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Assessing CO_2-e emission of railway crossing during maintenance activities

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Railway operation is considered as the most sustainable transportation. However, such observation often neglects environmental considerations during the maintenance stage, which is a carbon-intensive phase. This study aims to quantify carbon emissions related to the maintenance stage. In this study, we focused on railway turnout crossings (fixed manganese and movable) as a use-case located on Bandel (track section) 120 near Boden in Sweden for CO_2 estimations. We utilize 14 years (2010-2023) of maintenance data collected from the Swedish Transport Administration (Trafikverket or TRV) databases. Results indicate that logistics (transportation) during the maintenance stage are the most significant contributors to fuel consumption and CO_2-e emissions. Further, the interrelation between fixed and movable crossings demonstrates that the environmental impact of movable crossings is substantially higher than that of fixed crossings. The insight of this study can be integrated into decision-making models that combine Life Cycle Cost (LCC) and climate impact to optimize railway crossing replacement strategies.

Keywords: Life Cycle Assessment (LCA), Carbon emissions, Sustainable transportation, Railway maintenance, Railway infrastructure, Carbon footprint, Diesel, Emission factor, Environmental impact, Switches and Crossings (S & C), Greenhouse gases (GHGs), Carbon footprint.

1. Introduction

Sustainable transportation is a critical challenge across the globe. Globally, transportation contributes significantly to carbon emissions. It accounts for approximately 20% of total global carbon emissions (Olivier et al., 2017). According to Ritchie (2020), road transport accounts for 74% of total transport emissions, while railways contribute to only 1%. Similarly, the transportation sector in Sweden contributes to 30% of total national emissions, with rail traffic accounting for less than 1 % of total transport emissions (Sweden, 2020). Such observations indicate that railway transportation is the most sustainable and carbon-efficient mode of transportation. However, when examining the entire life cycle stages (from pre-design to end-of-life stages) of railway infrastructure, the maintenance stage emerges as a carbon-intensive phase. Previous studies have highlighted the substantial carbon emissions associated with railway maintenance activities (Lokesh et al., 2022; Kaewunruen et al., 2019; Rungskunroch et al., 2021). The maintenance stage, which is the longest phase in the railway infrastructure life cycle, is critical for optimising the cost, performance, and environmental impact of rail infrastructure assets. This stage involves the use of maintenance car/van and machinery, which emit considerable amounts of carbon. For instance, Lokesh et al. (2022) reported that the track maintenance stage is the most carbon-intensive phase in the life cycle, contributing to 70 % of its whole-life carbon emissions. Similarly, Kaewunruen et al. (2019) found that operation and maintenance account for 30 % of the total carbon emissions associated with the rail system. However, estimating CO_2 emissions from railways is a challenging and time-intensive process.

The conventional approach for the carbon emission calculation is the life cycle assessment (LCA) (Torrellas et al., 2013). It provides a holistic quantitative framework for assessing environmental impacts such as greenhouse gas emissions and energy consumption across life cycle stages from pre-design to end-of-life stages of the system (de Andrade and Márcio de Almeida, 2016; Jürgens et al., 2023). Numerous studies have demonstrated the applicability of LCA in the transportation sector (Stripple and Uppenberg, 2010; Kaewunruen and Lian, 2019; Hu et al., 2022). Such studies highlighted its accuracy in quantifying emissions across the entire value chain of the asset. However, conducting a comprehensive LCA remains a complex process due to lack of domain knowledge, methodological inconsistencies and data limitations (de Andrade and Márcio de Almeida, 2016; Shinde et al., 2018; Madu, 2007; Mourad et al., 2007; Landgraf et al., 2022). For instance, accurate fuel consumption estimates, detailed fuel type characterization across LCA stages, comprehensive machinery inventories, and maintenance procedures (highly dependent on the geographical location of the asset and seasonal variability during inspections and maintenance). These limitations of input parameters account for significant uncertainties in LCA calculations. To address these limitations and better understand carbon emissions, there is a growing need for a more comprehensive measurement-based method, e.g., a bottom-up approach. This approach focuses on individual assets and incorporates detailed asset-level data to understand better emission sources (Landgraf et al., 2022; Milewicz et al., 2023). Such approaches provide a more accurate estimate of carbon emissions and assist in developing effective strategies to minimize environmental impact. However, no comprehensive effort has been made to estimate the carbon emissions from railway crossing assets.

