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Strategy Analysis of Logistic Transportation Decarbonization Through Mode Shift as an Effort to Reduce Externalities: A Case Study of Pasar Induk Beras Cipinang

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Abstract
This research evaluates the potential for decarbonizing freight transport at Pasar Induk Beras Cipinang (PIBC), Jakarta's main rice market, through a modal shift from trucks to rail. Using an integrated methodology combining traffic surveys, mobile phone origin-destination data, and GHG Protocol calculations, we analyze emission reduction scenarios and their economic implications. The research reveals that current truck-based operations generate substantial emissions, with inbound freight contributing 268 tons CO_2e/day and outbound freight adding 36 tons CO_2e/day, primarily from the Surakarta-Tegal-Cirebon corridors. Our analysis demonstrates that strategic implementation of rail transport could reduce CO_2 emissions by 48% for inbound logistics, equivalent to shifting 11.3 kt/day to rail and saving Rp14.6 million daily in carbon taxes. Medium-duty trucks account for 82% of emissions, with peak activity occurring during nighttime hours. While Java's existing rail infrastructure has capacity for 180-360 tons/day through its northern and central lines, outbound emissions may still increase by 400% without additional interventions due to growing demand. These findings provide critical insights for achieving Indonesia's Net Zero Emissions target by 2050, highlighting the importance of prioritizing inbound logistics for mode-shift strategies. The study's methodology, particularly its innovative use of mobile big data for freight flow analysis, offers a replicable framework for urban freight decarbonization in similar emerging market contexts. The results underscore rail transport's viability for bulk commodity distribution in urban areas and provide quantitative evidence to support infrastructure investment decisions. This research contributes to sustainable logistics planning by offering policymakers and industry stakeholders actionable strategies for reducing transportation emissions while maintaining economic efficiency in Indonesia's crucial rice distribution network.

Introduction

Greenhouse gas (GHG) emissions from the transportation sector pose a major challenge to Indonesia's climate change mitigation agenda. According to the Energy Institute (2024), Indonesia ranks sixth globally in cumulative GHG emissions over the period 1850–2021. On a national scale, the transportation sector contributes approximately 27% of total energy-related emissions, making it a key driver of Indonesia's carbon footprint (Nabila & Aritenang, 2024). This situation is further exacerbated by the fact that Indonesia is the highest carbon emitter in Southeast Asia, underscoring the urgency of effective mitigation strategies in the transport sector.

As the country's economic hub, Jakarta faces critical challenges in managing urban freight transportation. Trucking dominates around 91.3% of total freight movement in Indonesia, while rail transport accounts for only 1.1% (Setijadi, 2018). The overreliance on road-based freight, particularly trucks, has led to substantial environmental and social consequences, including increased GHG emissions, high energy consumption, traffic congestion, and deteriorating air quality (European Environment Agency, 2021).

Rail transport offers a promising alternative with its potential to reduce GHG emissions and enhance logistics efficiency. Trains are capable of transporting large volumes of goods more efficiently in terms of fuel consumption compared to road transport. However, the adoption of rail freight in Indonesia remains limited due to various systemic and infrastructural challenges (Bina et al., 2014), hindering the optimal use of rail as a low-emission solution within urban logistics systems.

The *Cipinang Rice Central Market* (*Pasar Induk Beras Cipinang*, *PIBC*), a major rice distribution hub in Jakarta, currently relies heavily on truck-based supply from other regions. *Cipinang Station* (*CPN*), strategically located near *PIBC*, presents a strong potential to serve as a rail-based logistics node. Leveraging this station for rice distribution could significantly reduce traffic congestion, lower logistics costs, and most importantly, cut GHG emissions from the freight sector.

Previous research has explored various aspects of logistics decarbonization. For instance, Zhang et al. (2022) examined supply chain decarbonization barriers but focused primarily on industrial sectors, leaving a gap in urban freight-specific strategies. Similarly, Setijadi (2018) highlighted Indonesia's overreliance on trucking (91.3% of freight movement) but did not quantify the emission reduction potential of rail alternatives. These studies lack a detailed analysis of mode-shift feasibility and its economic externalities, particularly in high-volume commodity hubs like *Pasar Induk Beras Cipinang* (*PIBC*).

This study aims to comprehensively assess the potential for implementing a logistics mode shift strategy from trucks to rail at *PIBC*. The methodology involves mode-shifting modeling, detailed calculations of GHG emission reduction potential, and an externality analysis encompassing environmental, social, and economic impacts. Ultimately, this research seeks to offer strategic policy recommendations to support Indonesia's Net Zero Emissions target by 2050 (United Nations Environment Programme, 2022). The findings are expected to provide multiple benefits, including (1) a measurable reduction in CO_2 emissions (up to 48%) and associated carbon tax burdens, (2) improved urban traffic efficiency by alleviating truck congestion, and (3) a scalable model for decarbonizing other high-volume commodity hubs in Indonesia. Additionally, this study contributes to academia by advancing methodologies for freight emission modeling using mobile phone-based OD data—a novel approach in emerging market contexts.

