Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen
 Published by Research Publishing, Singapore.
doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P9621-cd

The effect of climate condition on the CO_2 emissions of maintenance activities: a case study from Railway

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Abstract:
Climate conditions significantly impact the working conditions for inspection and maintenance of railway assets, which may lead to higher carbon dioxide (CO_2) emissions. This study investigates the impact of seasonal climate variations on CO_2 emissions associated with inspection and maintenance activities for railway infrastructure.
A case study from a railway system in northern Sweden is analysed to demonstrate how climate condition affects CO_2 emissions during inspection and maintenance, across different seasons. To achieve this, CO_2 emissions are estimated under varying climate conditions by integrating multiple datasets and conducting interviews with maintenance experts.
The findings reveal that seasonal variations play a critical role in CO_2 emissions, with significantly higher emissions observed in cold weather due to increased fuel consumption. These insights underline the importance of accounting for climate-related factors in maintenance planning to mitigate environmental impact. The result of analysis can be used for maintenance planning strategies to reduce CO_2 emissions associated with railway asse.

Keywords: Climate condition, Cold weather impact, Seasonal variation, Railway maintenance, Carbon dioxide (CO_2) emissions

1. Introduction

Railway transportation plays a crucial role in sustainable transportation systems, particularly in Europe (Kim and Van Wee 2009). However, the life cycle of railway systems has notable environmental impacts, especially regarding their carbon dioxide (CO_2) emissions. The rising levels of CO_2 in the atmosphere contribute to the rapid progression of global warming and intensify climate change (Nunes 2023). Transportation accounts for 23% of global CO_2 emissions, with railways contributing 4.6% of that total (Jiang et al. 2021).

Over the past several decades, due to the substantial impact of CO_2 emissions on climate change, many studies have investigated the CO_2 emissions of railway assets during various life cycle phases. Life Cycle Assessment (LCA) in railway systems is a methodology used to assess the environmental impacts across the entire life cycle of railway components, including raw material extraction, manufacturing, operation, maintenance, and end-of-life disposal (Rempelos, Preston, and Blainey 2020). For instance, Kaewunruen, Sresakoolchai, and Yu (2020) studied the environmental impact of railway tunnels during construction and maintenance. They concluded that the construction process contributes about 97% of CO_2 emissions of the tunnel life cycle.

Operation and maintenance are usually the longest phases of the railway life cycle (Rungskunroch, Shen, and Kaewunruen 2021). Chipindula et al. (2022) conducted a comprehensive LCA analysis of a proposed high-speed rail (HSR) system along the Houston-Dallas I-45 corridor, evaluating GHG emissions across different phases of the system's life cycle. Rempelos, Preston, and Blainey (2020) conducted a cradle-to-grave analysis of GHG emissions for the four most common sleeper types used in the UK rail network. Their findings indicated that softwood sleepers are more environmentally friendly under low traffic loads, while concrete sleepers perform better under high traffic loads. Tuler and Kaewunruen (2017) analyzed the LCA of various mitigation methodologies aimed at reducing ground-borne vibration and rolling noise. In a recent study, Vignali (2024) utilized the LCA to compare the environmental impacts of two different track solutions: ballasted and ballastless tracks. The results showed that the ballastless track has a lower environmental impact compared to the ballasted track, primarily due to its extended life cycle.

Significant Railways' emissions come from constructing infrastructure, operation and maintenance (Krezo et al. 2016; Rungskunroch, Shen, and Kaewunruen 2021a; 2021b). Krezo et al. (2016) demonstrated that maintenance activities extend the lifecycle of railway assets while producing fewer CO_2 emissions compared to the construction phase. In another study, Krezo et al. (2018) estimated the CO_2 emissions associated with track adjustment and alignment restoration in ballasted track bed railways. In (Krezo et al. 2014), a detailed estimation of CO_2 and other GHG emissions from diesel-engine machines used in rail resurfacing maintenance in Australia was provided.

Energy consumption and fuel use across the railway lifecycle are critical contributors to CO_2 emissions, with diesel engines serving as the predominant power source in railway systems (Norris and Ntziachristos 2019). This reliance on diesel propulsion highlights the urgent need for strategies to mitigate environmental impacts. Hybridizing diesel multiple-unit railway vehicles has emerged as an effective approach to reduce fuel consumption and associated emissions, particularly in non-electrified regional networks (Kapetanović et al. 2021). Such advancements can significantly enhance the energy and environmental performance of railways.