This study aims to quantify carbon emissions associated with the maintenance of two distinct railway turnout crossing types: fixed manganese and movable. The analysis encompasses a comprehensive assessment of the inspection and maintenance activities performed on these crossings over a 14-year service life period (2010-2023).

2. Material and methods

2.1. *Use case: Railway turnout crossing*

The railway crossing is a critical component of railway turnout or switches and crossings (S & C) systems, enabling the diversion of trains from one track to another (Kaewunruen and Lian, 2019; Grossoni et al., 2021). It comprises several subcomponents, including the wing rail, guard rail, and the crossing nose or frog. Broadly, crossings are categorized into two types: fixed crossings and movable (or swing nose) crossings.

Crossings are among the most vulnerable assets in railway infrastructure due to exposure to adverse weather conditions and high-impact dynamic forces (Kaewunruen et al., 2015; Wang et al., 2017). Consequently, they are frequently

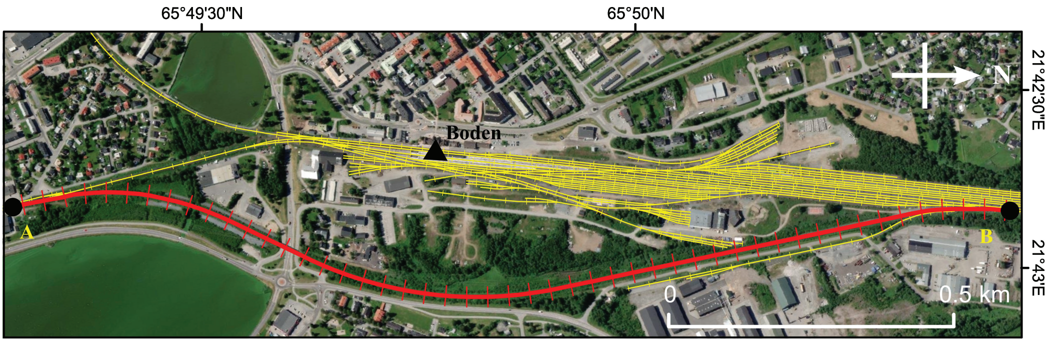

Fig. 1.: Location map of the fixed manganese (A) and movable (B) crossing. The railway track section in red indicates the Bandel 120. Background: Esri World Imagery

Table 1.: Description of fixed and movable crossing, obtained from Ban Informations System (BIS).

Component	Track name	Bandel (BDL)	Component* designation	Track switch	Length (m)
Fixed crossing	Stambanan genom Övre Norrland	BDL 120	A	EV-UIC60-760-1:15	NA
Movable crossing	Stambanan genom Övre Norrland	BDL 120	B	EVR-UIC60-760-1:15	13.8

* Distance (round trip) between production location to the fixed crossing is 5 km, and to the movable crossing is 10 km, via road transportation.

susceptible to wear, fatigue, and plastic deformation (Grossoni et al., 2021). Additionally, climate change and increasing freight and passenger traffic, further exacerbate operational and maintenance challenges of crossings. Therefore, crossings require frequent routine inspections and maintenance to ensure safety and reliability for uninterrupted railway operations. This study considered both the crossings (fixed and movable) located on the Bandel 120 near Boden, Sweden (Fig. 1). The detailed description of both crossings is provided in Table 1.

2.2. *Data set*

2.2.1. *Trafikverket (TRV) databases*

TRV is the government transport administration responsible for the long-term planning of the Swedish transport system, encompassing road, rail, sea, and air transport. For railway operation and maintenance planning, TRV utilizes several databases, including BIS (a railway asset information system), BESSY (an inspection system), and Ofelia (a fault report system). Table 2 provides a brief overview of these databases.

Table 2.: List of Swedish railway databases.

