Assessing the Whole-Life Carbon Footprint of Under Sleeper Pad Installation for Ballasted Track

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# Abstract

Increasing awareness of the problems posed by anthropogenic climate change in recent decades has led to growing concerns over the level of carbon emissions attributable to travel, transport and infrastructure development. Even though rail is a relatively low carbon mode, there is also pressure to reduce rail’s carbon emissions to help mitigate the extent of climate change. In this paper, we provide a Life Cycle Analysis study which estimates the effect on carbon emissions of installing Under Sleeper Pads (USPs) during track renewal on two conventional railway lines in the UK. We obtain three main conclusions. Firstly, the aims and scope of the analysis, life cycle inventory method, units used and life span of the intervention can all have an important influence on the result. Secondly, although the installation of USPs at track renewal could bring some reductions in CO2 emissions, these are very low compared to the associated financial and economic impacts, and some considerable time would be needed to generate these advantages. However, USPs might make rail travel cheaper and the increased demand could be an important indirect effect on CO2 emissions in the transport system due to the shift from other transport modes. Finally, the use of non-recycled rubber can offset the potential environmental benefits from the reduced requirement for track system interventions (maintenance and renewal needs), so the use of recycled carbon neutral rubber in USP manufacturing should be incentivised.

Key words: Carbon Footprint; Ballasted track; Track renewal; Track maintenance; Under Sleeper Pads.

# Introduction

Since 1970, global CO2 emissions have increased by about 90% and transport related carbon emissions currently represent around 14% of the global greenhouse emissions. These emissions primarily involve fossil fuels burned to power road, rail, air, and marine vehicles, but there are also significant emissions associated with the construction and maintenance of transport infrastructure. In the case of the UK’s rail network, the largest component of this infrastructure comprises 20,800 miles of track (9,846 route miles) and it has been estimated that maintaining and replacing this track leads to annual emissions of 430,000-934,000 tonnes of CO2, assuming that all rail sections contain 40% primary and 60% secondary material (Milford and Allwood, 2010). Similar levels of emissions are almost certainly generated by maintaining and replacing track systems on other rail networks around the world. Increasing awareness of the problems posed by anthropogenic climate change has led to growing concerns over the level of carbon emissions attributable to travel, transport and infrastructure development (Müller et al., 2013). Even though rail is a relatively low-emission mode of transport, a number of studies have attempted to quantify the carbon emissions produced by railway operations, both in an effort to identify ways to reduce such emissions further and also to emphasise the case for policies aimed at increasing rail’s mode share and thereby reducing the total carbon footprint of travel. A small number of studies have attempted to produce a whole-life carbon footprint for the British rail industry (for example RSSB 2010, or for particular routes for example, ObjectifCarbone, 2009) and these have generally found that the construction, maintenance and disposal of railway infrastructure has a significant carbon impact. It has been estimated that this may amount to anything from 2% (Facanha and Horvath, 2007) to 20% (Milford and Allwood, 2010) of total railway emissions, with total whole life energy consumption (including vehicles and fuel production as well as infrastructure) 93-160% higher than operational consumption according to one report (Chester, 2008).

The majority of carbon foot-printing analysis carried out previously for the rail sector has been linked to policy interventions that attempt to change mode choice or encourage environmentally-friendly behaviour, and studies of the carbon impacts of rail infrastructure construction and maintenance are relatively scarce. This paper helps to fill this gap in the literature by analysing the emission impacts of installing Under Sleeper Pads (USPs) during track renewal based on a case study of two routes in the UK. It compares the carbon footprint of two scenarios (do nothing vs installing USPs at renewal) over a 60 year time period. USPs are one of a number of track system interventions currently being trialled with the primary aim of reducing rail infrastructure maintenance costs (Ortega et al., 2017), but it is possible that they may also deliver some emission reduction benefits.

While the research described here focuses on the assessment of a particular type of infrastructure intervention in the UK, the general methodology used could easily be transferred to assess other interventions in different contexts. The remainder of this paper is structured as follows. Firstly, a brief literature review on the topics of life cycle inventory and life cycle assessment is provided. Secondly, the research includes a review of carbon foot-printing in the railway sector and explains the main stages followed in such an analysis. Thirdly, the parameters selected for the carbon foot-printing undertaken here and the corresponding results for two case study lines are shown. Conclusions and priorities for further research are summarised in the last section.

