*	*	-10%/+10%

Proportion of Leisure Users (%)	*	*	-10%/+10%
Life Cycle Cost from VTISM (£,Portsmouth line)	18,330,751	53,434,139	-49%/+49%
Life Cycle Cost from VTISM (£, ECML)	21,582,322	75,861,863	-56%/+56%
Installation Cost per USP (£)	10	20	-33%/+33%
Ground borne Noise reduction (dB)	4	6	-20%/+20%
Air borne Noise increase (dB)	0	2	-100%/+100%
Reliability improvement (%)	0.75	2.25	-50%/+50%
Comfort/Ride Quality (% of Ticket Price)	0	2	-100%/+100%
Trains on Time (%)	*	*	-5%/+5%
Trains Delayed (%)	*	*	-10%/+10%
Proportion of Full ticket (%)	*	*	-10%/+10%
Proportion of Season Ticket (%)	*	*	-10%/+10%
Proportion of People travelling with some discount card (%)	20	30	-20%/+20%
Average discount for each card (%)	20	40	-33%/+33%

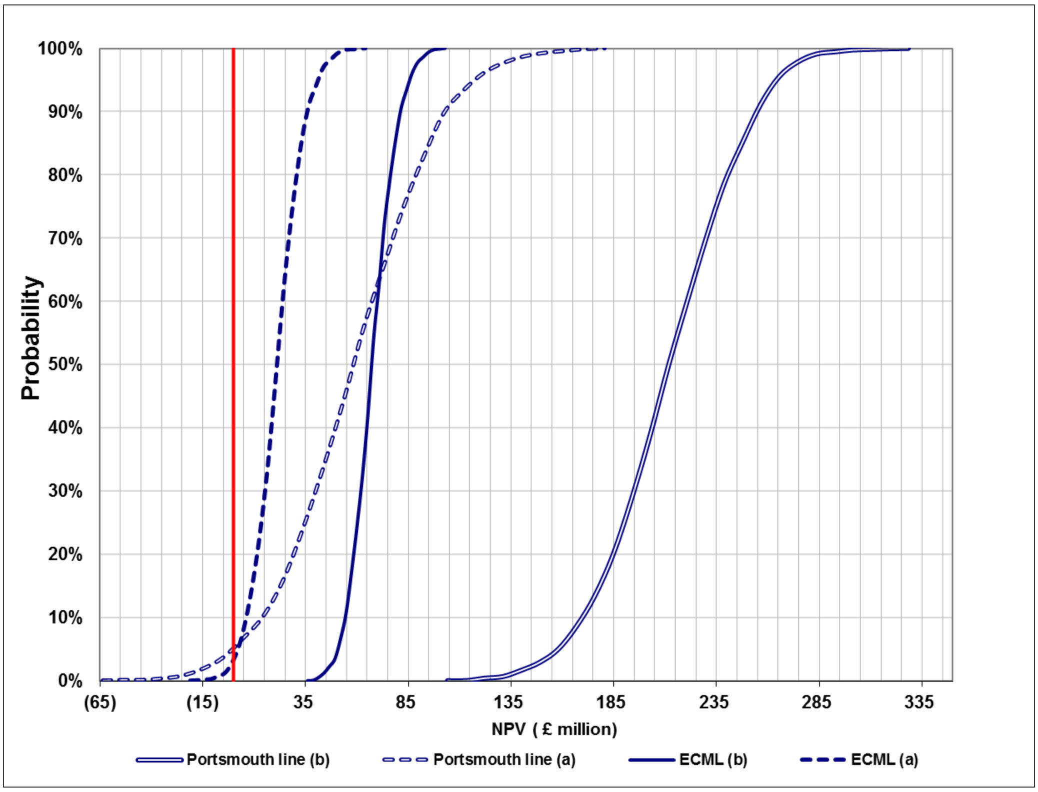
*Depends on route

4. Results

In this section we analyse the economic effect of installing under sleeper pads (USPs) in a hypothetical whole renewal for the Portsmouth line and the ECML. In order to display the range of possible outcomes, the results of the CBA are sorted and plotted as histograms and cumulative probability distribution curves (also called value at risk and gain curve (VARG)). We have run two models with different assumptions with respect to noise. That makes a total of four runs, two for each line. In the assumption a) we only consider an increase of air-borne noise for all houses within 300m of the track, whilst in the assumption b) we only consider the reduction of ground-borne noise for houses within 80m of the track and a slight increase of air-borne noise for the remaining 220m of houses.

