University of Birmingham

Research at Birmingham

Evaluation of CO2 emissions from railway resurfacing maintenance activities

Krezo, Steven; Mirza, Olivia ; Kaewunruen, Sakdirat; Sussman, Joseph

DOI:
10.1016/j.trd.2018.09.019

Document Version
Peer reviewed version

Citation for published version (Harvard):
Krezo, S, Mirza, O, Kaewunruen, S & Sussman, J 2018, 'Evaluation of CO_2 emissions from railway resurfacing maintenance activities', *Transportation Research Part D: Transport and Environment*, vol. 65, pp. 458-465. https://doi.org/10.1016/j.trd.2018.09.019

TECHNICAL PAPER

"Evaluation of CO_2 emissions from railway resurfacing maintenance activities"

(Title contains 8 words)

by

S. Krezo[1], O. Mirza[1], S. Kaewunruen[2], J.M. Sussman[3]

[1]School of Computing, Engineering and Mathematics, University of Western Sydney, Kingswood, Penrith 2751, New South Wales, Australia.

[2]Birmingham Centre for Railway Research and Education, School of Civil Engineering, The University of Birmingham, Edgbaston, B15 2TT UK.

[3]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

Submitted to

Transportation Research D: Transport and Environment

Corresponding Author:

Dr Sakdirat Kaewunruen
Senior Lecturer in Railway and Civil Engineering
Birmingham Centre for Railway Research and Education
School of Civil Engineering
The University of Birmingham
Edgbaston, B15 2TT UK
Tel: +44 (0) 7541 247 497
E-mail: s.kaewunruen@bham.ac.uk

Manuscript Summary:
Total pages: 19 (including 1-page cover)
Number of figures 1
Number of tables 8

Evaluation of CO_2 emissions from railway resurfacing maintenance activities

S. Krezo[1], O. Mirza[1], S. Kaewunruen[2], J.M. Sussman[3]

[1] School of Computing, Engineering and Mathematics, University of Western Sydney, Penrith 2751, New South Wales, Australia

[2]Birmingham Centre for Railway Research and Education, School of Civil Engineering, the University of Birmingham, Edgbaston, B15 2TT UK

[3]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

Abstract

This paper is the world first to investigate the CO_2 impact of railway resurfacing in ballasted track bed maintenance. Railway resurfacing is an important routine maintenance activity that restores track geometry to ensure safety, reliability and utility of the asset. This study consisted of an extensive field data collection from resurfacing machineries (diesel-engine tamping machines, ballast regulators and ballast stabilisers) including travel distances, working distances, fuel consumption and construction methodologies. Fuel consumption was converted to a kg CO_2/m using the embodied energies of diesel. Analyses showed that tamping machines emitted the highest CO_2 emissions of the resurfacing machineries, followed by ballast regulators and ballast stabilisers respectively. Tamping machines processed 4.25 metres of track per litre of diesel, ballast regulators processed 6.51 metres of track per litre of diesel and ballast stabilisers processed 10.61 metres of track per litre of diesel. The results were then compared to previous studies and a parametric study was carried out to consider long-term resurfacing CO_2 emissions on Australian railway track. The outcome of this study is unprecedented and it enables track engineers and construction managers to critically plan strategic rail maintenance and to develop environmental-friendly policies for track geometry and alignment restoration.

Keywords: Carbon footprint, Green house gas emission, Railway resurfacing, Strategic maintenance, Construction management.

1 Introduction

There has been a steady increase in the reliance on fossil fuel derived energy for the last century, which has resulted in increased CO_2 emissions (Lombard et al., 2008; US EPA, 2014; Raupach et al., 2007). Transportation has been fundamentally embedded in all activities in a society, ranging from logistics of medicine, raw materials, consumable products, technology products, energy sources, and other wide ranges of related human activities. The transportation sector is thus a significant contributor to CO_2 emissions (Lenzen, 1999; Ortmeyer and Pillay, 2001), mainly due to increasing infrastructure development and global transport requirements. It also contributes to air pollution through air borne particle emissions from stationary and mobile sources (Colvile et al., 2001). It is important to note that substantial railway transportation growth is expected in the near future (McGregor, 2013), and all modes of transportation sectors have an obligation to reduce CO_2 emissions from all phases of their life cycles, including construction, maintenance, operations and end of life (Kaewunruen et al., 2014; 2016).