# Literature Review

## Background to Life Cycle Analysis

Life cycle analyses (LCAs) are sometimes also known as ‘life cycle assessments’ or ‘cradle to grave analyses’, and the procedures involved in LCA are set out in ISO 14040 and 14044, part of the ISO 14000 series of environmental standards. ISO 14040 defines LCA as the “compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle”, meaning that it is essentially a tool for the analysis of the environmental burden of a product through all stages of its life cycle (Guinee, 2002). The ISO standards state that LCA should contain four main phases, which are illustrated below in Figure 1. A full LCA will consider all types of environmental impact, although CO2 emissions are the primary concern of this research, and this means that comprehensive LCAs can be hampered by the absence of a standardised method of estimating and measuring environmental damage (Madu, 2007).

Figure 1. Phases of a Life Cycle Analysis

[Figure 1 app. Here]

## Phases of a Life Cycle Analysis

### Definition of Goal and Scope

The first stage in a life cycle assessment is to set out the context of the assessment and to clearly define its scope and audience. This should include the boundaries of the system and functional unit(s) being studied, any assumptions and limitations which apply to the analysis, the level of sophistication of the study in relation to its goal, the allocation methods used to partition the impacts of shared processes, and the impact categories included. While it may seem that the imposition of system boundaries could limit the realism of the analysis, they are necessary because the product chain in some cases may be traced almost *ad infinitum*, making it effectively impossible to quantify the embedded emissions (Madu, 2007).

### Creation of a Life Cycle Inventory

In order to create a life cycle inventory (LCI) it is necessary to catalogue all flows to and from ‘nature’ and between different phases of production and system life for the system being assessed. This is achieved by constructing a flow model of the system from input and output data for all activities within the system boundary, but there are some problems which can arise if the system boundaries are incorrectly defined. During an LCA, each and every flow should be followed until its economic inputs and outputs have all been translated into environmental interventions (flows crossing the boundary between the product system and the environment) (Guinee, 2002), although it should be noted that there may also be relevant inputs and outputs which would not be considered during conventional economic costing.

Data on embedded emissions can either be obtained via bespoke studies or, more usually, via generic emission databases (as is the case for the research described in this paper). Once completed, the LCI should comprise a table detailing all inputs and outputs to and from the environment for all the processes and functional units involved in the system.

### Life Cycle Impact Assessment

Once the LCI has been created, a life cycle impact assessment (LCIA) is conducted to quantify the significance of the system’s environmental impacts. Impact categories, category indicators and characterisation models are selected, and the inventory parameters are then sorted and assigned to impact categories, with emissions estimated based on the LCI (Ueda, et al., 2003). The impacts of each category are then converted into common units and summed to estimate the overall impact for each category. These category impacts may then be weighted and combined to give the total project environmental impact, although this last phase is not compulsory for an LCIA under ISO 14044.

The consideration of all stages of a product’s life cycle in the LCIA overcomes the issue of problem shifting, where an environmental issue is ‘overcome’ by moving it to another stage in the product’s life cycle without necessarily giving any overall improvement (Guinee, 2002). Problems may still arise though if an individual process tree leads to the production of multiple products, as in such cases it can be difficult to assign emissions to particular products of interest (Madu, 2007). An example of how to conduct this step can be found in Del Pero et al. (2015) who carried out a full cradle-to-grave LCA of a heavy metro train. In their study, the LCA inventory is subdivided into four stages and each stage is then divided into Process Units. The division was done as follows:

1. Material acquisition, which is disaggregated into raw material extraction and production, and external transportation;
2. Manufacturing, which is split into manufacturing and assembly, and internal transportation;
3. Installation and use;
4. End of life, which is formed by the process units of recovery and disposal.

### Interpretation

In this final phase of the analysis, the results from the LCI and LCIA phases should be systematically evaluated to check for completeness, to carry out sensitivity, perturbation, uncertainty and consistency tests, identify any significant issues, and summarise the conclusions, limitations and recommendations of the LCA. A key element is to ensure that the outputs from the LCA meet the original goal.

The weaknesses of LCA are strongly related to the interpretation of the LCIA. The most important limitations of the methodology are the simplification to a monetary unit, the lack of well-founded data, the high complexity of the construction process, and conceptual confusions (Gluch and Baumann, 2004). Furthermore, the environmental assessment of future long-distance travel, such as by high speed rail, is also constrained by different gaps, with one of the most significant being the lack of data on future energy resources or vehicles (Chester and Ryerson, 2014). In order to fill these gaps, van der Leeuw et al. (2012) recommend taking into consideration the opinions of stakeholders and academics. Moreover the assessments should study the interaction between transport modes and, therefore, changes in energy use as a consequence of mode shift and multimodal transport.