Figure 1 shows the cumulative probability distribution curves of both case studies. It has the shape of a cumulative normal distribution, since we selected each variable to fluctuate between minimum and maximum values according to a normal distribution. The final outcome in terms of social welfare is almost always positive and fairly stable over the MonteCarlo analysis. Only the worst-case scenario under assumption a) (show in dash lines) brings some welfare loss with a 5.25% probability of a negative value whilst b) (shown in solid lines) still produces a global benefit greater than £104 million. These results demonstrate that the outcome of the analysis is quite robust. On the other hand, the results for the ECML are even more consistent, since the probability of a negative value in the worst case under assumption a) is lower than in the Portsmouth line, with only a 3.25% chance of having welfare loss. Assumption b) would bring a minimum social benefit of around £36 million. However, the maximum possible value is lower than for the Portsmouth line. Two factors explain this difference. The first one lies in the VTISM result. In the ECML case, the benefit from reduced track renewals and maintenance costs is around £49 million in its central scenario whereas this figure is reduced to £36 Million for the Portsmouth line. Secondly, the number of houses is much larger on the Portsmouth line than on the ECML and this increases the gap between the scenario a) where only the cost of air-borne noise is taken into account and b) where the benefit of reduced ground-borne noise is considered as well. Finally, under the arguably more realistic scenario b), the efficiency of the investment is higher on the Portsmouth line than on the ECML, since the average NPV is £144 million higher and the required investment for the installation of USPs is lower (£6 million vs £9.75 million). However, the NPV per head is much higher on the ECML than on the Portsmouth line.

Figure 1. NPV Cumulative Distribution Function.



Two conclusions arise from Figure 1. Firstly, under the majority of scenarios the expected NPV will be positive. Only taking into account just air borne noise the NPV might be negative with a probability of less than 5.5% on the Portsmouth line and less than 3.5% in the ECML. In fact, under this assumption the benefit for the Portsmouth line can be set between £14 million and £103 million with a probability of 80% and the mean of the sample is in the middle of that range is £59 million. Under the more realistic assumption of considering that the reduction of ground-borne noise dominates for buildings within 80m of the track whereas the increase of air-borne noise affects the remaining houses up to 300m, the benefit is even greater. The difference between the mean of both assumptions is very big at £153 million. The benefit for the ECML under assumption a) can be set between £6 million and £ 36 million with the same probability of 80%, with the mean being £21 million. For this line, the difference between the mean of both assumptions is reduced to £46 million. Secondly, there is a high variability between the minimum and the maximum value for the Portsmouth line based on the large number of houses surrounding the railway track line. For instance, under scenario b) the maximum value is more than three times higher than the minimum value. In other words, when a railway track is located in a suburban environment it is very important to reduce its externalities, particularly noise, otherwise the indirect costs generated by trains can outweigh the potential benefits. However for inter-urban lines these externalities are not so important for the final outcome. Below, table 3 shows the results of the four CBA carried out with the associate cumulative probability:

Table 3. NPV from the CBA parameter values

Probability	Portsmouth line		ECML	
	NPV Option a) (£ million)	NPV Option b) (£ million)	NPV Option a) (£ million)	NPV Option b) (£ million)
Minimum value	-63.75	104.082	-21.278	35.944
VARG 10%	13.745	169.356	6.172	54.296
Expected value (mean)	58.714	212.003	21.243	67.579
VARG 90%	102.945	254.778	36.137	81.247
Maximum value	180.602	328.289	64.295	102.92

In order to underpin the stochastic model, a sensitivity analysis of the variables has been conducted. Below Figure 2 shows the outcome for the Portsmouth line of a test carried out to analyse the sensitivity of the results to the changes of the variables studied in Table 2. The analysis was conducted through a tornado diagram to show the sensitivity of the NPV to the variables used in the methodology while keeping the remaining variables constant (Figure 2). On the left side of this figure, we find all the variables determining the final outcome in terms of NPV. Next to the definition of each variable, in brackets, we display the variation range tested for each variable. The variables with the largest influence on the NPV have been plotted in black, whilst the variables with little impact on the final outcome have been depicted in light blue. The economic variables have been represented at the top of the figure whilst the variables that could be managed by TOCs and the infrastructure manager are drawn in the middle and at the bottom of the graph. Figure 3 depicts this analysis for the ECML.