Routine railway maintenance is required to ensure the safety, reliability, functionality and utility of the railway assets. Ballasted track bed maintenance activities consist of renewal and re-construction tasks, ballast cleaning, resurfacing, rail-head grinding and re-railing. All of these activities are generally performed with the assistance of diesel power machineries. Railway track bed resurfacing restores track geometry and alignment to an acceptable condition (Railcorp, 2013). Machines for a resurfacing task consist of tamping machines (diesel engine), ballast regulators, and dynamic stabilisers. Tamping machines are used for packing, lifting and lining the track bed. Ballast regulators replenish ballast and rebuild shoulder profiles; then ballast stabilisers pass through the track in order to consolidate the ballast aggregates to a uniform fit ensuring a good interlocking between the crushed aggregates. The advantages of resurfacing include increased safety, extended track life, reduced riding discomfort, improved train-track interaction, and functionality of the infrastructure.

A critical literature review regarding CO_2 emissions from railway maintenance shows a very limited and lacking detail of actual activity-based measurement and estimation, and in fact the use of broad assumptions makes it difficult to verify the results. Milford and Allwood (2010) investigated the impact of rail designs over the life cycle. Due to limitation of data and previously published literature, they made assumptions regarding the fuel consumptions and track-processing rates of railway resurfacing machineries. They rightly recommended that further research be carried into the fuel consumption and CO_2 emissions from the machineries to verify the accuracy of their study. In addition, Kiani et al. (2008) investigated a life-cycle assessment of railway track beds, including ballasted and ballastless tracks. The authors found that over the life of the infrastructure, slab track bed constructions were not associated with higher CO_2 emissions than ballasted track bed. The maintenance CO_2 emissions study were based on a large number of assumptions and variable industry experiences; however, no field data collection was carried out to verify the accuracy. Therefore, this study herein expands these research horizons and removes unclear assumptions by carrying out extensive site-based data collection and cost-based reviews on resurfacing machineries and numerous interviews with relevant project managers and engineers in NSW, Australia.

The goal of this study is to estimate more accurately the CO_2 emissions from railway resurfacing practices. Field data collection and evidence-based review of project costs was carried out to ascertain the resurfacing methodology, travel distances, working distances and the fuel consumptions of diesel powered machineries (tamping machines, ballast regulators and ballast stabilisers). The study included Australian track bed construction methodologies, emissions factors and existing machineries used in ballasted track bed resurfacing. This paper aims at reporting CO_2/m metric in order to develop simplified calculations for parametric study.

A parametric study is carried out to forecast the future CO_2 emissions from railway resurfacing activities. The parametric study has utilised the data collected, design life expectation and standard track maintenance planning. The model considers 20, 50 and 100-year life-cycles of ballasted track bed. The exclusions from this data record include the machinery manufacture emissions (due to difficulty in obtaining accurate data from the manufacturers), the fuel consumption of work crews travelling to the depot or stabled locations (difficulty in accurately estimating the distances due to varied stabled locations), the fuel tanker used to re-fuel the resurfacing machineries (difficulty in accurately estimating distances due to varied stabled and re-fuelling locations) and hand tamping tools (as the results are negligible compared to the large resurfacing machineries). Note that there have recently been new types of tamping machines, which are more efficient and adopt electric power and hybrid (e.g. Plasser and Theurer's new models). However, these new types of tamping machines are not common in global practice at this stage and its use is still limited (e.g. in Europe and, to an extent, some rail construction companies). In this study, the scope of field measurements is placed on diesel-engine tamping machines. The study into the performance of hybrid and electric powered engine tamping machine will form a future study.

The outcome of the study will however be provided to decision makers and project planners (e.g. master schedulers, construction manager, maintenance and assets engineers) with a reasonably accurate CO_2 emissions estimates that can be used to plan and forecast CO_2 emissions from resurfacing activity when selecting materials for track beds. Researchers focusing on new railway infrastructure will benefit from this investigation by having reasonably accurate estimates when planning life-cycle assessments for ballasted railway constructions.

2 Methodology

Railway resurfacing activity is used to restore track geometry, restore ballast shoulder widths and replenish ballast crib levels (in order to improve lateral resistance of railway track). Resurfacing practices take place to restore railway track bed after re-construction activities and as a periodic maintenance activity. '*Re-construction resurfacing'* occurs where sections of track including the track bed are replaced and work needs to be carried out to ensure the track bed is returned to an acceptable condition. The re-construction resurfacing can experience extended delays as several passes (machines proceeding in working mode is considered a pass) over the same location may be required. '*Periodic maintenance activities*' occur routinely to ensure the ballasted track bed remains or is returned to an acceptable condition. Two forms of targeted periodic maintenance activities are performed: cyclic resurfacing and resurfacing for defects removal. Cyclic resurfacing is a periodic activity (either determined by age or traffic) in which track geometry is restored as an acceptable condition (preventative measure). Corrective resurfacing for defects removal occurs in problematic areas where defects in top or line geometry require corrections (Sydney Trains, 2013).