Materials and Methods

This section provides a comprehensive overview of the research design, which aims to develop a mathematical model and identify the optimal modal shift proportion in the context of transitioning logistics transportation from trucks to rail. The research is further directed at quantifying the potential for decarbonization by evaluating the reduction in greenhouse gas (GHG) emissions, and assessing the externalities associated with this shift, using rice distribution to *Cipinang Station* (*CPN*) as a case study. Through a structured and methodical approach, the research outlines each phase—from the formulation of objectives and scope delimitation, to data collection strategies and analytical procedures—ensuring that every step contributes meaningfully to a deeper understanding of the modal shift implications. Ultimately, this design culminates in a synthesis of findings aimed at providing evidence-based recommendations for sustainable transport policy and logistics planning in urban settings.

1. Research framework

This research is structured into four comprehensive phases, as depicted in Fig. 1. The first phase covers problem formulation, objective setting, literature review, and the collection of primary and secondary data related to traffic conditions, vehicle occupancy, emission factors, and carbon tax rates. The second phase involves adjusting Origin-Destination data using vehicle occupancy rates to analyze the potential for a modal shift from truck to rail. The third phase evaluates greenhouse gas (GHG) emissions through baseline calculations and simulations of modal shift scenarios. The final phase assesses the economic impact of carbon tax implementation by comparing logistics costs and potential trade-offs with and without rail-based freight strategies.

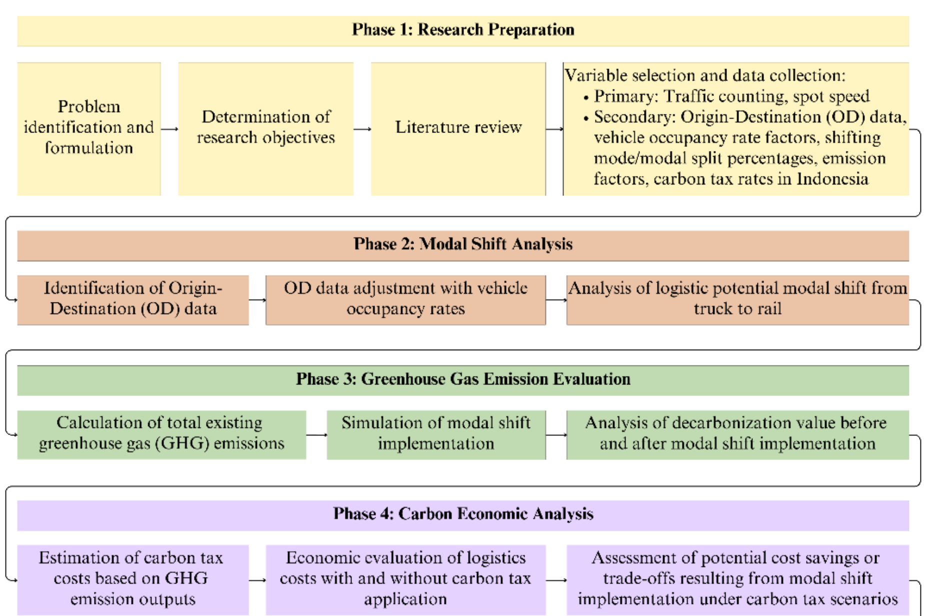


Fig. 1 Research workflow

Source: Author's analysis, 2024

2. Study area

This research focuses on analyzing the movement of rice logistics to and from *Pasar Induk Beras Cipinang* (*PIBC*), the primary rice distribution center serving the greater Jakarta region. The study is limited to land-based transportation, which is the dominant mode used for rice freight in the area. A purposive sampling method was applied to select a strategic urban road segment directly connected to *PIBC*, namely *Jalan Bekasi Timur Raya*, located in *Cipinang District*, *East Jakarta*, *DKI Jakarta*.

Figure 2. Research area in determining GHG emissions

Source: Data Map © Google, 2025

The selected road segment spans approximately 1 kilometer and is classified as an urban secondary arterial road, serving as a key link between dense residential areas and major economic activity centers, including a bus terminal and railway station. Although not part of the national road network, this segment plays a significant role in urban freight distribution, functioning as a logistics corridor within the *Freight Trip Attraction* (*FTA*) and *Freight Trip Production* (*FTP*) framework for *PIBC*.

Geometrically, the road consists of a divided dual carriageway with a physical median. The presence of designated bus lanes and slow vehicle lanes further suggests that the corridor serves a mid-level distribution function, though it does not qualify as a primary arterial road. The surrounding area is characterized by dense urban activities, with various public facilities and commercial zones contributing to high side friction, including parked vehicles, pedestrian traffic, and frequent access to adjacent properties.

