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Tracking Carbon in Executive Trains: A Study of Non-Traction Electricity and CO_2 Emissions in the Bima Train, Indonesia

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Abstract

Non-traction electricity consumption in train operations includes auxiliary loads such as lighting, air conditioning (AC), power outlets, and other electronic devices are essential for passenger comfort and safety. Although smaller than traction energy, the carbon emissions from non-traction electricity consumption remain significant, particularly when electricity is supplied by fossil-fueled diesel generators. This study quantifies the total annual CO_2 emissions generated from non-traction electricity used in executive-class train cars applying a quantitative approach based on measured energy consumption and emission factors. Data analyzed include electrical energy consumption (kWh), daily operating duration and frequency, and the annual operating period of a single train set as the unit of analysis. Emission calculations were performed using an emission factor of 0.64–0.74 kg CO_2/kWh for diesel generator-based systems, incorporating operational assumptions such as constant AC usage and auxiliary load patterns. Sensitivity analyses to evaluate the effect of variations in operating patterns. Results indicate that total annual CO_2 emissions range from 511 to 591 Tons per train, with AC identified as the dominant contributor to non-traction energy use. Scenario simulations suggest that integrating renewable energy sources, particularly solar panels, combined with targeted energy efficiency improvements, can reduce non-traction emissions by approximately 25–40% compared to current operational conditions. Thus, effective management of non-traction energy is a critical component of railway decarbonization, and implementing renewable energy solutions alongside efficiency-based strategies offers a substantial opportunity to reduce operational emissions, supporting sustainable railway operations and contributing to Indonesia's net zero emissions target by 2060.

Keywords: non-traction electricity; CO_2 emissions; executive class trains.

1. Introduction

The transportation sector remains one of the fastest-growing contributors to global greenhouse gas (GHG) emissions, driven by increasing demand for passenger and freight mobility and ongoing reliance on fossil fuel-based energy sources. Recent literature highlights that the concepts of transportation carbon emission and transportation carbon footprint are crucial to understanding and comparing the environmental performance of different transportation modes, as both reflect operational energy use and associated GHG outputs throughout the system lifecycle. Such understanding is critical for sustainable mobility planning, particularly as modal competition increasingly considers not only cost and speed but also carbon intensity as a determinant of environmental viability and policy preference in decarbonization strategies [1]. While railways are recognized as a mass transportation mode that is more efficient and environmentally friendly than road-based transport, they still face significant hurdles regarding total decarbonization. To date, attention regarding carbon emissions has focused primarily on traction or drive systems. However, auxiliary loads in passenger carriages exhibit significant variations in consumption depending on journey duration and cabin comfort requirements [2]. Consequently, while prior research has extensively analyzed traction energy and vehicle operation, studies addressing energy consumption from non-traction subsystems such as station lighting, air conditioning, power outlet, and signaling infrastructures remain limited and relatively understudied in the literature. Specifically, research on railway energy consumption has traditionally focused on rolling stock operational energy, often overlooking detailed quantification and efficiency evaluation of stationary and auxiliary systems that contribute significantly to total energy use in rail operations [3], [4]. A systematic strategy is required to integrate energy efficiency across all

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operational aspects of the railway, as significant energy savings and reductions in environmental impact are only realized when efficiency measures are coordinated among vehicle, operational, and infrastructure subsystems, rather than implemented in isolation, especially in developing contexts with complex operational challenges [5].

In practice, non-traction systems require a substantial electricity supply, the majority of which is still derived from fossil fuel plants, particularly coal [6], [7]. Data shows that more than 80% of Indonesia's electricity supply originates from fossil energy, with coal being the largest contributor [6]. Environmental assessments of railway transportation highlight that the electrical energy source is the primary determinant of life-cycle operational emissions [8]. This results in high CO_2 emission intensity per kWh in Indonesia, meaning that non-traction electricity consumption in railways contributes indirectly but significantly to carbon emissions [9]. In urban railway studies, empirical monitoring of metro rail energy consumption indicates that non-traction subsystems such as station operation including lighting, air conditioning, escalators and other support systems can account for nearly half of total electrical energy use, underscoring the importance of incorporating non-traction loads in energy efficiency analyses of urban rail transit systems [10]. Furthermore, global studies suggest that non-traction energy consumption can account for up to 15% of the total operational emissions of a railway system [11].

Given these conditions, a systematic and quantitative evaluation of non-traction energy consumption is needed to support decarbonization strategies in the railway sector. Therefore, this study aims to analyze the annual CO_2 emissions generated from non-traction electricity consumption in executive-class railway carriages in Indonesia, using an energy-based emissions calculation approach. In addition, this study evaluates the contribution of major auxiliary systems and explores potential emission reduction scenarios through energy efficiency improvements and alternative energy integration.