For future research, using game theory to identify carbon-efficiency decision process, understanding the project planning and scheduling is essential. The planning methodology of railway resurfacing projects is: civil maintenance crews and track inspection vehicles are used to identify defects. Due to the complexity and weekday use of the NSW rail network, weekend shutdowns (possessions) are the ideal time to carry out resurfacing works (Sydney Trains, 2013). The task scheduling is generally carried out by the resurfacing department. The first step in the construction planning is to ascertain which machineries are available for the possession weekend and do not overlap with other construction projects that require resurfacing support over the same period. Consultation is carried out with the network or asset owners to identify known geometric defect areas; with previous program sheets identifying the location of recurring defects. The allocation of plant is prioritised to recurring defect areas with the remaining time set for cyclic resurfacing (Sydney Trains, 2013).

2.1 Railway resurfacing machinery data collection

The data collection commenced with re-fuelling the resurfacing machineries to the capacity of the fuel tanks. Then a measurement is taken for the travel distance. Once at the worksite, the distance of track processed in work mode is recorded and the number of passes of each of the machineries is recorded. The number of passes varies depending on the project. Re-constructions will typically require the tamping machine and ballast regulator to process the track multiple times to ensure the correct track height is achieved. However, production tamping typically requires only a single pass as the lifting height is small and can be achieved with one pass. The distance travelled to return to the stabling location is recorded; with this process repeated until the resurfacing works are complete. Finally, the machineries are refuelled by a mobile fuel tanker and the fuel consumption recorded. The machineries observed in the data collection are shown in Table 1.

2.2 Estimating CO_2 emissions from railway resurfacing machineries

Diesel powered resurfacing machineries are used to reduce manual labour and to increase the distance of track bed to be resurfaced. The reduction in manual labour introduces diesel powered machineries which contribute significant CO_2 emissions.

The CO_2 emissions from the machineries used in railway re-construction projects were evaluated by using the National Greenhouse Gas and Reporting Scheme (Department for Climate Change and Energy Efficiency, 2013) technical guidelines database and the Australian National Greenhouse Accounts Factors (NGA, 2012). The NGA (2012) determined that the emissions from a given fuel be estimated using Equation 1.

$$E_{ij} = Q_i \, EC_i \, EF_{ij} \tag{1}$$

where:

E_{ij} (kg) is the emissions of gas type j for fuel type i;

Q_i (kg) is the quantity of type i fuel consumption;

EC_i (GJ/kL) is the energy content factor of type i fuel;

EF_{ij} (kg/GJ) is the gas j emission factor for fuel i.

Since CO_2 is the largest contributor to greenhouse gas (GHG) emissions (Carbon Neutral, 2011), only this gas type has been considered in the current study. The fuel used by the machines for the trackwork investigated in the current study was diesel. The EC_{diesel} value is 38.6 GJ/kL according to NPA (2012 pp 15), and the $EF_{\text{diesel-CO2}}$ value is 69.2 kg CO_2/GJ (Department for Climate Change and Energy Efficiency, 2012), where kg CO_2/GJ stands for kilogram of CO_2 emission per gigajoule of energy. Hence for estimating CO_2 emission by diesel fuel, Eq. (1) can be written as

$$E_{diesel\text{-}CO2} = Q_{diesel}\, EC_{diesel}\, EF_{diesel\text{-}CO2} \qquad (2)$$
$$= 2671.1\, Q_{diesel}$$

3 Results and Discussion

The results of the data collection, including travel distances, work distances, fuel consumption and resurfacing activity, are shown in Table 2. The total fuel consumptions for grouped machineries (grouped as tamping machines, ballast regulators and ballast stabilisers); travel distances, working distances and fuel consumption over metre of track processed for each machinery type are shown in Table 3.

Table 4 shows the estimated CO_2 emissions from the railway resurfacing machineries from the site data collection. The results of study show that on average the tamping machines are able to process 4.25 metres of track for every litre of fuel used, processing 9,683 metres of track using 2,279 litres of diesel; the ballast regulators processed 6.51 metres of track for every litre of fuel used, processing 9,301 metres of track with 1,429 litres of diesel; whilst the ballast stabilisers processed 10.61 metres of track for every litre of fuel used, processing 6,940 metres of track with 654 litres of diesel consumed.