3. Freight vehicle classification and operational characteristics

In the context of Indonesia's urban freight distribution system, particularly within key commodity hubs such as *Pasar Induk Beras Cipinang* (*PIBC*), the classification of freight vehicles serves as a foundational element for traffic impact assessment, environmental emission analysis, and transportation infrastructure planning. The classification framework adopted in this study is based on official regulations issued by the *Toll Road Regulatory Agency* (*Badan Pengatur Jalan Tol*/*BPJT*) under the Ministry of Public Works and Housing (*PUPR*), which categorizes motor vehicles into six primary groups.

This vehicle classification system incorporates multiple criteria, including the number of axles, functional usage (i.e., private, commercial, or freight transport), and the physical dimensions and payload capacity of each vehicle. These attributes are used as proxies to determine the dynamic impact each vehicle type imposes on the roadway infrastructure. For logistics operations at *PIBC*, road-based freight transport is primarily dominated by truck vehicles of various configurations. The specific truck categories referenced in this study follow *BPJT*'s granular classification, as outlined below:

Table 1. Freight Vehicle Classification

Group	Number of Axles	Vehicle Type
Group 4	2 axles	Light-duty vehicles such as pick-ups, micro trucks, and small delivery vans (e.g., box trucks)
Group 6a	2 axles	Light trucks equipped with two axles
Group 6b	2 axles	Medium trucks with two axles
Group 7a	3 axles	Heavy-duty rigid trucks with three axles (commonly referred to as *tronton*)
Group 7b	4–5 axles (articulated)	Articulated trucks (*gandengan*)
Group 7c	5–6 axles (semi-trailer)	Semi-trailer trucks composed of a tractor head and detachable trailer

Source: Ministry of PUPR, (2017)

For Groups 7b and 7c, vehicle classification is determined based on the total number of active axles in contact with the road surface. This is typically assessed using axle counter systems installed at toll gates, which detect axle configuration in real time for the purpose of tariff determination and traffic categorization.

The legal foundation for the national vehicle classification system is outlined in the Regulation of the Minister of Public Works and Housing No. 16/PRT/M/2017, which establishes the basis for vehicle categorization across Indonesia's national toll road network. The classification framework is periodically updated to reflect evolving logistics patterns, including changes in commercial fleet composition, payload distribution, and the broader integration of road freight transport policy with national goals for emission reduction and traffic safety (*Ministry of Public Works and Housing*, 2017).

4. Mobile Phone-Based Origin-Destination (OD) Data for Traffic Flow Simulation

Origin-Destination (*OD*) data serves as a critical input in modern transportation planning and infrastructure management. *OD* matrices enable the estimation of travel demand by quantifying the number of individuals moving between zones across a given transport network during specific time intervals. The resulting mobility maps derived from these matrices allow policymakers to assess spatial travel patterns and optimize the performance of road networks.

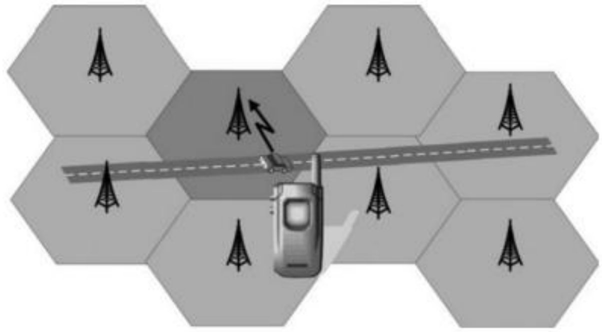


Figure 3. Cellular-Based OD Zoning Framework for Freight Flow Analysis
Source: Telkomsel, (2024)

This study adopts a contemporary approach that leverages mobile phone location data as a proxy for capturing vehicular movement, thereby generating near real-time *OD* matrices. Unlike traditional survey-based methods, this approach provides a scalable, automated, and cost-efficient alternative for monitoring traffic conditions across wide geographic areas.

The methodology involves passively tracking the geospatial location of mobile phones that are switched on and moving inside vehicles. Each mobile phone, when connected to a cellular network, is treated as a proxy or "probe vehicle," provided that the user is a subscriber of the cellular provider. In this study, data was obtained from *Telkomsel*, one of the largest mobile network operators in Indonesia. The dataset comprises 30 days of aggregated daily *OD* flows, disaggregated by direction:

1. *FTA* (*Freight Trip Attraction*): Movements into the *Pasar Induk Beras Cipinang* (*PIBC*) from other cities,
2. *FTP* (*Freight Trip Production*): Movements from *PIBC* to external destinations.

The following tables present the *Origin-Destination* (*OD*) data extracted from *Telkomsel* mobile network records. The dataset captures estimated daily freight flows to and from the *Pasar Induk Beras Cipinang* (*PIBC*), categorized as *Freight Trip Attraction* (incoming trips) and *Freight Trip Production* (outgoing trips). The figures are reported in terms of both individuals (persons/day) and equivalent vehicle movements (vehicles/day), with adjustments made from partial user coverage (58%) to full population extrapolation (100%).