# Rail Infrastructure LCA

## Review of Rail Infrastructure Carbon Foot-printing

The majority of the studies about rail’s carbon footprint have focused on ‘direct’ or ‘tailpipe’ emissions from the operation of rail vehicles (for example, Bergin et al., 2009), as these are the most immediate (and most easily calculated) carbon impacts of rail travel. This also gives comparability with most studies of carbon emissions from other travel modes, as the majority of these also concentrate on tailpipe emissions alone. In general, such studies conclude that rail’s environmental performance is superior to that of other modes, with lower carbon emissions per passenger kilometre (for example ATOC (2007) and Baron et al. (2011)). There are two main reasons for the higher environmental impact of road transport compared to trains. Firstly, with the actual weight limits on European road vehicles, each freight train can be equivalent to up to forty trucks (Mayer et al. 2012). In fact, European countries where these weight limits have been relaxed reported an overall efficiency increase (see a review in Ortega et al., 2014). Nevertheless, the lower rolling resistance of steel on steel compared to rubber on tarmac mean that the energy required to move a given weight by rail is lower than for road transport. Secondly, road vehicles are primarily powered by diesel whereas rail traction is predominantly electric in many (but not all) countries (Mayer, et al., 2012). However, the flexibility that enables road door-to-door movements makes road transport essential for many movements. Therefore, intermodal operations constitute a good option, although emissions savings have a high variation depending on the route, and these savings are complex to forecast (Craig, et al., 2013).

For the case of passenger traffic, it should be noted that the magnitude of rail’s emission advantage is heavily dependent on train occupancy levels (Chester and Horvath, 2010; Chester et al., 2010). Surprisingly, Garcia (2010) found in a tail pipe analysis in Spain that energy consumption was 29% lower per passenger for high speed trains than for conventional trains. This result lies in the more homogeneous speed profile, fewer stops, fewer curves, higher load factors, the fact that high speed trains use electric traction whereas some conventional trains use diesel, and finally, for competing routes the distance covered by high speed is less than in conventional trains. This emphasises the point that infrastructure design is a key determinant of energy consumption. An analysis of UK rolling stock emissions (Esters and Marinov, 2014) showed that energy consumption varies proportionally with the square of speed, and therefore high speed electric trains can turn out to generate more carbon than diesel trains at maximum operational speed. The difference between both studies occurs because inertial/grade resistance and distance travelled were not considered in the second study as well as the current UK energy balance (e.g. how energy is generated and used). Furthermore, tailpipe emissions are not the only carbon emissions which result from rail transport, and research has found that rail modes can have the smallest proportion of operational to total energy use due to the low fuel requirements per passenger relative to the substantial supporting infrastructure (Chester and Horvath, 2009).

While analysis of infrastructure-related emissions has been less common than well-to-wheel analysis of vehicle-related emissions, there have still been several studies of this issue. For example, a number of papers have attempted to measure full LCA of railway track (Lee et al., 2008; von Rozycki et al., 2003; Tuchschmid, 2009; Spielmann and Scholz, 2005), although they vary in the extent to which they cover all relevant factors. Embodied emissions from the construction and decommissioning of high speed rail infrastructure may be particularly significant, due to the large quantities of steel and concrete (materials whose production is highly energy intensive) used in such infrastructure (Network Rail, 2009). An SNCF study of the Rhine-Rhone HSL found that quicklime used in ground treatment was in fact the largest source of civil engineering CO2 emissions during the construction process, accounting for 33% of the CO2 emissions (Objectif Carbone et al., 2009). These conclusions can be equally true for new conventional lines. It is also not clear that the construction of rail infrastructure has a greater environmental impact than road construction, with Facanha and Horvath (2007) suggesting that, in fact, the CO2 emissions associated with the construction of rail infrastructure are lower than those associated with road infrastructure per ton-mile of freight moved over the lifetime of the infrastructure. Structures such as tunnels or bridges can reduce operational emissions by reducing the need for gradients, although they may result in higher embedded emissions (Pritchard, 2015). Indeed, bridges were also responsible for carbon emissions based on the fact that these aerial structures need considerable amounts of steel (Yue, et al., 2015). For instance, on the projected high speed line in California, tunnels and aerial structures represent only 15% of the planned length but they were projected to be responsible for 60% of the carbon emissions from construction of the basic infrastructure (Chang and Kendall, 2011). In the case of Turkey’s high speed railways, infrastructure was found to be responsible for 58% of environmental load (e.g., carbon emissions, acidification and so on), whereas operations were responsible for the remaining 42%. This gap was even greater for conventional railways but in the other way (Banar and Özdemir, 2015), implying that the infrastructure of conventional railways is less carbon intense. Grossrieder (2011) conducted a comprehensive LCA of the projected high speed line between Oslo and Trondheim. Infrastructure produced the largest share of the carbon footprint (87.5% of gCO2 in pkm or 87.74% of gCO2 in vkm), whereas operation accounted for approximately 11.5% and rolling stock for less than 1% of the total emissions. The result is explained by the low number of trains operated, as well as an intensive use of cement, steel and extruded polystyrene during the construction phase.