The estimated CO_2 emissions from the railway resurfacing activities in the data collected showed that tamping machines generated 6,088 kg CO_2 over 9,683 metres of track processed, ballast regulators generated 3817 kg CO_2 over 9,301 metres of track processed and ballast stabilisers generated 1747 kg CO_2 over 6,940 metres of track processed. The results show that the tamping machines emitted 37 % more CO_2 emissions than the ballast regulators and 71 %

more CO_2 emissions than the ballast stabilisers. The ballast regulators emitted 44 % more CO_2 emissions than the ballast stabilisers.

The results of the data collection were then compared over a 1,000 km track processed distance. As shown in Table 5, to process 1,000 km of ballasted railway track, the tamping machines consumed 235,360 litres of diesel fuel and generated 628,675 kg CO_2. To process 1000 km of ballasted railway track, the ballast regulators consumed 155,360 litres of diesel fuel and generated 414,985 kg CO_2. To process 1000 km of ballasted railway track, the ballast stabiliser consumed 94,240 litres of diesel fuel and generated 251,727 kg CO_2. In total, the estimated CO_2 emissions from all resurfacing machineries emitted 1,295,387 kg CO_2 for resurfacing 1000 km of ballasted track bed.

Research shows that machineries stabled closer to the worksite location save time and delay. This is done to maximise the time to perform resurfacing activities during shutdowns and reduce the likelihood of being delayed.

4 Comparative Study

The results were compared with previous studies carried out by Kiani et al. (2008) and Milford and Allwood (2010). Table 6 shows the assumptions made by these studies. Table 7 shows the comparison of diesel fuel consumption for resurfacing 1,000 km of ballasted railway track between the current study, Kiani et al. (2008) and Milford and Allwood (2010). Kiani et al. (2008) and Milford and Allwood (2010) used a slightly different methodology, with Kiani et al. (2008) reporting on CO_2 emissions from a tamping machine and ballast regulator whilst Milford and Allwood (2010) reported on tamping machines and stoneblowing machines.

Kiani et al. (2008) used fuel consumption per hour (litre/hour) and construction speed (hours/km) to ascertain the total fuel consumption per kilometre. The values used by Kiani et al. (2008) for fuel consumption in tamping machines were 15 litre/hour with a construction speed of 32 hours/km. The ballast regulator values were 10 litre/hour with a construction speed of 17 hours/km. The authors found that tamping machines used 480,000 litres of diesel for every 1000 kilometres (km) of track processed, with the ballast regulator consuming 170,000 litres for every 1000 km of track processed. The total diesel fuel consumption for resurfacing machineries in the Kiani et al. (2008) study was 650,000 litres.

Due to limited literature, Milford and Allwood (2010) assumed fuel consumption and working distances, which were based on new machineries. Milford and Allwood (2010) used a fuel consumption of 70 litre/hour and a construction distance of 1200 m/hour for tamping activities. Milford and Allwood (2010) used stoneblowing machines (slightly different construction methodology when compared to this study); with the stoneblowing consuming 70 litre/hour with a construction distance of 440 m/hour. The results showed that tamping consumed 58,380 litre of diesel per 1000km and stoneblowing used 159,380 litres of diesel per 1,000 km. The total diesel fuel consumption in the study was 217,470 litres.

The results of the Kiani et al. (2008) study were compared to this study. Kiani et al. (2008) estimated 40% more fuel consumption for combined tamping and ballast regulating activities. When the results of all resurfacing (tamping machines, ballast regulating and ballast stabilising) from this study are compared to Kiani et al. (2008); Kiani et al. (2008) estimated 25% more diesel fuel consumption. The results Kiani et al. (2008) predicted show higher CO_2 emissions compared to this paper, as the authors based the data on personal communications. As witnessed in the data collection in this study, delays during working are common, which may not have been taken into account in the estimate of Kiani et al. (2008).

Comparing Milford and Allwood (2010) to the tamping machine results of this study; this study estimated three times more fuel consumption in tamping machine activities. Milford and Allwood (2010) estimated a total of 217,470 litres of diesel fuel consumption for tamping and stoneblowing a 1000 km section of railway track (this is a different construction methodology to the one used in this study). When comparing the total resurfacing fuel consumption between Milford and Allwood (2010) to this study; this study estimated 55% more diesel fuel consumption for resurfacing. The results are significantly higher than those estimated by Milford and Allwood (2010). However, due to limited information, Milford and Allwood (2010) based their results on the internet sources and personal communications, which most likely did not account for delays, which are commonly experienced in practice.