To address these objectives, the study is guided by the following research questions:

1. What is the total annual CO_2 emission generated from non-traction electricity consumption in executive-class railway car?
2. Which non-traction components contribute most significantly to overall energy consumption and emissions?
3. To what extent can emission reduction be achieved through energy efficiency measures and the integration of cleaner energy sources?

By addressing these questions, this research is expected to provide a more comprehensive understanding of non-traction emissions and contribute to the development of effective strategies for reducing the carbon footprint of railway transportation in Indonesia.

With the increasing electrification of the transportation sector, it is vital to understand the carbon footprint of all operational aspects, including non-traction. Energy efficiency strategies such as adopting energy-saving technologies, integrating renewable energy sources, and optimizing the design of station systems and supporting facilities are important first steps in reducing CO_2 emissions in railway operations. Recent reviews highlight that the strategic incorporation of renewable sources like solar and wind power into rail networks can significantly enhance energy efficiency and reduce environmental impact, while the implementation of energy-efficient technologies supports sustainability objectives at both operational and infrastructure levels [12], [13]. Consequently, an in-depth analysis of CO_2 emissions resulting from non-traction electricity consumption in the Indonesian railway network is highly relevant for supporting the energy transition agenda and sustainable transportation development [14].

2. Experimental Methods

To calculate the CO_2 emissions resulting from non-traction electrical energy consumption, methodologies based on electrical emission intensity factors are commonly employed in the literature, linking electricity use with grid emission characteristics. Such approaches align with global research highlighting that improvements in non-traction energy efficiency through enhanced load management systems and energy-saving technologies are critical for emission reduction in electric railways [15]. The fundamental formula used is shown in Equation (1).

$$CO_2\ emission\ (kg) = Energy\ consumed\ (kWh) x\ Emission\ Factor\ (kg \frac{CO_2}{kWh}) \tag{1}$$

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In this context, energy (kWh) is calculated from the total consumption of non-traction electrical devices, such as air conditioners (AC), lighting systems, and sockets, over a specific operational period. As the power source is a diesel-fired generator, the emission factor refers to the value derived from diesel combustion. Diesel generators contribute significantly to carbon dioxide emissions as part of their total pollutant output, and research on emission control highlights the importance of quantifying and mitigating these emissions from diesel generator sets in global electricity generation contexts [16]. Based on established emission factors and typical generator efficiencies, researchers commonly convert diesel emissions to a per-unit electricity basis. It results in emission intensities in the range of approximately 0.64–0.74 kg CO_2 per kWh of electricity generated, depending on fuel quality and operational efficiency. A methodological approach is widely used for calculating indirect emissions from non-traction electricity consumption in transport systems [17]. Meanwhile, an average emission factor of 0.8 kg CO_2/kWh is employed for a small genset [18]. Total CO_2 emissions associated with non-traction electrical energy consumption can be estimated by multiplying the total consumed electrical energy by the corresponding emission factors. Such approach is commonly adopted in the literature for transparent greenhouse gas accounting and life cycle assessment. This emission factor methodology underpins evaluation of emission reduction strategies such as improving energy efficiency and transitioning to low-carbon energy sources. Empirical studies on diesel-electric locomotives have also demonstrated a strong correlation between engine operational load and the amount of greenhouse gases produced, with CO_2 emission factors increasing significantly at higher load conditions [19].

2.1. Data Collection

The data used in this study is secondary data obtained from scientific publications and technical reports referring to operational data from PT. Kereta Api Indonesia (see Table 1). This data includes the power specifications (kW) of non-traction equipment such as air conditioning (AC) systems, lighting, electrical outlets, and other supporting systems on executive class trains. The Bima train was chosen as the research object because it is a long-distance executive train service with high-level facilities, which implies significant non-traction electrical energy consumption. Furthermore, its consistent operational pattern and role as a premium service of PT. Kereta Api Indonesia make it representative for analyzing CO_2 emissions from the passenger railway sector.

The Bima train configuration consists of seven passenger cars and one dining car, with all electricity supplied by a diesel generator. Data on the stored power of each device, extracted from the literature, was then used to calculate energy consumption based on operational duration and load factor.

To more accurately represent actual energy consumption, a load factor approach was applied to represent variations in device operation. The total energy consumption per trip was calculated in kilowatt-hours (kWh) and subsequently aggregated to estimate annual usage. Load factor values for each non-traction device were derived from a combination of literature on train energy consumption and operational assumptions for executive-class trains. Specifically, the air conditioning system was assigned a load factor of 72%, lighting 80%, power outlets 58%, and auxiliary systems 65%. These values reflect typical variations in actual usage over a full day of operation and are consistent with previous studies on passenger train energy consumption [20], [21].