Energy consumption in diesel engines varies under different climatic conditions. In cold weather, diesel fuel consumption increases due to additional energy demands for cold starts, extended warm-up periods, higher friction from more viscous lubricants, and incomplete combustion caused by lower cylinder wall temperatures (Issa et al. 2020). Additionally, at low ambient temperatures, the injected fuel often fails to reach the auto-ignition temperature quickly, leading to ignition delays, inefficient combustion, which further increases in energy consumption (Kaltakkıran and Ceviz 2021).

Moreover, climate conditions not only affect energy consumption but also have a substantial impact on the overall performance of railway systems. Extreme weather phenomena, such as space weather events, can significantly disrupt railway infrastructure. Solar storms and geomagnetically induced currents (GICs) impact critical components like signaling systems, power networks, and track circuits. These disruptions pose safety and operational challenges, necessitating robust mitigation strategies to enhance system resilience (Thaduri, Galar, and Kumar 2020).

Despite the critical role of railway maintenance in ensuring system reliability, previous research has not adequately explored the impact of climatic conditions on CO_2 emissions of inspection and maintenance activities. Addressing this gap, this paper provides the comprehensive evaluation of seasonal variations in CO_2 emissions of inspection and maintenance activities on the Northern Sweden railway.

The study's primary aim is to investigate how CO_2 emissions during maintenance activities vary with the seasons. The focus is on a moveable crossing located on the railway track leading to or from Boden, Northern Sweden. This Crossing was chosen for analysis due to its frequent replacement, making it a significant contributor to maintenance-related emissions in switch and crossing (S&C) systems.

Our contribution is to provide a detailed analysis and understanding of the environmental impact of railway maintenance under varying climatic conditions, offering critical insights for designing more sustainable and efficient maintenance strategies in cold climate regions.

2. Methodology

A switch and crossing (S&C) is a critical component of the railway system, designed to enable rolling stock to change direction from one track to another. It is a complex system composed of several sub-systems and sub-components. The crossing, which is the part of the system where two railway tracks intersect and allows trains to transition from one track to another, is the most frequently replaced component.

In Sweden, various types of crossings are used, including movable, fixed manganese, glued, and heat-treated crossings Figure 1a shows the movable crossing, while Figure 1b highlights the interchangeable movable point in yellow colour. The crossing considered in this study is approximately 14 meters long and is made of carbon steel.

The lifecycle of a railway crossing consists of several stages, including the pre-design stage, product stage, construction and production stage, stage of use, and final stage, as depicted in Figure 2 (Nissen 2009). Each stage involves specific activities. Inspection and maintenance are integral to the stage of use. This study focuses on assessing the CO_2 emissions associated with inspection and maintenance activities for the movable crossing during different seasons. To evaluate CO_2 emissions across various seasons, the following steps are implemented:

- Data collection and preparation
- Interviews with Experts to gather and complete required information
- Evaluation of CO_2 Emissions across different seasons

The following sub sections provide a comprehensive explanation of each step.

a) b)

Figure1. a) The movable crossing b) The movable point (Vossloh 2023)

A0 Pre-design stage	A0	Pre studies
A1-A3 Product stage	A1	Raw material supply
	A2	Transport
	A3	Manufacturing
A4-A5 Construction production stage	A4	Transport
	A5	(Construction and) installation process
B1-B8 Stage of use	B1	Usage
	B2	Maintenance
	B3	Repair
	B4	Exchange
	B5	Reconstruction
	B6	Operating energy
	B7	Operating processes other
	B8	Users' energy use
C1-C4 Final stage	C1	Dismantling, demolition
	C2	Transport
	C3	Residual product treatment
	C4	Disposal

Figure 2. lifecycle of crossing

2.1. *Data Collection and Preparation*

The data for this study was collected from multiple sources provided by the Swedish Transport Administration, Trafikverket. These include the Bessy database, which records inspection data and measurements gathered during inspections, and the Ofelia database, which documents all asset failures required to corrective maintenance. Both databases cover a period of 14 years, from 2010 to 2023. Additionally, the weather and climate history for Boden from 2010 to 2023 is illustrated in Figure 3 (Weather and Climate 2024). Furthermore, four interviews with maintenance experts were conducted to collect other necessary information.

In Northern Sweden, the months are categorized into seasons as follows: October to April is classified as winter, May as spring, June to August as summer, and September as autumn.