Database	Description	Observations
Bessy	Record of safety and maintenance inspections	Inspection, corrective maintenance, and conditioned-based maintenance
Ofelio	Record of track faults and disruptions/failures	Corrective maintenance
BIS	Record of track information system	Assets information register

Railway maintenance is broadly categorized into three types, including corrective maintenance, preventive maintenance, and condition-based maintenance (predictive maintenance). In this study, we focus on corrective and condition-based maintenance, as preventive maintenance is not performed on the studied railway crossings. The corrective maintenance is carried out when the railway asset fails, while condition-based maintenance is performed to preserve the asset in acceptable operating conditions (performed when asset degradation is detected) (Fumeo et al., 2015; Sresakoolchai and Kaewunruen, 2023)

2.2.2. *Expert interview*

Semi-structured expert interviews were conducted with experienced Swedish railway maintenance contractors. The interviews aimed to supplement existing data and address critical information gaps necessary for precise CO_2 emission calculations. Four semi-structured interviews were conducted with professionals (Swedish railway maintenance contractors) responsible for maintaining the specific crossings analyzed in this study. Each interview lasted approximately 1 hour. The key information collected includes the time required for specific maintenance actions, the distances traveled for inspections, the equipment and vehicle utilized for a particular action, the type of fuel machinery utilized, and their respective fuel consumption rates (Table 3).

Table 3.: Summary of expert interview.

Machinery	Action	Fuel consumption rate	Fuel type
Maintenace car/van	Inspection	0.1 l/km	Diesel
Maintenance measuring vehicle	Track geometry inspection	22 l/hr	Diesel
Power generator	Power supply	1.25 l/hr	Diesel
Grinding machine*	Grinding	-	-
Welding machine*	Welding	-	-
* Power supply source is generator			

2.3. *Data processing*

In this study, we limit our analysis only to the maintenance of crossings. We utilize 14 years (2010-2023) of maintenance data, including inspection records, transportation, and maintenance activity records, obtained from the Bessy and Ofelia database inventories. The collected data encompasses inspection frequencies, crossing maintenance location, and maintenance activities details (Table 4). Additionally, by integrating information from these datasets with insights gathered through expert interviews, we compiled comprehensive information on maintenance activities.

Table 4.: Summary of inspection and maintenance activities for fixed and movable railway crossing from 2010 to 2023.

Actions	Number of actions on crossing		Source of CO_2 emission
	Fixed	Movable	
Inspection			
Safety inspection (Säkerhetsbesiktning)	85 (6/year)	86 (6/year)	-Maintenance car/van
Maintenance inspection (Underhållsbesiktning)	14 (1/year)	14 (1/year)	-Maintenance car/van
NDT inspection (OFP-besiktning)	0 (Not performed)	13 (1/year)	-Maintenance car/van
-Track geometry inspection	28 (2/year)	28 (2/year)	-Maintenance measuring vehicle
Maintenance			
Condition-based maintenance			
Welding (overlay new material and repair welding)	6	3	-Maintenance car/van -Power generator -Grinding machine -Preheating device -Welding machine
Grinding (Surface defect, plastic deformation, and resurfacing)	1	2	-Maintenance car/van -Power generator -Grinding machine
Miscellaneous (adjustment and exchange)	NA	4	-Maintenance car/van
Corrective maintenance			
Welding (overlay new material and repair welding)	9	NA	-Maintenance car/van -Power generator -Grinding machine -Preheating device -Welding machine
Grinding (Surface defect, plastic deformation, and resurfacing)	7	1	-Maintenance car/van -Power generator -Grinding machine
Miscellaneous (adjustment and exchange)	NA	4	-Maintenance car/van
Lubrication	NA	1	-Maintenance car/van
Snow cleaning	NA	3	-Maintenance measuring vehicle

Delimitation of the study

The following considerations were made in this study for fuel consumption estimates:

- For safety and maintenance inspections, the distance traveled by the maintenance car/van from Boden to the crossing site was considered.
- For track inspections, the time required by the maintenance measuring vehicle to travel from Boden railway station to the crossing site was considered.

2.4. *Carbon emissions calculation*

Railway maintenance is a crucial stage in the life cycle assessment (LCA) process, as it extends the lifespan of rail infrastructure assets and ensures uninterrupted operations. This study aims to quantify CO_2-e emissions associated with the maintenance of railway crossings. The CO_2 is considered as it is the primary contributor to greenhouse gas (GHG) emissions.

In the maintenance stage, the primary sources of carbon emissions arise from fuel consumption by vehicles and machinery used for inspections and maintenance activities. However, the available dataset does not include direct estimates of fuel consumption. Therefore, for transportation, we estimate fuel consumption by integrating the fuel consumption rate of the car/van or maintenance measuring vehicle with the distance traveled to the crossing site. Similarly, for maintenance machinery, fuel consumption is estimated based on the machinery fuel consumption rate and the time spent in operation.

In this study, we estimate the CO_2-e emissions by incorporating fuel combustion data from inspection activities, condition-based maintenance, and corrective maintenance operations.