Figure 2. Sensitivity Analysis for the Portsmouth line

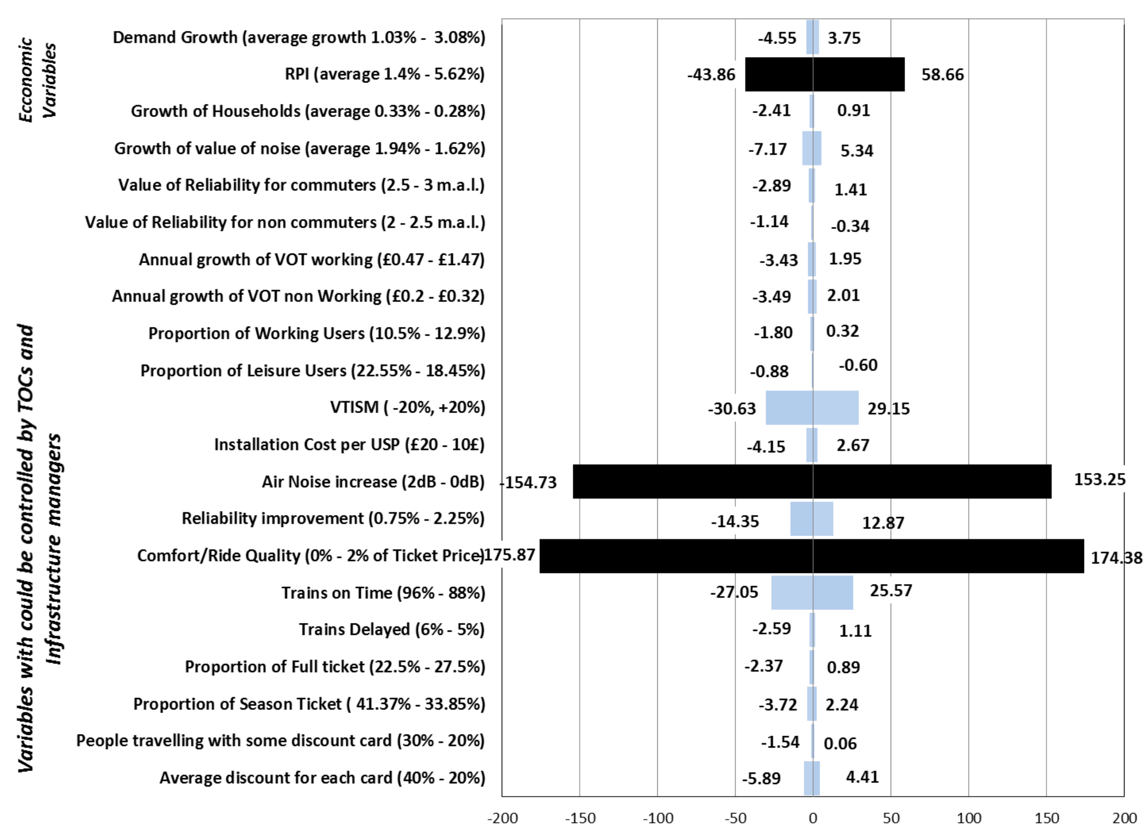


Figure 2a