Data validation was performed by comparing the estimated results with similar studies on railway systems and publicly available energy consumption data. This approach ensures that the calculation results are within a realistic range and scientifically sound.

Table 1. Train details

No.	Description	Information
1	Type of Car	Executive class passenger car
2	Number of Cars	7 passenger cars 1 dining car
3	Non-traction Device	Lighting, Air Conditioner (AC), electrical outlets, support system
4	Power Source	Diesel Generator Set

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2.2. Case Study

Electrical load calculations were performed on the Bima train traveling from Surabaya to Jakarta and back. The train configuration includes one locomotive, seven passenger cars, one dining car, and one generator car. Non-traction loads include lighting, outlets, AC, and supporting equipment in the passenger and dining cars. The Bima train operates for a total of 20.75 hours per day. The number of daily operations for the Bima train can be seen in Table 2.

Table 2. Train schedule

No.	Name of Train	Description	Schedule	Periods
1	Bima (7)	Surabaya – Gambir	19.20-05.45	10 hours 25 minutes
2	Bima (8)	Gambir – Surabaya	17.00-3.20	10 hours 20 minutes

3. Results and Discussion

3.1. Estimation of Non-Traction Energy Consumption

Non-traction energy consumption is divided into two categories: passenger carriages and dining carriages. Air Conditioning systems are typically the largest non-traction energy consumers, making efficiency control in this area crucial for reducing total emissions [22]. Detailed power consumption is shown in Tables 3 and 4. Accurate modeling of energy consumption allows operators to identify the most energy-intensive devices during long-haul journeys [23]. The electrical load factor of passenger cars on night trains is assumed to be 0.8. This value was chosen because non-traction electrical loads are dominated by continuous loads such as air conditioning and lighting systems. The system operates relatively stable throughout the journey, resulting in a high average power to maximum power ratio. The electrical load factor in the dining car is assumed to be 0.6, considering the fluctuating load characteristics with the dominance of cooking equipment operating intermittently and the significant difference between the peak load and the average load during the trip.

Table 3. Electrical power consumption for passenger car

No.	Load	Power (W)	Volume	Total power (W)
1	Air conditioner	7,150	2	14,300
2	TL lamp	20	30	600
3	Baggage lamp	4	28	112
4	Reading lamp	4,5	45	203
5	Information lamp	14	10	140
6	Exhaust fan	18	2	36
7	Television	100	2	200
8	Power outlet	25	50	1,250
			Total	17,129
			Load factor	0.8
			Total × load factor	13,703

Table 4. Electrical power consumption for dining car

No.	Load	Power (W)	Volume	Total power (W)
1	Air conditioner	7,150	2	14,300
2	TL lamp 1	20	3	60
3	TL lamp 2	40	11	440
4	Television	100	1	100
5	Exhaust fan	18	5	90
6	Dispenser	250	2	500
7	Refrigerator	115	2	230
8	Information lamp	14	10	140
			Total	15,860
			Load factor	0.6
			Total × load factor	9,516

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From Table 3, the total power required from 1 passenger car is 13,703 W or we can round it up to 13.7 kW and from Table 4, the total power from 1 dining car is 9.5 kW. Next, the total energy consumption is calculated per year using the following equation.

$$Total\ Energy\ per\ Year\ (kWh) = Total\ power\ in\ 1\ carriage\ \times Number\ of\ cars \times Duration\ of\ power\ usage\ in\ 1\ year \quad (2)$$

Table 5. Total electrical energy consumption (kWh)

No.	Cars	Total power (kW)	Number of cars	Duration in 1 year (hours)	Total electrical energy consumption (kWh)
1	Passenger	13.7	7	7,573.75	726,323
2	Dining	9.5	1	7,573.75	71,951
				Total	798,274

From Table 5, we can convert from annual electrical energy consumption to CO_2 emissions by multiplying the emission factors which can be seen in Table 6.

Table 6. Annual emission CO_2 (Ton)

No.	Total electrical energy consumption (kWh)	Emission factor (kg/kWh)	Annual CO_2 emission (Ton)
1	798,274	0.64	511
2	798,274	0.74	591

3.2. Annual CO_2 Emissions

The study results show that annual CO_2 emissions from the non-traction electrical system range from 511 to 591 Tons per train, depending on the emission factor used (0.64–0.74 kg/kWh). This variation of approximately 15% highlights the sensitivity of emission estimates to the carbon intensity of the electricity supply. The magnitude of these emissions confirms that non-traction loads such as air conditioning, lighting, and on-board service systems are significant sources of environmental impact, with percentages visible in Figure 1. Particularly on long-distance executive services like the Bima train, auxiliary systems are operated continuously for extended journey durations. Compared to similar studies on passenger train systems, the study results are consistent with the finding that auxiliary energy consumption, predominantly from the AC system, can dominate non-traction loads and contribute substantially to total emissions. From a life-cycle perspective, operational energy use remains the largest contributor to long-term environmental impacts, reinforcing the importance of improving energy efficiency during daily operations. These findings suggest that current emission levels could pose a challenge to achieving Indonesia's net zero emissions target by 2060 if no mitigation measures are implemented.