Table 8 shows the comparisons in CO_2 emissions for resurfacing of 1,000 km of ballasted railway track between the abovementioned study, Kiani et al. (2008) and Milford and Allwood (2010). Kiani et al. (2008) estimated 1,282,138 kg CO_2 from tamping a 1000km of railway track, 51 % more than the findings in this study. When comparing total resurfacing CO_2 emissions, Kiani et al. (2008) estimated 1,736,229 kg CO_2 per 1000km of railway track, which is 26% more CO_2 emissions when compared to the estimates of this study. Kiani et al. (2008) estimated higher CO_2 emissions for tamping machines and total resurfacing compared to this study, likely due to the fact that the machine data used in the Kiani et al. (2008) study was the preferable scenario which did not include delays as were experienced in the field study. There is also a difference in country specific diesel fuel emissions factors used; as the Australian emissions factor is slightly higher than that of the UK fuel data.

Milford and Allwood (2010) found that tamping 1,000 km of ballasted railway track emitted 155,540 kg CO_2; three times less CO_2 emissions when compared to tamping CO_2 emissions estimates from this paper. When comparing total resurfacing CO_2 emissions, Milford and Allwood (2010) estimated 580,488 kg CO_2 for 1,000 km of railway track, which is 55% less than the CO_2 emissions than estimated in this paper. Milford and Allwood (2010) estimated lower CO_2 emissions for tamping machines and total resurfacing compared to this study, likely due to the fact that the machine data used in the Milford and Allwood (2010) used machine manufacturers specifications and speeds and these sources do not include incidents or delays that may occur in practice. There is also a difference in country specific diesel fuel emissions factors used. Australian emissions factors are slightly higher than that of the UK.

When comparing the CO_2 emissions from tamping machines between Kiani et al (2008) and Milford and Allwood (2010); Kiani et al. (2008) estimated 10 times more CO_2 emissions from tamping machine practices. When comparing the total resurfacing activities of Kiani et al. (2008) to Milford and Allwood (2010); Kiani et al. (2008) estimated three times more CO_2 emissions. The estimates from Kiani et al. (2008) are significantly higher than that of Milford and Allwood (2010); this is due to Kiani et al (2008) using a much lower construction speed (32 hours/km) whereas Milford and Allwood (2010) used a much larger construction speed (50 minutes/km).

The purpose of this investigation was to report on the CO_2 emissions from railway resurfacing practices and this was achieved by carrying out an extensive field-based study of railway resurfacing practices. The need for this study comes from broad assumptions made by previous authors reporting on maintenance CO_2 emissions in life-cycle analyses. The findings of this study show that the estimates found in the previous studies were either higher or lower than the results found in this study. The assumptions used in previous studies were verifiable and this study highlights the discrepancies in data and the potential risk of using various CO_2 emission models. The outcome of this paper is aimed at providing an alternative source of more accurate CO_2 emission database obtained from extensive and detailed field studies.

5 Parametric Study

A parametric study has been carried out to estimate the CO_2 emissions for various resurfacing distances and time periods. Currently in Australia, there is an estimate of over 42,000 kilometres of railway tracks (Australasian Railway Association, 2014). For the purpose of the parametric study, the scale variables of 1,000, 2,000, 5,000 and 10,000 kilometres of ballasted track bed resurfacing have been considered for the annual renewals. The variations in annual resurfacing distances allow decision makers and planners to analyse the impact of railway resurfacing on maintenance CO_2 emissions when different scenarios are considered.

Figure 1 shows the CO_2 emissions from resurfacing activities. If 1000km of ballasted track was resurfaced annually 1,290,750 kg CO_2 would be emitted. After 20 years of resurfacing 1000km annually 25,815,000 kg CO_2 would be emitted. After 50 years of resurfacing 1000km annually 64,537,500 kg CO_2 would be emitted.

If 2000km of ballasted railway track was resurfaced annually 2,581,500 kg CO_2 would be emitted. After 20 years of resurfacing 2000km annually 51,630,000 kg CO_2 would be emitted. After 50 years of resurfacing 2000km annually 129,075,000 kg CO_2 would be emitted.