Baron et al. (2011) found a carbon footprint up to 5 times larger for the High Speed lines in Taiwan and China than for the lines in Southern Europe. This difference is mainly explained by space constraints during construction and by operational emissions stemming from the electricity mix of each country.

For a heavy metro train, Del Pero et al. (2015) found that material acquisition was the second most important stage due to resource consumption and emissions during the extraction of iron and bauxite. In contrast, the influence of the manufacturing and end of life stages were much lower. Finally, Chester and Cano (2016) remark on the importance of infrastructure construction emissions occurring once, whereas the kilometres travelled per passenger on average are spread over a long period of operation. In other words, this should clearly be taken into account in any LCA and therefore life span is very important in such an analysis.

## Units Used

There is some variation between studies as to the units used to quantify infrastructure CO2 impacts, which can make comparison between studies difficult. Millford and Allwood (2010) used CO2 emissions per metre of single track per year (kg CO2/m yr). Von Rozycki et al (2003) used CO2 emissions per 100 passenger km (kg CO2/100 pkm), while Tuchschmid (2009) used a basis of CO­2 emissions per gross tonne km, with emissions per passenger km used for passenger traffic. It should be noted that where emissions are measured in passenger or tonne kilometre (arguably the most useful measure for comparison with other modes) traffic density is likely to have a significant influence on the relative carbon efficiency of a particular railway line, even allowing for increasing maintenance requirements with increased traffic levels (Tuchschmid, 2009). Peters et al. (2011) note that the emission metrics used as well as different treatments of time could result in a great influence on LCA. With respect to time, it seems clear that the same effect can have diverse values depending on the year when is accounted for, the life span of the track (Krezo, et al., 2016) or the time horizon for evaluation of the emissions, to name but a few. Therefore, Peters et al. (2011) recommend the use of different emission metrics depending on the impact to be evaluated, whereas the aim and scope of the study may define different time scales.

## Track Components and Construction

When carrying out an LCA of railway track-related emissions, it is not sufficient simply to treat ‘railway track’ as a single entity, as it is in fact made up of a number of different components, which each have very different characteristics. The precise mix of components will vary between different track designs. For instance, Milford and Allwood (2010) examined the CO­2 impacts of construction, maintenance and disposal of all the main components in UK track infrastructure. They identified the main types of component from the Network Rail GEOGIS infrastructure database for inclusion in their emissions model, whilst Chester (2008) used a more generalised approach in his hybrid LCA of track construction, basing emission levels on the estimated total quantities of aggregate, concrete, steel and wood used. As well as the quantities of different components required for a given section of track, the service life of these components will also affect track life cycle emissions. Milford and Allwood (2010) estimated these based on values from the Network Rail Vehicle Track Interaction Strategic Model (VTISM).

Once these values have been collected, the CO2 impact of the construction phase of each component can be calculated using material quantities and carbon intensity values, track characteristics and service life values (Milford and Allwood, 2010). As well as the elements directly relating to the track and sub-base, if a new line is being built or if an existing route is being widened then emissions from construction of the track formation will also need to be accounted for. It may also be necessary to allow for the effects of changes to land use- if, for example, extensive deforestation is required for construction of the line (Åkerman, 2011).

So, at this stage of the analysis it is necessary to consider component, processing and transport emissions for each item of the track. Component processing during track installation, including tasks such as rail cutting and welding will also produce emissions, but specific estimates of such figures are scarce, with the only set identified provided by Lee et al (2008). Emissions will also be produced by the transport of track components and materials during the construction process. Such emissions will be highly site-specific, as they will obviously depend on the distance from the material source to the construction site, and also on the mode of transport used.