5. Average Vehicle Occupancy (AVO)

In this study, Origin-Destination (OD) data was obtained in units of individuals (persons per day). To convert these figures into vehicles per day, the concept of Average Vehicle Occupancy (AVO) was applied, which represents the average number of passengers (including the driver) per vehicle. The AVO value is calculated using the following formula:

$$Occupancy\ Rate\ (OR_{i,m}) = \frac{Total\ Number\ of\ Person}{Total\ Number\ of\ Vehicles}$$

The AVO values adopted in this study are presented in Table 1, which outlines average occupancy rates by vehicle type or classification.

Table 2. Average Vehicle Occupancy Rate by Vehicle Category

Freight Vehicle Classification	AVO (person/vehicle)
Group 4	1.54
Group 6a	1.67
Group 6b	1.67
Group 7a	1.67
Group 7b	1.67
Group 7c	1.67

Source: Field survey and author's analysis, 2024

These values were used to estimate the number of logistics vehicles passing through Pasar Induk Beras Cipinang (PIBC) per day—both for Freight Trip Attraction (FTA) and Freight Trip Production (FTP). This conversion forms the basis for traffic load estimation and impact analysis in the study area.

6. Traffic Counting for Estimating Vehicle Type Proportions

Traffic counting is a fundamental method for monitoring traffic flow on specific road segments. In this study, it was employed to estimate the proportion of vehicle types on the main access roads to and from Pasar Induk Beras Cipinang (PIBC), in order to capture the volume and composition of vehicles passing through the area. This method complements mobile phone-based Origin-Destination (OD) data in estimating logistics movement.

The traffic survey was conducted over a continuous 24-hour period, covering both weekday and weekend observations, with a 15-minute recording interval. The collected data were then aggregated into hourly intervals to identify peak-hour periods based on time-distribution quartiles. The observation schedule and methodology refer to standard practices from previous traffic studies (e.g., Chen et al., 2007).

The traffic count results were used to calculate the proportion of vehicles by classification group. These proportions were subsequently applied to the person-based OD dataset to estimate the distribution of vehicles by type crossing PIBC access roads. Through this approach, the analysis enables a more accurate representation of logistics vehicle types based on time intervals and traffic intensity.

7. Demand Forecasting and Growth Scenario Modelling

The estimation of demand growth is a critical step in evaluating the impact of logistics mode shifting from road-based to rail-based freight transportation. The decarbonization potential is quantified by comparing baseline greenhouse gas (GHG) emissions from existing logistics conditions with projected emissions under alternative rail-shift scenarios. Demand growth is estimated in units of kilograms per day (kg/day), based on total logistics weight transported across all vehicle classes. Three projection scenarios are developed to simulate different rates of demand and rail mode adoption over time:

1) Business as Usual assumes no significant modal shift or policy intervention;
2) Pessimistic reflects conservative growth with limited logistics system readiness;

3) Optimistic represents accelerated modal shift supported by infrastructure and policy improvements.

These scenarios incorporate dynamic factors such as mode substitution potential and regional logistics expansion, particularly around the PIBC area. Secondary data from the POLAR FTUI report (2024) are used to define scenario assumptions, as shown in Table 5.3.

Table 3. Potential Freight Demand Using Rail Based on OD Location (kg/day)

Demand Growth Factor	2024	2025-2030	2031-2035	2036-2040	2041-2045
Business as Usual	90%	5%	5%	5%	5%
Pessimistic Scenario	-	5%	5%	5%	5%
Optimistic Scenario	-	5%	10%	10%	10%

Source: Telkomsel OD data and POLAR FTUI projections, 2024

8. Estimating Potential Modal Shift to Rail Logistics

The forecasted freight demand for rice commodities serves as the foundation for estimating the potential modal shift—or willingness to shift—from road to rail-based logistics. This potential reflects the portion of projected demand considered technically and economically feasible for transition. Table X presents scenario-based projections of potential demand that could shift to rail, expressed in kg/day, for the period 2024–2045. Three growth scenarios are applied: Business as Usual, Pessimistic, and Optimistic.

Table 4. Potential Modal Shift Using Rail Based on OD Location (kg/day)

Willingness to Shift	2024	2025-2030	2031-2035	2036-2040	2041-2045
Business as Usual	90%	0%	0%	0%	0%
Pessimistic Scenario	-	3%	5%	7%	10%
Optimistic Scenario	-	7%	10%	15%	20%

Source: Author mode shift model simulation, 2024

Each scenario assumes varying degrees of rail readiness, market acceptance, and logistical compatibility. The output serves as a critical input to emission reduction modeling, where potential shifting volumes will be combined with rail distance, emission

9. Emission calculation method

This study adopts the Greenhouse Gas Protocol (GHG Protocol) developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) to estimate greenhouse gas (GHG) emissions resulting from truck and rail-based freight transportation. The GHG Protocol is a globally recognized framework designed to help public and private sectors measure, manage, and mitigate GHG emissions across operational activities and supply chains.