If 5000km of ballasted track was resurfaced annually 6,453,750 kg CO_2 would be emitted. After 20 years of resurfacing 5000km annually 129,075,000 kg CO_2 would be emitted. After 50 years of resurfacing 5000km annually 322,687,500 kg CO_2 would be emitted.

If 10,000km of ballasted track was resurfaced annually 12,075,500 kg CO_2 would be emitted. After 20 years of resurfacing 10,000km annually 258,150,000 kg CO_2 would be emitted. After 50 years of resurfacing 10,000km annually 645,375,000 kg CO_2 would be emitted.

Based on these results, it is found that ballasted track bed resurfacing practices emit a significant amount of CO_2 emissions. As a case study, the parametric study can provide a reasonably accurate set of estimates of CO_2 emissions from resurfacing practices considering various track distances over different stages of a life-cycle, which can be used by planners and decision makers as a CO_2 emissions forecasting tool.

6 Conclusion

This paper estimates the CO_2 emissions from railway resurfacing activities by carrying out an extensive field study, which observed the travel distances, working distances and fuel consumptions of tamping machines, ballast regulators and ballast stabilisers. The field-based study provided accurate data from resurfacing machineries. The fuel consumptions were converted to CO_2 emissions and compared to previous studies. The results will be used in future life-cycle analyses and for reporting on emissions for maintenance operations. The outcome will establish a decision-making framework to enable carbon-efficient practice in railway industry.

According to the field data and extensive review of project costs, it is found that tamping machines processed 4.25 metres of track bed per litre of diesel fuel; ballast regulators processed 6.51 metres of track bed per litre of diesel fuel and ballast stabilisers processed 10.61 metres of track bed per litre of diesel fuel. The results of previous studies by Kiani et al. (2008) and Milford and Allwood (2010) showed that there was a vast difference in fuel consumption and subsequent CO_2 emissions, with Kiani et al. (2008) estimating 10 times more CO_2 emissions than Milford and Allwood (2010). These estimates could not be verified but the difference was due to assumed construction speed.

The results of the field data collection compared to the previous studies showed that Kiani et al. (2008) estimated 26% more CO_2 emissions; whilst Milford and Allwood (2010) estimated 55% less CO_2 emissions. As stated, the difference in results was due to construction speeds, for instance, not taking into account real-time delays experienced in practice and also a difference in country specific diesel fuel emissions factors between the UK and Australia.

A parametric study considered resurfacing activities for various lengths of track over different stages of the railway infrastructures life-cycle. The results found that resurfacing 1,000 km of resurfacing contributed 25,907,740 kg CO_2 after 20 years and 64,769,350 kg CO_2 after 50 years. 2,000 km of resurfacing contributed 51,815,480 kg CO_2 after 20 years and 129,538,700 kg CO_2 after 50 years. 5,000 km of resurfacing contributed 129,538,700 kg CO_2 after 20 years and 323,846,750 kg CO_2 after 50 years. 10,000 km of resurfacing contributed 259,077,400 kg CO_2 after 20 years and 647,693,500 kg CO_2 after 50 years.

Acknowledgements

The authors would like to that the Asset Operations Group in Railcorp, John Holland Rail Division, MTSP Group, all engineers, team leaders and site personnel for their assistance in the data collection. The authors are very grateful to European Commission for H2020-MSCA-RISE Project No. 691135 "RISEN: Rail Infrastructure Systems Engineering Network" (www.risen2rail.eu).

7 References

Australasian Railway Association, 2014. 'Networks Map', [URL http://www.ara.net.au/Network-maps]

Briggs, J., 2014. "Personal communications". Sydney Trains, Australia.

Carbon Neutral, 2011. "Australia's greenhouse gas emissions". Carbon Neutral, Canberra, Australia. http://www.carbonneutral.com.au/climate-change/australian-emissions.html

Colvile, R., N., Hutchinson, E., J., Mindell, J., S., Warren, R., F., 2001. "The transport sector as a source of air pollution". Atmospheric environment. Volume 35. Pp. 1537 – 1565.

Department for climate change and energy efficiency, 2012. "Australian national greenhouse accounts". National Greenhouse Accounts Factors. Commonwealth of Australia, Canberra. Pp 17.

Department of the Environment, 2014. "National Greenhouse Accounts Factors". Australian Government Publication.

Kaewunruen, S., Sussman, JM., Einstein, HH., 2014, "Strategic framework to achieve carbon-efficient construction and maintenance of railway infrastructure systems," Frontiers in Environmental Sciences, (submitted).

Kaewunruen S, Sussman JM, Matsumoto A. 2016, Grand challenges in transportation and transit systems. Front Built Environ. 2(4).