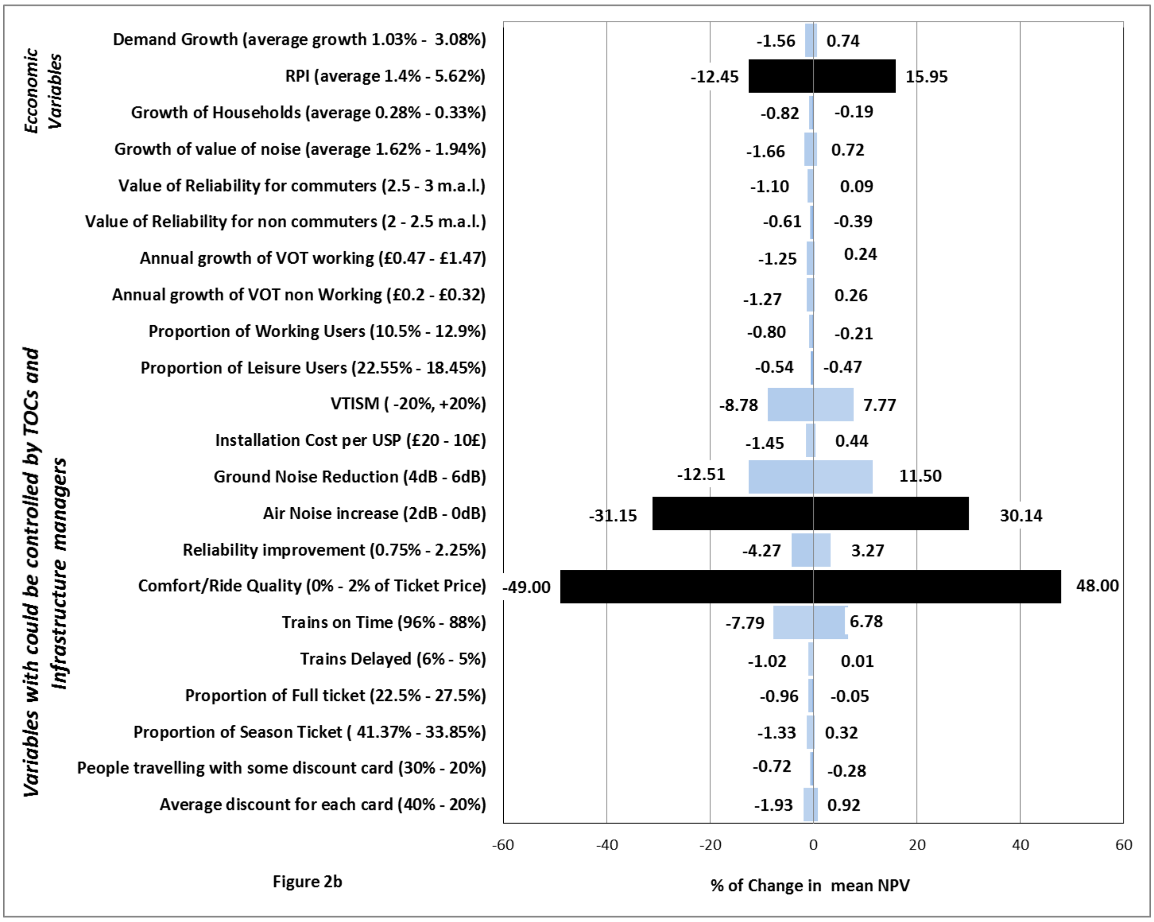


Figure 2b

Figure 3. Sensitivity Analysis for the ECML.