## Track Maintenance

Not all studies consider emissions resulting from track maintenance, and there is often little detail of what is considered as forming part of such maintenance, even in studies which do estimate the resulting emissions. Milford and Allwood (2010) calculated maintenance emissions from three main activities (rail grinding, tamping and stoneblowing), with maintenance frequency based on Network Rail estimates, and the resulting emissions calculated indirectly, based on the fuel consumption of the vehicles involved. Similarly, Chester (2008) estimated maintenance emissions (from material replacement, grinding and inspection) based on equipment used and labour productivity, as well as making use of rail maintenance factors from the SimaPro software, which are based on the German and Swiss long-distance networks. Krezo et al. (2016) estimated carbon emissions from ballasted track maintenance and renewal works, finding that emissions due to material contribution were always at least 90% of the total carbon emissions, whilst the machinery contribution was found to have the remaining percentage. As well as maintenance emissions, non-maintenance operating emissions relating to track may need to be considered, such as those resulting from the energy used to heat electric points (Rozycki et al., 2003). Renewals and replacement of the track system have the most significant impact on LCA and, since slab track requires fewer replacements, it is therefore the most energy efficient over long timescales, such as 120 years in the case of railway infrastructure (Kiani, et al., 2008). Nevertheless, for shorter periods the break-even point is difficult to find because the LCA depends also on the kind of soil where the track is built, the use of recycled products and the tonnage carried over the line (Mason, 2013).

## End of Life Factors

A factor which is sometimes overlooked in LCA is the disposal of infrastructure when it becomes life-expired. Milford and Allwood (2010) suggest that emissions from this phase are chiefly related to transport, although landfill and incineration will also generate emissions, as will the process of dismantling the track. Moreover, different recycling methods can lead to differences of energy consumption and emissions (Lee, et al., 2010).

## Infrastructure Insurance

Chester (2008) suggest that the emissions resulting from insuring rail infrastructure should be included in railway LCAs, and give estimates based on the emissions of the insurance providers. However, such emissions do not appear to be considered by any other studies since it is quite possible that these emissions are very low, or even negligible, and could be included within infrastructure management.

# Case Study: London-Portsmouth and Newcastle-Edinburgh

This section provides an illustrative example of the calculation of the carbon footprint of installing under sleeper pads (USP) at renewal on the railway routes from Newcastle to Edinburgh and from London to Portsmouth. The Newcastle-Edinburgh line (122 miles) was built in the 19th century and forms part of the electrified East Coast Main Line from London to Edinburgh. Trains operate at relatively high speed with few intermediate stops and are classified as medium-high tonnage, with slightly more than two million passengers using the line in 2014 (Data from Office of Rail and Road). The London to Portsmouth line (74 miles) carried 23.2 million passengers in 2014 (Data from Office of Rail and Road), was also built in the 19th century and includes some of the busiest sections of railway in the UK, with a high service frequency. London is the origin or destination of the majority of journeys, trains operate at medium to high speed, and while commuter flows dominate there is also significant freight traffic on part of the route.

USPs are rubber pads with a high degree of elasticity which are installed underneath sleepers on ballasted tracks, with the aim of improving track performance. The installation of USP changes track stiffness with the main benefits arising from a prolonged track service life and reduced maintenance volumes (Marschnig, 2011). For this study, we measured the impacts of USPs on maintenance costs and volumes using a proprietary rail industry software called VTISM (Vehicle Track Interaction Strategic Model) (SERCO, 2014). These impacts are captured by a 25% reduction in the Local Track Section Factor (LTSF) modifier following the installation of USPs (Le Pen, 2015). This factor takes into account the local track variation from a base deterioration rate, so this reduction means a better track geometry due to a reduced deterioration rate. VTISM by default undertakes the first renewal in 2009, so that was set as the base year for the LCA. The main assumptions made in the analysis are explained below. Table 1 shows the emissions parameters for different components whilst Table 3 includes the emissions per type of intervention (renewal, maintenance and inspection). Although dismantling the complete track system has been included in the analysis, the disposal or recycling of materials from the renewal projects were not considered. The inclusion of these topics would depend on the particular process used and, as it is not clear what this process would involve in reality, for the sake of clarity they are not included in the carbon footprint. The assumptions are only valid for single track, so in order to be valid for double track the calculations have been properly adjusted (e.g., double the mass component needed). Finally, we have assumed that rail demand would be identical in both scenarios because the gain in comfort and reliability per head is relatively small (Ortega, et al., 2017) and would not result in more people travelling. We therefore focused our study only on impacts directly related to rail infrastructure.