The emission inventory in this study refers to Scope 3 – Category 4 (Upstream Transportation and Distribution), which focuses on the movement of goods from producers to intermediary locations—in this case, from rice-producing regions to Pasar Induk Beras Cipinang (PIBC). Goods transported under this category are not delivered directly to end-consumers, but to central distribution hubs for further handling.

GHG emissions are calculated by aggregating direct and indirect emissions associated with fuel combustion during freight transport. The estimation adopts the WRI Indonesia adaptation of IPCC-based methods, which uses emission factors from fuel types and considers vehicle energy efficiency to convert distance traveled into fuel consumption.

Carbon emissions are expressed in terms of CO_2 equivalent (CO_2e), accounting for gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) through Global Warming Potential (GWP) coefficients. The total emission per person per trip is determined using the following equation:

$$Total\ Carbon\ Footprint\ Emissions\ per\ Vehicle\ (kgCO_2eq) = \sum_{i=1}^{N}\left(\frac{D_i\ x\ EF_{sk}}{FCF_{ij}}\right)$$

Where:

i = Index of each trip (1, 2, ..., N)

D_i = Distance traveled in trip i (km)

FCF_{ij} = Fuel consumption factor for vehicle type j in trip i (km/liter)

EF_{sk} = Emission factor of fuel type k ($kgCO_2eq$/liter)

This formula allows for emission estimation based on actual transport distances, fuel efficiency, and load occupancy rates. It ensures that emission outputs reflect the operational realities of freight logistics in the PIBC supply chain context.

10. Externality valuation: Carbon tax conversion

As part of internalizing the environmental externalities of freight transport emissions, this study incorporates a carbon tax valuation framework in accordance with Indonesia's national policy. The carbon tax is one of the instruments under the Nilai Ekonomi Karbon (NEK) policy aimed at climate change mitigation and sustainable economic growth.

The implementation of the carbon tax in Indonesia follows the Undang-Undang No. 7 Tahun 2021, which stipulates a tax rate of Rp30,000 per ton of CO_2e it represents a critical step for developing countries in mainstreaming carbon cost into decision-making.

$$Carbon\ Tax = Emissions\ (kgCO_2eq)\ x\ Tariff\ (Rp/kgCO_2eq)$$

In this study, emission results calculated through the GHG Protocol are multiplied by the carbon tax tariff to monetize the external cost of carbon emissions. This valuation serves as a proxy to quantify the environmental burden associated with freight transportation and reflects the opportunity cost of emissions under Indonesia's climate mitigation agenda. The objective of applying this carbon cost is not only to quantify externalities but also to align the assessment with national climate policy instruments and support the transition toward low-carbon logistics systems.

Results and Discussions

This section presents insights into the influence of logistics mode selection on greenhouse gas (GHG) emissions. Through an empirical analysis encompassing travel behavior around the Pasar Induk Beras Cipinang (PIBC), traffic volume measurements, and vehicle classification proportions, the study underscores the urgent need for a modal shift from conventional road freight (primarily trucks) to rail-based logistics in order to reduce emission levels.

Furthermore, an external cost analysis—represented through the valuation of carbon tax—reinforces the strategic significance of transport mode choices in achieving decarbonization objectives. The findings provide evidence-based recommendations for policymakers to prioritize the operationalization of Cipinang Station (CPN), located less than 1 km from PIBC, as a key logistics transfer hub. Such a shift would not only reduce emissions but also enhance the overall efficiency of the road network by alleviating traffic congestion and supporting sustainable urban freight mobility.

1. Traffic counting analysis

Traffic counting was conducted over a continuous 24-hour period to assess the distribution of vehicle types and traffic patterns based on time of day and vehicle classification. The observed road segment, approximately 100 meters in length, is categorized as a secondary arterial type 4/2D and considered representative of daily logistical flows to and from Pasar Induk Beras Cipinang (PIBC). The data collected enable a detailed breakdown of traffic composition by vehicle type, diurnal variation in flow intensity, and hourly volume distribution, providing a foundation for emission estimation and mode-shifting assessments.

2. Vehicle Volume Conversion Using Average Vehicle Occupancy (AVO)

Origin-Destination (OD) data provided by the Ministry of Transportation is originally expressed in person-trip units. To estimate actual freight vehicle movements and corresponding carbon emissions, this data must be converted into vehicle-trip units per day. For this purpose, the Average Vehicle Occupancy (AVO) parameter is utilized, representing the average number of persons (including drivers) per vehicle class, adjusted to suit the characteristics of freight logistics transport in Indonesia.