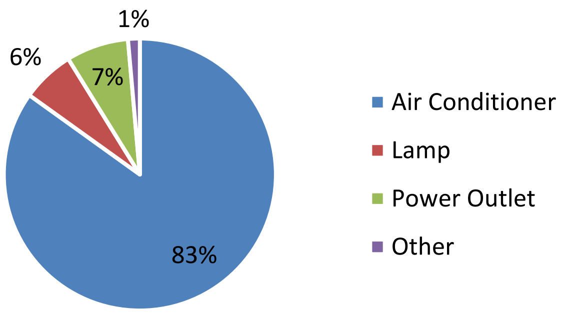

Figure 1. Percentage of train load

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To address this issue, several mitigation strategies can be considered. Improving air conditioning efficiency through advanced control systems and energy-efficient components offers the greatest potential impact, given its dominant and sustained load profile. Furthermore, replacing diesel-based power systems with battery energy storage systems could significantly reduce direct emissions during operation. The integration of renewable energy technologies, such as rooftop solar panels, could further support low-power loads, although their contribution remains limited. Operational measures, including load management in dining cars and the adoption of energy-efficient equipment, could also help reduce peak demand and improve the overall electricity load factor. Furthermore, long-term emission reductions are strongly influenced by the decarbonization of the national electricity grid, underscoring the need for alignment between railway electrification and broader energy transition policies.

It should be noted that this study relies on secondary data; therefore, the results are subject to uncertainties related to data assumptions and input parameters. While the findings provide reasonable estimates of emission levels, further validation through direct field measurements is recommended to improve accuracy and reliability.

4. Conclusion

Non-traction electrical systems contribute significantly to CO_2 emissions, with annual emissions estimated at 511–591 Tons per train, equivalent to approximately 1.4–1.6 Tons of CO_2 per day depending on the applied emission factor. These results confirm that auxiliary systems represent a significant portion of operational emissions in rail services, particularly on long-distance executive trains such as the Bima train. Given the magnitude of these emissions, reducing non-traction energy consumption is crucial to support Indonesia's net zero emissions target by 2060.

The findings indicate that dominant loads, such as on-board air conditioning, are major contributors to total energy use; thus, mitigation strategies should prioritize improving their efficiency. The source of renewable energy, specifically solar photovoltaic (PV) systems, has significant potential to reduce emissions and reduce reliance on diesel-based generators. Integration of solar energy into rail systems, whether through installation on station infrastructure, trackside, or even train rooftops has been shown to offset a substantial portion of auxiliary energy consumption. For example, rooftop PV systems could supply a portion of the auxiliary load for locomotives, resulting in measurable CO_2 reductions on the order of tens of Tons per year per trainset when installed at scale. More broadly, studies on rail-deployed solar indicate that PV integration can contribute a significant share of local electricity supply. An initiative demonstrates that solar plants supplied up to 60% of metro energy demand and delivered a renewable share of 76% at a metro network level substantially lower grid energy dependence and associated emissions. Integrating such renewable solutions into station systems and ancillary facilities, combined with intelligent energy management strategies including load optimization on high-consumption units such as dining cars, can further enhance operational sustainability and reduce overall CO_2 emissions.

However, this research has several limitations. The analysis is based on secondary data and assumptions regarding load factors and operational patterns, which may not fully capture real-time variations in energy consumption. Hence, the results should be interpreted as rough estimates rather than definitive values. Future research should focus on direct field measurements, detailed load profiles, and the integration of real-time monitoring systems to improve accuracy. Furthermore, extended studies are needed to evaluate the economic feasibility and technical performance of renewable energy integration in railway systems.

From a policy perspective, the research findings highlight the need for a comprehensive decarbonization strategy that includes non-traction systems as a key component. Aligning rail energy usage with national renewable energy targets, promoting investment in clean technology within trains, and encouraging innovation through technology transfer are critical steps to achieving Indonesia's net zero emissions target by 2060.

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railway operations, which have contributed to the contextual understanding of this study. Moreover, the authors also acknowledge the valuable contributions of academic colleagues and reviewers whose feedback has significantly improved the quality of this manuscript. Furthermore, this research was conducted using secondary data; therefore, the authors appreciate all institutions and previous studies that have made data and references available to support this work.

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