Table 1. Emissions per component of single track.

[Table 1 app. Here]

All the values included in Table 1 have been based on the ARUP database COST2, which gives estimations of carbon emissions for different rail infrastructure interventions in the UK context. Each component has been calculated as follows:

* Rails. The calculations assume two rails per track, transported to site by rail. The labour and plant data are based on the output of a rail laying machine being given (Kiani, et al., 2008) as 37h per km. This has been rounded to 200 m per shift.
* Sleepers: Based on a sleeper spacing given as 600 to 700 mm between centres (~1500 per km), and a sleeper laying machine with an output of 14 h per km of single track (Kiani, et al., 2008).
* Rail Clips: Assumes two per rail, which leads to four per sleeper for single track. Transport, Labour and Plant are not included, as it is assumed rail clips will be installed at the same time as sleepers. The same applies for rail baseplates, rail pads and under sleeper pads.
* Rail baseplate (steel): Assumes two per sleeper. The same configuration as used by Milford and Allwood (2010) was selected. They studied track components in the UK railway network and, baseplates must be included in current track and double headed configurations.
* Under Sleeper Pad: Assumes one per sleeper.
* Ballast: Assumes 0.08m3 ballast per track m of single track and 1,600kg per m3. This represents a relatively shallow formation which was chosen due to the higher embedded factor recommended by ARUP database COST2 compared to the literature studied (e.g. 7 times higher than the embedded factor recommended by Milford and Allwood). Labour and plant based on a tamping machine with an output of 32 h/km (Kiani, et al., 2008) and an eight hour shift.
* Rail Pad: Assumes two per sleeper.

In order to estimate machine emissions we have included the same construction speed as in Kiani et al. (2008), whose research is based on parameters for the UK. Below, Table 2 shows the values for the carbon analysis per kg/day per type of machine. All these parameters assume a shift of 8 hours.

Table 2. Emissions per day and machine with interventions in single track

[Table 2 app. Here]

Four interventions conducted with machines do not appear in Table 4: traxcavation (track excavation), stoneblowing, rail grinding and geometry recording. The performance of traxcavator and stoneblower machines can vary within a wide range due to the traxcavation of a different soil or the addition of more ballast than expected (Milford and Allwood, 2010). In order to give consistency within the study we have used the same proportion of carbon emissions for these machines with respect to tamping as Milford and Allwood, with stoneblowing emissions assumed to be 2.73 times higher than tamping emissions and rail grinding emissions 6.54 times higher. It is not possible to determine the type and quantity of soil to be excavated by the traxcavator machine in particular circumstances, so we assume the same performance and emissions as rail grinding (the highest of the machine emissions). The geometry recording can be made at almost commercial speed (i.e. the speed at which a train operates carrying passengers) (Arasteh, et al., 2014), so we assume the same emissions as the class 165 diesel passenger train with two coaches. For visual inspection and pedestrian ultrasonic testing we assume the staff have to travel 50 km to the railway track (i.e. the same distance as in other interventions in table 1) and that their walking speed would be low (1-2 km/h) so that each day they can measure or inspect ten km of single track. The level of rail repair will depend on the amount of damage to particular sections of rail, so we have assumed the same emissions for this as for the rail grinding machine. Due to the lack of data for individual switches & crossings (S&C) on the route, S&C renewals are assumed to have double the emissions of the double track and have to be carried out with traxcavation. S&C are the parts of track systems used where lines join or diverge, and require more track components than plain line sections (Kaewunruen, et al., 2015). Finally, the complete renewal and traxcavation process can be divided into three steps:

1. Step 1: Dismantling of existing track. Although there is no real world evidence of the emissions from dismantling the whole track system after construction as recurrent maintenance is a more usual process (Lee, et al., 2008), we have included it in the analysis as this might eventually occur in practice. Transport to site is included later in the components, so only working hours for machines and labour are considered here.
2. Step 2: Traxcavation.
3. Step 3: Installation of new materials and associated processed in the following order: ballast, USP (when used), sleeper, rail baseplate, rail pad, rail, rail clips and tamping.

As previously noted, the impact on track stiffness of modified renewal procedures is given by changing the LTSF in VTISM (SERCO, 2014). This is divided by cost and volume and can differentiate between the whole period analysed and the output for each year. The program outputs the results according to the works which are undertaken to the track system, such as re-railing or tamping. Below, Table 3 offers the different work types included in VTISM and their respective carbon emissions used for the calculations, which have been estimated following the assumptions described above.