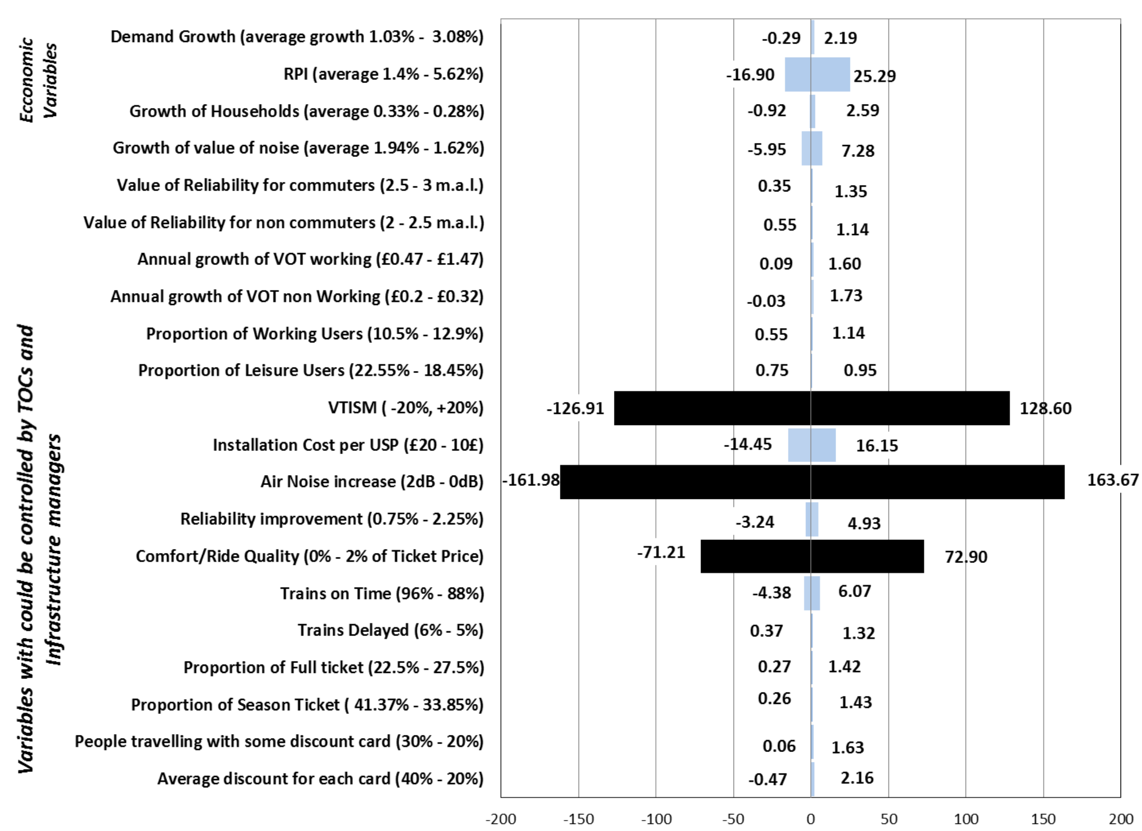


Figure 3a

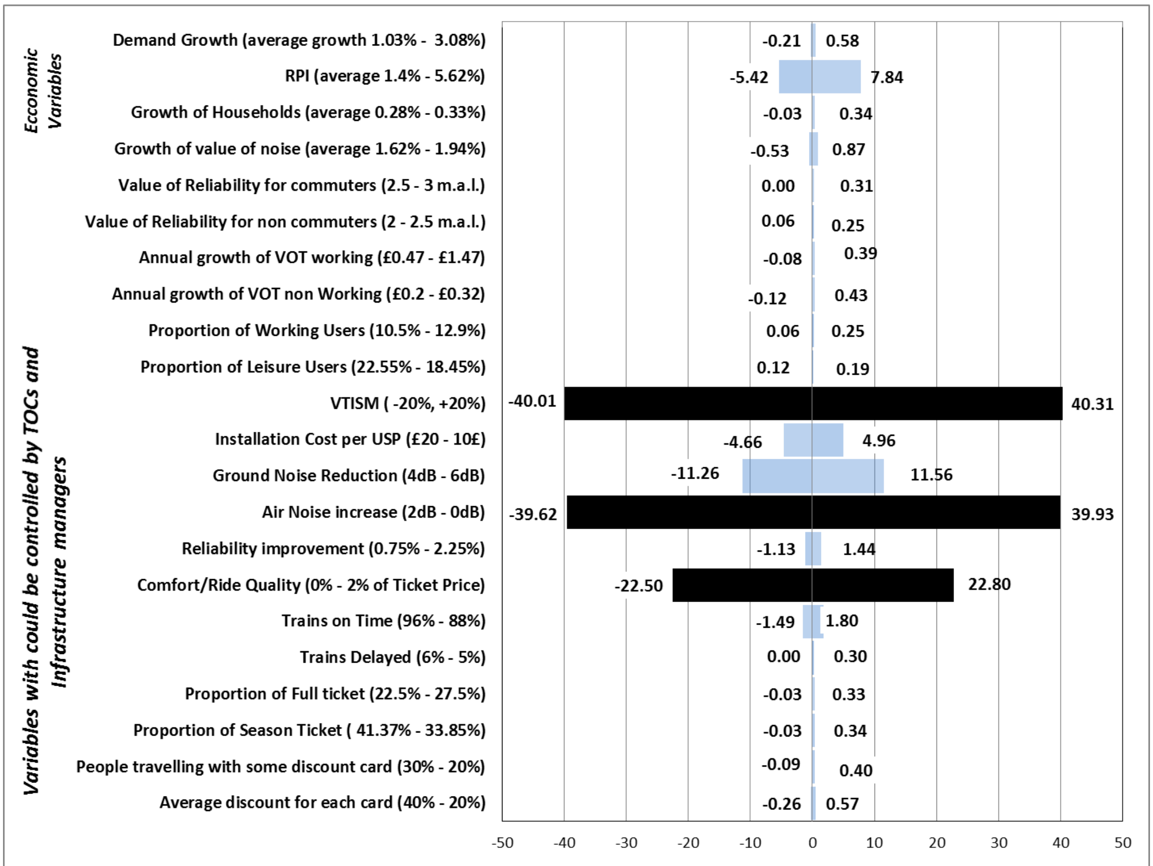


Figure 3b

It is noteworthy that all stakeholders potentially benefit: train operating company, infrastructure manager, travellers and non-users. The only exception would be found for non-users living between 80m and 300m of the railway track, who might experience an increase in air-borne noise. The financial benefit to Network Rail is around £30 million for the Portsmouth line and £39 million for the ECML. In these calculations we have not taken into account the financial compensation between Network Rail and TOCs due to delays and cancellations as this is a pecuniary transfer, but the financial benefit could be higher for Network Rail albeit at the expense of other stakeholders, namely TOCs. For the Portsmouth line this might mean a risk of underspending on maintenance given the fact that the social NPV is in the more likely scenarios much higher than the sum of financial benefit for Network Rail and reliability improvement. However, that is not the case in the ECML since the NPV could be even lower than the Network Rail benefit. So, another interesting lesson from this comparison is that for suburban lines the benefits might not accrue to the stakeholders who made the investment but for inter-urban lines this stakeholder would gain more. This could be a negative incentive for the infrastructure manager to focus investment on more rural lines which generate less potential benefits for the whole of society but which are better for the financial results of the company.

As expected, VTISM indicates that there are less interventions in the track than in the base case. An indirect positive effect, not measured here, would be the reduction in buses which replace trains during engineering possessions, with a consequent reduction in road congestion. The improvement in comfort and ride quality could be easily internalised through a higher (or lower) ticket price and the housing market can internalise the effect of noise. However, the fairness of such ticket pricing measures could be argued since many rail travellers are captive users. Similar concerns could be raised relating to the distribution of costs and benefits from the investment, because the majority of the benefits will not accrue to the stakeholders who made the investment but (for example) to homeowners and local residents.