The general equations for the evaluation of CO_2-e from a given fuel can be expressed as:

$$\text{CO}_2\text{-e} = Q_i \times EF_{i-CO_2} \tag{1}$$

where CO_2-e or CO_2 equivalent (kg CO_2-e) is a standardized unit used to measure the global warming potential (GWP) of different greenhouse gases (GHGs) relative to carbon dioxide (CO_2), Q_i is the quantity of fuel consumed (L), and EF_{i-CO_2} is the emission factor (kg CO_2-e/L).

The amount of CO_2 generated from different fuel types depends on their emission factor (EF). It relates the rate of pollutant quantity of greenhouse gas emitted from the given unit of activity (Turner et al., 2015). In the current study, we consider diesel as the fuel used during the maintenance stage (for transportation and equipment). The $EF_{Diesel-CO_2}$ is 2.8 kg CO_2-e/L (Toller, 2018)

3. Results

3.1. *Assessment of fuel consumption and CO_2-e emission during maintenance stage activities*

Table 5 and Fig. 2 present the fuel consumption and associated CO_2-e emission with each activity during the maintenance stage for both fixed and movable railway crossings. The quantity of fuel consumption is assessed based on the distance traveled and the maintenance activities conducted in 14 years, as illustrated in Table 1 and Table 4. Our results show that the inspection of crossing is the main contributor, as it contributes more than 70 % to fuel consumption and CO_2-e emission. The maintenance activities (condition-based and corrective maintenance) contribute to about 30 % of total fuel consumption and CO_2-e emission. Further, a comparison of both crossings shows that the movable crossing dominates fuel consumption and associated CO_2-e emission. We found that the movable crossing accounts for twice the emissions of the fixed crossing for both inspection and maintenance activities. Interestingly, our findings for condition-based maintenance do not observe a significant difference in fuel consumption and associated CO_2-e emissions for fixed and movable crossings. We found that both crossings account for less than 10 % in fuel consumption and emissions.

Table 5.: Total fuel consumption in maintenance stage of fixed and movable crossing from 2010-2023.

Activities	**Fuel consumption (L)**	
	Fixed crossing	**Movable crossing**
Inspection	70.07±3.50	155.13±7.76
Conditioned based maintenance	9.44±0.47	9.65±0.48
Corrective maintenance	19.56±0.98	33.63±1.68

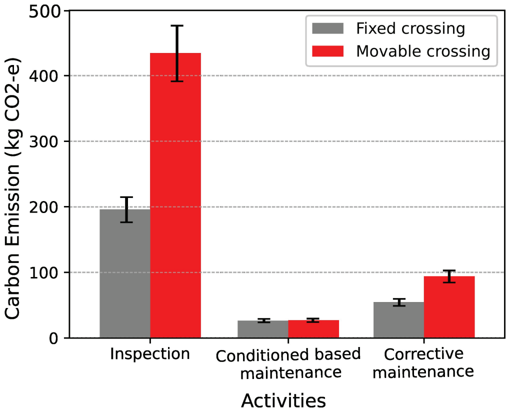

Fig. 2.: Total carbon emission in the maintenance stage of fixed and movable crossing from 2010-2023. Error bars in black indicate 95% confidence interval.

3.2. *Assessment of fuel consumption and CO_2-e emission from machinery in maintenance stage*

Table 6 summarizes the fuel consumption of various machinery involved in the maintenance of fixed and movable crossings. The fuel consumption is categorized into two main components: logistics and equipment. Logistics includes fuel consumption by car/van and maintenance measuring vehicles used to access the maintenance site, while equipment encompasses fuel consumption by machines such as welding, grinding, and resurfacing machines employed to perform the maintenance tasks (Table 4).

Table 6.: Total fuel consumption by logistics and equipment during maintenance stage of fixed and movable crossing from 2010-2023.

Machinery	**Fuel consumption (L)**	
	Fixed crossing	**Movable crossing**
Logistics	81.57±4.07	164.13±8.20
Equipment	17.50±0.87	34.27±1.71

Our analysis reveals that logistics constitutes the dominant source of fuel consumption. We found it contributes to more than 80 % to fuel consumption and CO_2-e emission for both crossings, whereas, maintenance equipment contributes to less than 20 % of total fuel consumption and CO_2-e emission. Consequently, logistics has a substantially greater impact on CO_2-e emissions, as shown in Fig. 3. We also illustrate the differences in fuel consumption and CO_2-e emissions between fixed and movable crossings. Results depict that the fuel consumption and emissions are consistently higher (approximately twice) for movable crossings across both logistics and equipment categories.