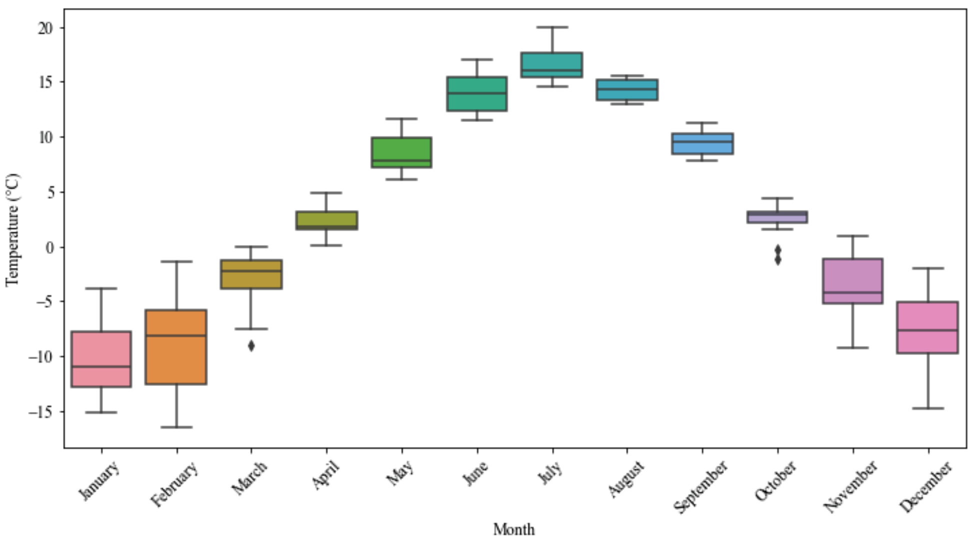

Figure 3. Monthly Temperature Distribution in Boden (2010-2023)

2.2. *Interview with experts*

Maintenance, safety checks, Non-Destructive Testing (NDT), and track alignment inspections are various types of inspections conducted on the crossing. Following the inspection, maintenance teams evaluate and prioritize identified irregularities based on the urgency of the required actions. These priorities are classified into categories A, V, M, B, Å, and Ö. Categories A and V indicate the need for immediate corrective maintenance, while the remaining categories correspond to preventive maintenance. The framework for inspection and maintenance procedure is illustrated in Figure 4.

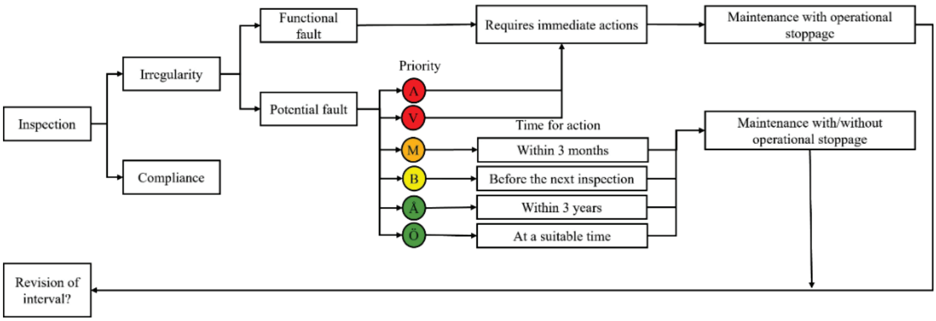

Figure4. Framework for the inspection and maintenance procedure adopted by Trafikverket

The machinery used for inspection and maintenance were identified through interviews with maintenance experts and contractors and are summarized in Table 1. Table 1 specifically includes the specifications of machines that directly contribute to CO_2 emissions.

2.3. *CO_2 emissions released by machinery during inspection and maintenance*

CO_2 is directly emitted from fuel consumption of machinery during inspection and maintenance activities. The CO_2 emissions are calculated as follows:

$$E = Q_i \times EF_{i-CO_2} \tag{1}$$

where

E (kg CO_2) is the amount of CO_2 emissions;

Q_i (L) is the quantity of fuel type i consumed;

EF_{i-CO_2} (kg CO_2/L) is the CO_2 emission factor for fuel type *i*.

Table 1. Machinery characteristics

Machinery	Purpose	Fuel Consumption	Fuel Type
Volkswagen Caddy Van	Transportation	0.1 L/km	Diesel
IMV 100 vehicle	Track alignment inspection	22 L/h	Diesel
Generator	power supply for IMV 200 vehicle	5 L/h	Diesel
Generator MDG6000CLE	power supply for welding and grinding	1.25 L/h	Diesel
Rail preheater	rail preheating for welding	10 L for preheating 4 welding points	Propane

Since CO_2 is the most significant GHG contributing in climate change, this gas type is considered in this study. $EF_{Diesel-CO_2}$ value is 2.8 kg CO_2/L (klimatkalkyl 2024) and $EF_{Propane-CO_2}$ value is 1.52 kg CO2/L (eia 2024).