Three variables dominate the outcome for the Portsmouth line: RPI, increased air-borne noise and improvements in Comfort/Ride Quality. The remaining variables have less impact on the NPV, although ground-borne noise would have an important impact. The large influence of RPI is explained by inconsistencies with the GDP deflator. This effect also reflects an inflation risk. As it could be anticipated the three most important variables are not the same variables in the ECML case: VTISM (i.e. Life Cycle Cost), increased air-borne noise and finally improvements in Comfort/Ride Quality. The effect of ground-borne reduction on the final outcome for the ECML would not be as significant as for the Portsmouth line.

For the Portsmouth line each one dB increase in air-borne noise alters the NPV by almost £90 million under assumption a) or £65 million under assumption b). Ground-borne noise is also very important since each 1 dB reduction brings a benefit of £25 million, mainly for the buildings within 80 meters of the track. These figures are lower for the ECML than the Portsmouth line. Under assumption a) each one dB increase in air-borne noise reduce the NPV by £33 million or £27 million under assumption b). Each 1 dB reduction in ground-borne noise means £8 million of social benefits. The difference of the effect of USPs on noise are partly explained by the more rural or more urban characteristics of each line. Any track intervention improving Comfort/Ride Quality just by 1% of the ticket price leads to a social gain of £103 million on the Portsmouth line and only £15 million on the ECML. A reliability improvement of 1% would lead to a smaller benefit of nearly £10 million for the Portsmouth line and of £1 million for the ECML. This is also the case for the proportion of trains on time, each increase of 1% in the base level means a NPV decrease of around £4 million on the Portsmouth line and less than £1 million on the ECML, which is almost negligible. Logically, the better the base punctuality of the system the less the effect of USP, and this is what the figure is telling us. This result is based on the fact that this proportion is assumed to be constant along the infrastructure life, but different for the USPs and base cases.