The conversion process follows three sequential steps:

1) Transform OD person-trip data into daily units (if originally presented monthly);
2) Apply vehicle class proportions derived from traffic counting surveys;
3) Divide the adjusted trip volume by the respective AVO for each vehicle class to obtain vehicle-trip estimates.

This approach allows for more accurate carbon footprint calculation and alignment with emission modeling frameworks based on vehicle kilometers traveled (VKT).

3. Vehicle Type Proportion and Implications for Emissions

Traffic composition on the surveyed road segment is predominantly non-logistics, with two-wheeled vehicles (Vehicle Class 1) comprising 82% and private passenger cars (Vehicle Classes 2 and 3) making up 14% of the total daily volume. Freight vehicles—ranging from medium-duty to heavy-duty trucks (Vehicle Classes 4 through 7c)—account for only 4% of total traffic, yet they are a major contributor to emissions due to their larger physical dimensions, fuel consumption, and operating loads.

Despite representing a small share of total vehicle movements, logistics trucks exert significant environmental and infrastructural impacts, including road surface degradation, high fossil fuel usage, and substantial greenhouse gas (GHG) emissions. As such, decarbonization strategies should prioritize targeted interventions within this vehicle segment—particularly through mode shifting from road to rail and enhancements in freight transport efficiency.

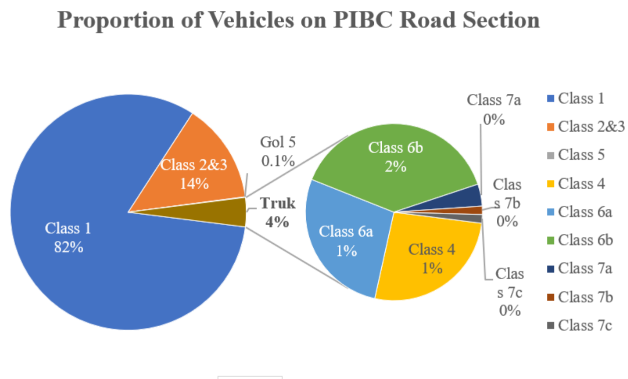


Fig 4. Proportion of Vehicles on the East Bekasi Raya Road Section, Cipinang District

Source: 24-hour traffic survey results, 2024

4. Traffic Flow Pattern of Logistics Vehicles

Logistics traffic on the observed road segment shows peak activity during early morning hours (05:00–10:00), dominated by two-axle trucks (Vehicle Class 6b). Similar patterns are seen in Classes 4 and 6a, indicating that most rice distribution to PIBC occurs before and shortly after market opening.

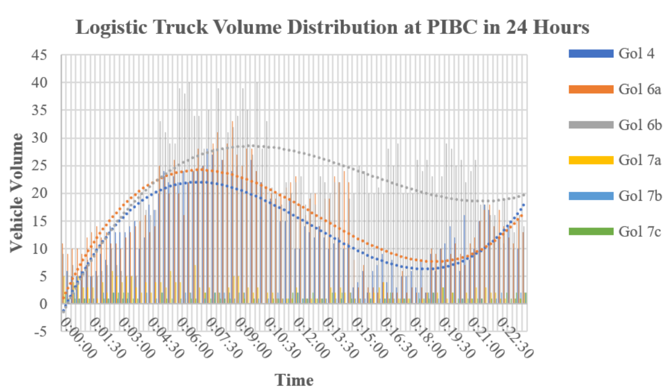


Figure 5. Logistic Truck Volume Distribution at PIBC in 24 Hours

Source: Telematics data and field surveys, 2024

A decline in traffic is observed during midday (10:00–15:00), followed by a moderate increase in the afternoon (15:00–19:00), especially for Classes 6a and 6b. A second peak occurs at night (20:00–04:00), reflecting overnight operations aimed at avoiding congestion. Heavy-duty vehicles (Classes 7a–7c) operate in smaller volumes and more sporadically. This dual-cycle pattern (morning and night) reflects the adaptive behavior of freight operators in urban settings.

5. Rail Logistics Service Plan

To enhance efficiency and reduce emissions, rail transport is recommended as the preferred mode for long-haul logistics distribution. Compared to road freight, rail offers superior energy efficiency and lower carbon intensity. Based on this study, two types of areas are prioritized for modal shifting from road to rail logistics serving PIBC:

1) Regions located more than 300 km from or to PIBC, suitable for inter-city freight movement.
2) Regions within 300 km that demonstrate high shipment volumes and are supported by active freight terminals.

Figure 6. Java and Madura Railway Network Map of KAI Logistics

Source: Infrastructure documents PT. KAI, 2023

The proposed rail service will utilize two parcel routes:

1) Central Parcel Line (Jakarta–Semarang–Surabaya via the central corridor), typically consisting of 6 freight wagons.
2) Northern Parcel Line (Jakarta–Semarang–Surabaya via the northern corridor), usually comprising 9 freight wagons.