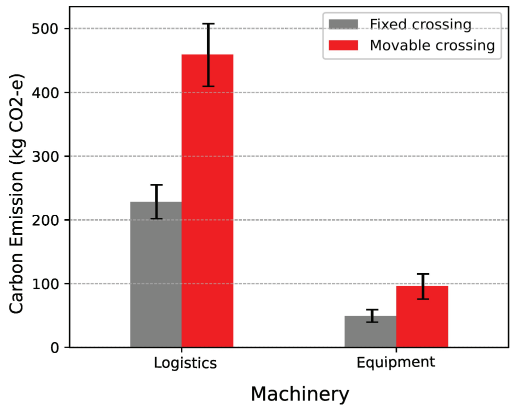

Fig. 3.: Total carbon emission by logistics and equipment during maintenance stage of fixed and movable crossing from 2010-2023. Error bars in black indicate 95% confidence interval

4. Discussion

Accurate CO_2-e emission evaluation is essential during the railway maintenance stage to minimize environmental impact. In this part, we discuss the findings obtained by analyzing the maintenance stage of railway crossings. Our results reveal that the fuel consumption and associated CO_2-e emissions during inspection activities are significantly higher than the maintenance activities (condition-based and corrective maintenance). This discrepancy can be attributed to the frequent and consistent inspection planning scheduled throughout the year for efficient railway operations. For instance, our inspection inventory indicates that the Swedish railway network requires six safety inspections (every two months), one maintenance inspection, one non-destructive test (NDT), and two track alignment inspections annually (Table 4).

Further, our analysis uncovered that logistics contributes significantly to fuel consumption, consuming approximately four times as much fuel as maintenance equipment. This finding is consistent with previous research by Chipindula et al. (2022). In the life cycle assessment of a high-speed rail system in Houston-Dallas, their findings indicated that vehicle operation and maintenance are the primary contributors to global warming potential, accounting for approximately 93% of the total life cycle impact.

Furthermore, while comparing fixed and movable crossings, our findings show that the fuel consumption and emissions are consistently higher for movable crossings. We suggest that this disparity can be attributed to the additional maintenance requirements for movable crossings, such as lubrication, snow-clearing, and the inclusion of non-destructive testing (NDT) inspections for fault detection, which are not required for fixed crossings. Also, the distance traveled by the maintenance measuring vehicle for movable crossings is more than that for fixed crossings. Moreover, fuel consumption during maintenance activities varied depending on the specific maintenance process employed and the equipment utilized. Our maintenance databases revealed that movable crossings are more susceptible to obstructions, such as snow removal during winter season, along with wear and plastic deformation. For instance, the movement of the frog in movable crossings requires frequent adjustments, lubrication, and snow clearing. Consequently, fuel consumption and associated CO_2-e emissions for the maintenance of movable crossings are higher than those for fixed crossings.

Interestingly, for condition-based maintenance, the difference in fuel consumption and CO_2-e emissions between fixed and movable crossings is not substantial. This can be explained by the fact that both crossing types experience similar surface defects, such as wear, tear, and deformations. Consequently, similar maintenance actions, such as welding and grinding, are typically performed on both types of crossings, resulting in comparable fuel consumption and CO_2-e emissions.

5. Summary and conclusions

This study assesses the environmental impacts associated with fixed and movable railway crossings. Our findings indicate that the inspection activities and the related logistics (transportation) during the maintenance stage are the most significant contributors to fuel consumption and CO_2-e emissions. The dominance of these categories can be attributed to their high frequency of service over the 14 years (2010–2023). Furthermore, the study demonstrates that the environmental impact of movable crossings is substantially higher than that of fixed crossings. This disparity can be attributed to the increased complexity and maintenance requirements of movable crossing components. Lastly, the overall findings and insights in this study offer a more comprehensive understanding of the environmental impacts of railway crossings. We believe that the adopted bottom-up approach in this study provided robust results. Further, it should be noted that this approach is a data-sensitive approach, and assumed or limitations in information of key parameters may affect the outcomes. Future research can be extended to assess live monitoring of carbon emissions and estimate environmental impacts in other stages of the life cycle.

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