3. Results

Table 2 shows the frequency of activities across different seasons based on the result of data collection and interview with experts. The distance between the maintenance workshop and the crossing is approximately 4 kilometres. Based on the literature review and expert interviews, it is assumed that fuel consumption in cold weather increases by approximately 13–33% for vehicles (Kauranen et al. 2010) and 10–15% for generators compared to warm weather. Fuel consumption for various activities across different seasons is presented in Table 3.

Table 4 presents the CO_2 emissions per activity during inspection and maintenance across different seasons. The last four columns summarize the total emissions generated over the period 2010–2023.

The results clearly indicate that CO_2 emissions are higher during colder seasons (spring, autumn, and winter) compared to the warmer season (summer). This increase is due to higher energy consumption and longer average working time in winter.

Preheating contributes the most to CO_2 emissions, with values ranging from 15.20 kg CO2 in summer to 17.48 kg CO_2 in winter. The increase in winter emissions is attributed to the additional energy required to achieve and maintain the necessary temperatures for welding and maintenance activities in cold weather conditions. Grinding and welding activities also show significant seasonal variability. For instance, welding emissions rise from 3.50 kg CO_2 in summer to 4.03 kg CO_2 in winter, reflecting increased fuel consumption and operational challenges when temperatures are low.

The total emissions for only crossing inspection activities over 14 years are:

- 100.09 kg CO_2 in summer
- 358.41 kg CO_2 in winter

And for maintenance activities are:

- 20.45 kg CO_2 in summer
- 25.53 kg CO_2 in winter

Although the average working time is assumed to remain constant across seasons in this study, the significant variation in fuel consumption highlights the impact of cold weather on energy requirements.

Table 2. Frequency of activities across different seasons (2010-2023)

Activity	spring	summer	autumn	winter
Track alignment inspection by IMV 100 vehicle	-	-	-	28
Track alignment inspection by IMV 200 vehicle	-	28	-	28
Maintenance inspection	2	9	-	3
Safety inspection	4	24	4	54
preheating	-	1	2	1
grinding	-	1	3	2
welding	-	1	2	1

Table 3. Fuel consumption across different seasons

Activity	speed (km/h)	Average working time (min)	Q_i (L)			
			spring	summer	autumn	winter
Track alignment inspection by IMV 100 vehicle	80	4.010	-	-	-	1.96
Track alignment inspection by IMV 200 vehicle	160	4.005	-	0.33	-	0.45
Maintenance inspection	-	15	0.98	0.80	-	1.06
Safety inspection	-	15	0.98	0.80	0.90	1.06
preheating	-	15	-	10.00	11.00	11.50
grinding	-	30	-	0.63	0.69	0.72
welding	-	60	-	1.25	1.38	1.44

Table 4. CO_2 emissions from crossing inspection and maintenance activities and total during 2010-2023

Activity	*E* (Kg CO_2)				Total *E* (Kg CO_2)			
	spring	summer	autumn	winter	spring	summer	autumn	winter
Track alignment inspection by IMV 100 vehicle	-	-	-	5.49	-	-	-	153.71
Track alignment inspection by IMV 200 vehicle	-	0.93	-	1.25	-	26.17	-	34.89
Maintenance inspection	2.76	2.24	-	2.98	5.51	20.16	-	8.94
Safety inspection	2.76	2.24	2.53	2.98	11.02	53.76	10.12	160.88
preheating	-	15.20	16.72	17.48	-	15.20	33.44	17.48
grinding	-	1.75	1.93	2.01	-	1.75	5.78	4.03
welding	-	3.50	3.85	4.03	-	3.50	7.70	4.03

4. Conclusions

In this study, CO_2 emissions of inspection and maintenance activities were evaluated under different climatic conditions for moveable crossing by integrating multiple databases and conducting interviews with maintenance experts. The findings highlight the significant impact of seasonal variations on CO_2 emissions during railway crossing inspections and maintenance. Cold weather conditions result in considerably higher emissions due to increased fuel consumption.

Future research could consider variations in working time and investigate alternative methods or innovative technologies to reduce emissions, particularly during winter maintenance operations.

Acknowledgement

The authors gratefully acknowledge the funding provided by Sweden's innovation agency, Vinnova, for the project titled "Ny policy för utbyte som med hänsyn till en hållbar miljö" (Diarienummer: 2022-03842). The authors also extend their gratitude to Trafikverket for their valuable support and collaboration.

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