Based on data from POLAR, the maximum daily cargo capacity is:

1) Central Parcel Line: up to 180,000 kg (180 tons), assuming a per-wagon capacity of 30 tons.
2) Northern Parcel Line: up to 360,000 kg (360 tons), assuming a per-wagon capacity of 40 tons.

Field measurements indicate a bulk density of 820 kg/m³ for rice. This allows the estimation of shipment volumes and transport frequency based on available capacity and cargo weight, providing a practical framework for logistics planning under existing infrastructure constraints.

6. Logistics Characteristics and Travel Patterns around PIBC

Field observations and traffic count data reveal that the dominant logistics mode to and from Pasar Induk Beras Cipinang (PIBC) is road freight, particularly using trucks with two axles. Among these, medium-duty trucks (Vehicle Class 6b) account for approximately 2% of total daily traffic, followed by light trucks (Class 6a) at 1%, and small commercial vehicles such as pickup trucks and box vans (Class 4) at 1%. These vehicle types represent the majority of rice logistics operations, requiring maneuverability within urban areas despite transporting smaller loads. These movement types are illustrated in Figure 7, reflecting the directional flow of goods within the supply chain. To capture logistics flows in and out of PIBC, freight movement is categorized into two main types:

1) Freight Trip Attraction (FTA): inbound movements toward PIBC from rice-producing regions
2) Freight Trip Production (FTP): outbound deliveries from PIBC to consumption centers such as Jabodetabek and Bandung

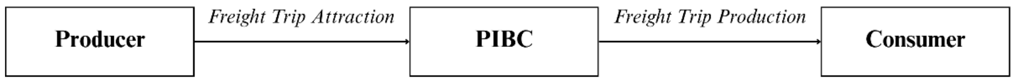


Figure 7. Travel Pattern of FTA and FTP PIBC Logistics Transportation
Source: Mobile-based OD data analysis, 2024

Analysis of travel characteristics includes vehicle volume, physical dimensions, and fuel usage, all of which influence environmental impact. Additional variables such as travel distance and shipment density also support emission modeling and mode-shifting projections from trucks to rail.

7. Greenhouse Gas (GHG) Emissions from Freight Trip Attraction and Production

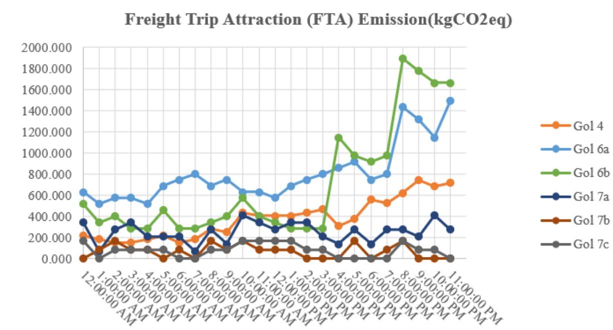


Figure 8. FTA Emissions by Group
Source: Emissions calculation using the GHG Protocol, 2024

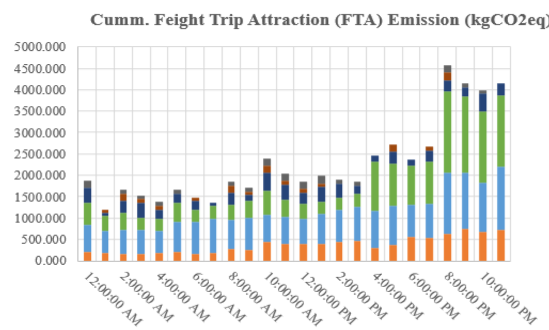


Figure 9. Cumulative FTA Emissions by Group
Source: Simulation of the fashion shift scenario, 2024

The estimation of greenhouse gas (GHG) emissions from logistics activities associated with Pasar Induk Beras Cipinang (PIBC) reveals substantial environmental impacts, particularly from inbound freight movements (Freight Trip Attraction/FTA). The analysis indicates that the largest emission contributions originate from Surakarta (29.08%), Tegal (13.16%), and Cirebon (8.09%), with respective emission values of 77,944.56 $kgCO_2e$, 35,289.02 $kgCO_2e$, and 21,691.48 $kgCO_2e$. These figures reflect the high intensity of rice logistics flows from these production hubs toward PIBC.

Disaggregated analysis by vehicle classification demonstrates that medium-duty trucks, specifically those categorized under Vehicle Classes 6a and 6b (two- to three-axle trucks), are the primary contributors to inbound emissions. These vehicle types dominate freight transport due to their operational flexibility and load capacity, particularly in dense urban environments.

Temporal patterns reveal that logistics-related emissions peak during the evening hours (approximately 19:00 to 22:00), suggesting a strategic shift of operations to off-peak periods to mitigate urban traffic congestion. In contrast, heavy-duty trucks (Classes 7a through 7c) contribute marginally to total emissions, with a more dispersed temporal profile.