Table 4. NPV attributed to different topics with the maximum and minimum for each line

Variable	Portsmouth line		ECML	
	Minimum (£ Million)	Maximum (£ Million)	Minimum (£ Million)	Maximum (£ Million)
Air Noise	0	-129.94	0	-53.76
Ground – borne noise	101.77	152.65	30.84	46.26
Comfort/Ride Quality	0	205.65	0	30.61
Reliability improvement	7.99	23.98	0.87	2.6
Financial Benefit (Network Rail)	29.88	29.88	38.97	38.97
TOTAL	139.64	282.22	70.68	64.68

Finally, Table 4 shows the cost/benefit attributed to each topic in the option b) for both lines. In this case, we have kept the financial benefit attributed to Network Rail constant at its average, since this is the cost we have more information about and therefore less uncertainty. The rail industry does have some degree of control of the comfort and ride quality, and air-borne noise as well as ground-borne noise. Fortunately these variables have the greatest influence on the result and they can be managed by TOCs and the infrastructure owner (i.e. Network Rail) and therefore there is room for realistic and achievable upgrades of the track. For instance, the installation of USPs at renewal is easily achievable, whereas a whole new design railway track would be almost impossible to get, particularly in suburban lines with space constraints. As stated previously all the stakeholders would benefit from the installation of USPs. Non–users living within 80 metres of the track would have lower induced vibration in the houses and as result they will receive less ground-borne noise. Users would benefit from a better Comfort/Ride Quality making their trip more pleasant. TOCs would offer a more reliable service and would avoid buses for some routes during possessions. The infrastructure owner would spend less money on track renewals and maintenance improving in this way its financial balance. Only non-users living between 80m and 300m of the railway track would see welfare losses. However, at this distance train noise would not probably be the primary source of noise and can in any case be eliminated through the installation of noise barriers along the railway track.

5. Conclusions

In order to perform effective cost modelling of potential advances in track and sub-base construction and maintenance, and to reliably optimise the timing of maintenance interventions, it is necessary to place values on the various factors that are affected by such interventions. These values can vary within a range and the commonly deterministic approach used in CBA could have some flaws. So, in order to overcome the intrinsic weakness of the CBA methodology, in this research we have chosen a stochastic approach underpinned with a sensitivity analysis to study the economic impact of installing Under Sleeper Pads (USPs) in two different routes in the UK: the London-Portsmouth line and the East Coast Main Line (ECML). The Portsmouth line is a typical suburban route with a high proportion of commuters whereas the ECML is a high speed line with less users and more distance between stations. Some conclusions can be drawn from the research, which could be applied to any railway operation in a developed region facing high maintenance costs and growing demand. The results shown in this paper are informed by laboratory tests. A future area of research is to have them validated by field trials. Taking together the laboratory tests, the economic analysis, and initial field tests suggest that large-scale field trials are worthwhile.

First, the installation of USPs could potentially bring important benefits for almost all stakeholders, with the exception of some houses that could see increase exposure to air-borne noise. This seems to be the case in developed countries with old rail infrastructures and high demand, such as the UK, where it appears that minor interventions which improve reliability and comfort/ride quality and at the same time reduce externalities could potentially bring important social benefits. However, it is possible that the benefits will not accrue to the stakeholders who made the investment, particularly for suburban lines. In inter-urban lines the infrastructure owner would be the main beneficiary from the investment. There could be a negative incentive for the infrastructure manager to invest primarily in these lines with less potential benefits for the whole society but indeed much better for the financial results of the company. Nevertheless, for these inter-urban lines the efficiency gain per capita basis is higher than in the case of suburban lines.

Second, although it could seem trivial, noise matters. In fact, interventions that increase this externality might have a negative impact overall. In other words, when a railway track is located in an urban environment it is very important to reduce its externalities otherwise the costs triggered by the train noise can outweigh the potential benefits. Nevertheless on inter-urban lines these externalities are not so important for the final outcome.

Finally, this analysis suggest that in the case of suburban or urban lines there is a high degree of uncertainty regarding the results from investment in USPs, whilst the outcome of the investment is relatively more certain in the case of interurban lines. As a result, investments of this kind made in suburban environments must be analysed particularly rigorously, and measures to reduce potential losers should be included in the investment to increase equity and fairness of those investments.

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The Authors declare that there is no conflict of interest.

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