Table 3. Emissions by Activity Description

[Table 3 app. Here]

After installing USP at renewals the LTSF is modified and this is reflected in the subsequent maintenance and renewal volumes. Below, Figure 2 shows the renewal and maintenance volumes under both scenarios (with USP and without USP) for both study routes. It can be anticipated that the main emissions savings from the new policy arise from the changes in 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 minimum renewal of steel sleepers, but because the volumes involved are negligible (around 0.1% of the total emissions in the whole period) and identical for both scenarios these have been omitted from the analysis. According to VTISM, in the base year around 13% of the total London-Portsmouth route would be renewed with traxcavation, with the corresponding figure for the Newcastle-Edinburgh route being only 6%. From that year onwards, around 1% would be traxcavated and renewed each year in the USP scenario for both lines, whilst this percentage would be higher without USPs. On the London-Portsmouth route the length traxcavated and renewed would be 76.35% of the total route with USPs whereas it would increase to 109.19% without USPs. Due to the higher deterioration rate, some stretches would face two renewals in the service life. The corresponding figures for the Newcastle-Edinburgh route would be 72.27% and 86.28% respectively. For both routes, some stretches would, for example, only replace rails because sleepers would be in a good condition, whereas other stretches would need a full renewal with traxcavation. The differences between the replacement and maintenance regimes are based on the scheduled interventions for implementation over the years, which are given by actions from Network Rail’s renewal and maintenance budgets. These actions take into account the actual geometry of the track as well as the expected geometry after renewal and maintenance activities.

Figure 2. Renewal and maintenance volumes

[Figure 2 app. Here]

The CO2 emissions per track mile are obtained by multiplying the parameters from Table 3 and the output from VTISM given in Figure 2. The aggregated results over the whole route per type of intervention are shown below in Table 4, with the relative savings displayed below in Figure 3.

Table 4. Total CO2 Emissions by Activity Description

[Table 4 app. Here]

Figure 3. Relative savings per intervention and line

[Figure 3 app. Here]

Some conclusions can be drawn from Figure 3 and Table 4. First, with respect to the aggregate figures, carbon emissions are quite similar in both scenarios for the Newcastle-Edinburgh route, whereas for the London-Portsmouth route there is a reduction of more than 8,000 tonnes of CO2. Second, these reductions are very small when compared to the total carbon emissions. In other words, these savings represent only 0.16% of the carbon emissions for the Newcastle-Edinburgh route and 2.82% of the carbon emissions for the Portsmouth line. Third, for the London-Portsmouth route the two main differences lie in the complete renewal and traxcavation, and in stoneblowing. 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.

Another important conclusion is that the use of non-recycled rubber in USPs can outweigh the potential environmental benefits from the reduction in track system interventions (maintenance & renewal needs). If carbon neutral USPs were installed at renewal, carbon emission savings would rise to 16,200 tonnes of CO2 on the London-Portsmouth route and 12,050 tonnes of CO2 on the Newcastle-Edinburgh route. End-of-life tyres can be treated and used as under sleeper pads in railway tracks (Sol-Sanchez, et al., 2014) whilst keeping railway track geometry at adequate standards (Sol-Sanchez, et al., 2016), making this a realistic option. The net greenhouse gas emissions of this USP, when considering the avoided primary production and not only reprocessing, would be negative (Turner, et al., 2015), making the figure even better.

In order to have a clear picture of the differences between both scenarios over the whole period, Figure 4 presents the accumulated difference in maintenance and renewals over time. Inspections have not been included because they are identical in both scenarios. For the London-Portsmouth route the break-even point is achieved in year 35: before this the installation of USPs is environmentally negative whereas afterwards the effect is positive. In contrast, for the Newcastle-Edinburgh route the maintenance impact would be positive after 22 years of the intervention whilst the renewals impact would be positive only in the last year of the period studied. Consequently, the environmental benefits from reduced maintenance needs would offset the increased burden from the renewals only three years before the end of the period.