Kiani M, Parry T, Ceney H, 2008. “Environmental life-cycle assessment of railway track beds”. Proceedings of the Institution of Civil Engineers. Engineering sustainability 161. Issue ES2.

Lenzen, M., 1999. “Total requirements of energy and greenhouse gases for Australian Transport”. Transport Research D. Vol. 4. Pp. 265 – 290.

Lombard, L. P., Ortiz, J., Pout, C., 2008. “A review on buildings energy consumption information”. Energy and Buildings. Elsevier. Volume 40. Issue 3. Pp. 394 – 398.

McGregor, G., 2013. “Sydney’s rail future – What’s next for the suburban network?”. Permanent Way Institute 2013 Annual Conference. Transport for NSW planning and Projects Division. Australia.

Milford, R. and Allwood, J., 2010. “Assessing the CO_2 impact of current and future track in the UK”. Transport Research Part D 15, pp 61 - 72.

Ortmeyer, T., H. and Pillay, P., 2001. “Trends in transportation sector technology energy use and greenhouse gas emissions”. Proceedings of the IEEE. Volume 89. No. 12. Pp. 1837 – 1847.

Railcorp, 2013. “TMC 211 – Track Geometry and Stability”. Railcorp Engineering Manual – Track. Sydney, Australia.

Raupach, M., R., Marland, G., Ciais, P., Le Quere, C., Canadell, J., G., Kleeper, G., Field, C., B., 2007. “Global and regional drivers of accelerating CO_2 emissions”. Proceedings of the National Academy of Sciences of the United States of America. Volume 104. No. 124. Pp. 10288 – 10293.

Sydney Trains, 2013, Engineering Standards and Track Maintenance Plans, Sydney, Australia.

US Environmental Protection Agency, 2014. “Sources of greenhouse gas emissions”. US department of Environmental Protection Agency, USA.

Table 1. List of machineries covered in the data collection.

Machine	ID	Characteristics	Model	Engine Capacity
Tamper	1	Switch / points tamper	Plasser - 07/275	9.05 Litres
Tamper (2)	2	Mainline	Plasser - 09-16 Cat	6.99 Litres
Tamper (3)	3	Combination Tamper	Plasser - 09/32s Dynamic	23.9 Litres
Regulator	4	Broom, blades, plough	Plasser - SSP 302	11.0 Litres
Regulator (2)	5	Broom, blades, plough	Plasser - SSP 302	9.05 Litres
Regulator (3)	6	Broom, blades, plough	Plasser - SSP 302	11.0 Litres
Stabiliser	7	Ballast stabiliser	Plasser - DTS 62	9.05 Litres
Stabiliser (2)	8	Ballast stabiliser	Plasser - DTS 62	9.05 Litres

Table 2. Fuel consumption over distance travelled and track processed by resurfacing machineries.

Machine	Travel (m)	Work (m)	Q_{diesel} (L)	Practice
1	8,834	582	370	Production & re-construction
1	700	1,382	377	Production
2	19,111	3,210	313	Production & re-construction
2	9,700	830	170	Production & re-construction
3	16,624	2,814	679	Production & re-construction
3	5,300	865	370	Production & re-construction
4	8,834	502	270	Production & re-construction
4	700	790	175	Production
5	19,111	3,210	196	Production & re-construction
5	9,700	1,120	120	Production & re-construction
6	16,624	2,814	415	Production & re-construction
6	5,300	865	253	Production & re-construction
7	19,111	3,210	160	Production & re-construction
7	9,700	321	105	Production & re-construction
8	16,224	2,814	195	Production & re-construction
8	5,300	595	194	Production & re-construction

Table 3. Average results of the field data collection.

Machine and ID	Travel (m)	Work (m)	Q_{diesel} (L)	Average track processed over fuel consumed (m/L)
Tampers (1, 2, 3)	60,269	9,683	2,279	4.25
Regulators (4, 5, 6)	60,269	9,301	1,429	6.51
Stabilisers (7, 8)	50,335	6,940	654	10.61

Table 4. CO_2 emissions from railway resurfacing machineries.

Machines	Work (m)	Q_{diesel} (L)	$E_{diesel\text{-}CO2}$ (kg CO_2)
1, 2, 3	9,683	2,279	6088
4, 5, 6	9,301	1,429	3817
7, 8	6,940	654	1747

Table 5. Estimate of CO_2 emissions of railway resurfacing machines for 1000 kilometres.