Figure 4. Accumulated CO2 Emissions difference

[Figure 4 app. Here]

These emissions savings would bring a social benefit of roughly £350,000 (Portsmouth line) or £58,109 (Newcastle-Edinburgh route) in a 60 year period with a discount rate of 3.5% (recommended by WebTAG), which is negligible compared to the expected financial benefit of USPs on both lines, which is £17 million for the London-Portsmouth route and £19 million for the Newcastle-Edinburgh route (Rempelos, 2016). When these figures are calculated per traveller, the analysis would favour the Newcastle-Edinburgh, route based on usage which is 12 times higher for the London-Portsmouth route than for Newcastle-Edinburgh. The overall small economic benefit lies in the fact that the positive environmental effects take place after some years of renewals, meaning that they are heavily discounted in the cost-benefit analysis process. In fact, a higher discount rate would further reduce these benefits. Other parameters (or even track configurations) could have also been chosen for the analysis. For instance, source to site distances of some track components, particularly ballast and rail, could be higher than 50 km. The methodology shown in the paper allows the track configuration and input parameters to be easily amended, permitting sensitivity analysis to be undertaken. For example, both cases studies have been tested with higher source to site distances (300 km) for ballast, rail and concrete sleepers, which give slightly greater saving emissions (967 CO2 tonnes for the Edinburgh –Newcastle and 8,464 CO2 tonnes for the Portsmouth route) with USPs than with shorter source to site travel distances. The elasticity of emissions to travel distance is very low (0.572 CO2 tonnes per km for the Edinburgh – Newcastle and 0.864 CO2 tonnes per km for the Portsmouth route). Furthermore, the model was also tested with a double ballast mass component (e.g. that could mean double ballast height) obtaining similar gains. That is greater saving emissions of 977 CO2 tonnes for the Edinburgh –Newcastle and 8,486 CO2 tonnes for the Portsmouth route, which gives elasticities of 1.3 and 2 CO2 tonnes per kg respectively. This higher elasticity is explained by the high embedded factor recommended by ARUP database COST2; in fact, using the embedded factor recommended by Milford and Allwood, this elasticity would be much lower (0.23 CO2 tonnes per kg for the Edinburgh –Newcastle and 0.78 CO2 tonnes per kg for the Portsmouth route), which suggests that the selection and interpretation of embedded factor is very important for this type of analysis. As a general rule, the greater benefit is explained by higher emissions per activity (i.e. the extra renewal and maintenance needs in the Base Case are multiplied by higher emissions factors). In other words, the higher the emissions considered per activity, the greater would be the benefit due to the use of USP. One impact not considered in the appraisal is that USPs might make rail travel cheaper with the consequent increase in demand potentially having an important indirect effect on CO2 emissions from the transport system as a whole, thanks to a shift from other more polluting transport modes.

# Conclusions

Since 1970, global CO2 emissions have increased by about 90% and transport related carbon emissions currently represent around 14% of the global greenhouse emissions. These emissions primarily involve fossil fuels burned for road, rail, air, and marine transport. Along with increasing fiscal constraints, this means that there is growing pressure on the UK rail industry to find ways to reduce its costs and, even though rail is a relatively low carbon mode, there is also pressure to reduce rail’s carbon emissions to help mitigate the extent of anthropogenic climate change. This paper has provided a review of LCA for railway track systems, and analysed the carbon impacts of installing USPs at renewal on two UK rail routes. Based on the results from this research we are able to offer three main conclusions:

Firstly, the literature in this area emphasises that, before conducting any type of environmental appraisal, it is necessary to define the aims and scope of the analysis. The data available to develop the life cycle inventory as well as the boundaries of the study will play a key role in determining the outputs. The units in which the results are presented could also influence the perception of the research. For the two routes studied the life span of the project could change the best solution in terms of total CO2 emissions, so it is important to carry out a sensitivity analysis of the chosen project life. The same applies to the embedded factor and mass component of the most important items in the track (e.g. ballast). In other words, every parameter that influences emissions per activity should be checked to avoid any misinterpretation of the results.

Secondly, the use of USPs at track renewal could bring some reductions in CO2 emissions, although the potential benefits are very low compared to the direct financial and economic benefits of this measure and compared to the total carbon emissions on both routes. An important indirect effect could be the increased rail demand from other transport modes due to reduced fares. Furthermore, even minor investments, such as track renewals, need time to bring social and environmental benefits. The rail industry might therefore be able to find more effective ways of reducing CO2 emissions, for example by reducing steel and concrete components thanks to reduced renewal needs and reduced use of maintenance machines. This would not only help the environment but the industry through cost reduction.

Finally, the use of non-recycled rubber, such as in the production of USPs, can outweigh the potential environmental benefits from fewer interventions (maintenance and renewal needs) and therefore less material and energy being wasted in the track. Recycled carbon neutral USPs would provide much better results for both routes considered here. From an environmental point of view, it is worth incentivising the use of recycled material in track systems where possible, which could be achieved through conditions imposed by the infrastructure owner.

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