Machine (ID)	Track processed (km)	Q_{diesel} (L)	Estimated $E_{diesel\text{-}CO2}$ emissions ($kgCO_2$)
Tampers (1, 2, 3)	1000	235,360	628,675
Regulators (4, 5, 6)	1000	155,360	414,985
Stabilisers (7, 8)	1000	94,240	251,727
	Total:	**484,960**	**1,295,387**

Table 6. Assumptions of resurfacing machineries from previous studies.

Machineries	Fuel consumption per hour (l/hour)	Construction speed
Kiani et al. (2008)		
Tamping machine	15	32 hours/km
Ballast regulator	10	17 hours/km
Milford and Allwood (2010)		
Tamping machine	70	50 mins/km
Stone blowing	70	2.2 hours/km

Table 7. Q_{diesel} comparison between Krezo et al. (2014), Kiani et al. (2008) and Milford and Allwood (2010) for 1000 km of ballasted railway track resurfacing.

Machine	Krezo et al. (2014) Q_{diesel} (L)	Kiani et al. (2008) Q_{diesel} (L)	Milford and Allwood (2010) Q_{diesel} (L)
Tamping Machine	235,360	480,000	58,380
Ballast Regulator	155,360	170,000	
Stabilisers	94,240		
Stoneblowing			159,090
Total	**484,960**	**650,000**	**217,470**

Table 8. Estimated $E_{diesel\text{-}CO2}$ emissions comparison between Krezo et al. (2014), Kiani et al. (2008) and Milford and Allwood (2010) for 1000 km of ballasted railway track resurfacing.

Machine	Krezo et al. (2014) $E_{diesel\text{-}CO2}$ emissions ($kgCO_2$)	Kiani et al. (2008) $E_{diesel\text{-}CO2}$ emissions ($kgCO_2$)	Milford and Allwood (2010) $E_{diesel\text{-}CO2}$ emissions ($kgCO_2$)
Tamping Machine	628,675	1,282,138	155,540
Ballast regulator	414,985	454,091	
Stabiliser	251,727		
Stone blowing			424,948
Total	**1,295,387**	**1,736,229**	**580,488**

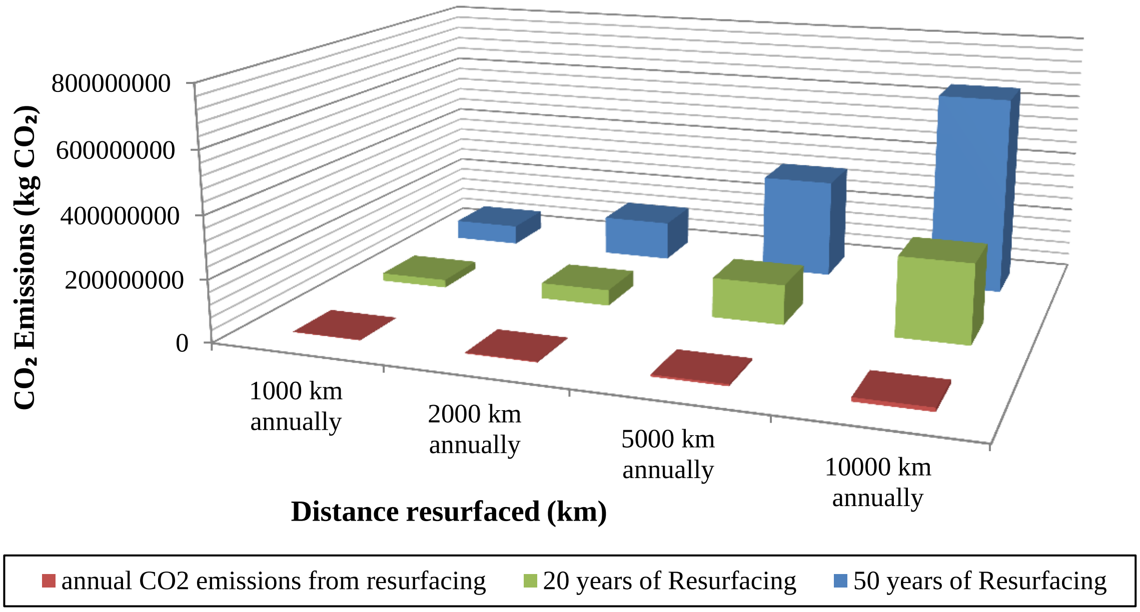

Figure 1. Projected CO_2 emissions from resurfacing activities from distances over the life of the infrastructure.