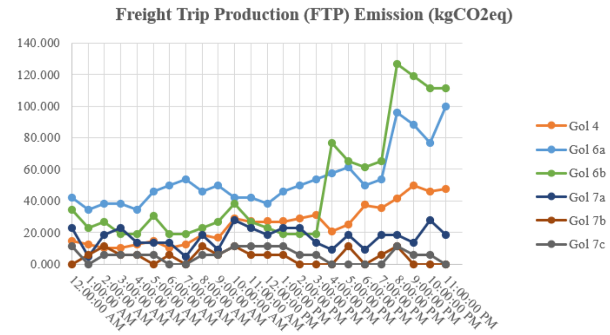


Figure 10. FTP Emissions by Group

Source: Results of emissions calculations based on field data, 2024

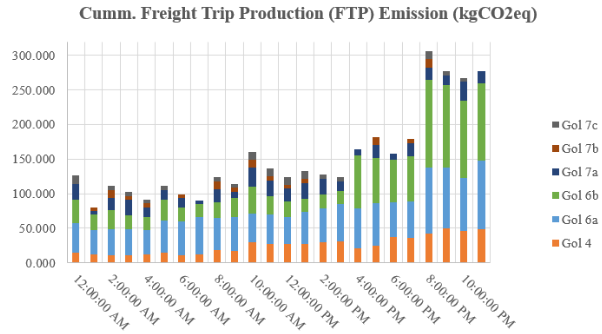


Figure 11. Cumulative FTP Emissions by Group

Source: Analysis of emission projections 2024-2045, 2024)

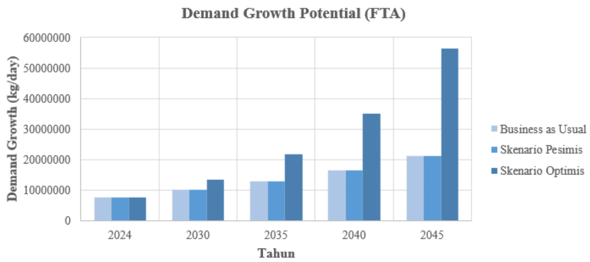
For outbound movements (Freight Trip Production/FTP), the highest emission load is attributed to shipments destined for the Bandung metropolitan area, accounting for approximately 59% of total FTP-related emissions, or 213,141.31 $kgCO_2e$. This is primarily driven by the combination of high freight volume and relatively long transport distance. Other significant destinations include Tangerang (10%), West Jakarta (7%), and Depok (7%), indicating a spatial concentration of rice distribution toward greater Jakarta and surrounding urban centers.

Collectively, these findings underscore the dominant role of medium-range distribution corridors and medium-duty vehicles in generating logistics-related GHG emissions. The results emphasize the necessity for decarbonization strategies that target specific freight segments through vehicle-type regulation, route optimization, and modal shifting—particularly toward more sustainable modes such as rail-based logistics.

8. Freight Demand Growth for Rice Commodities at PIBC

Based on scenario-based projections, freight demand associated with rice distribution to and from PIBC is expected to grow significantly over the next two decades. In 2024, the baseline demand is estimated at 7,631,462.67 kg/day for inbound freight (FTA) and 3,838,927.08 kg/day for outbound freight (FTP).

The projected growth is disaggregated by five-year periods and visualized in Figures 5.12 and 5.13. Figure 5.12 illustrates the demand growth for inbound logistics (FTA), while Figure 5.13 shows the trend for outbound logistics (FTP).



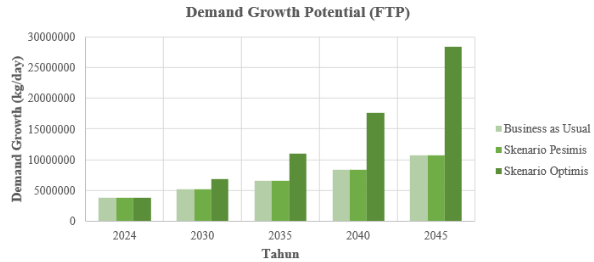


Figure 12. FTA Demand Growth Potential **Figure 13. FTP Demand Growth Potential**

Source: BAU/Pessimistic/Optimistic scenario modeling, 2024

Under both the Business as Usual and Pessimistic scenarios, freight demand increases steadily at a conservative growth rate of 5% per five-year period. The Optimistic scenario, however, projects a significantly higher growth trajectory, reflecting improved rail logistics readiness and policy-driven modal shift acceleration.

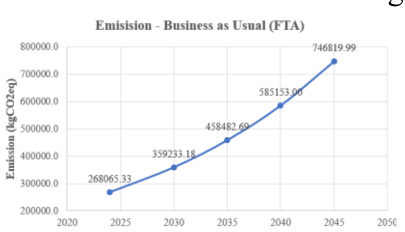
These projections serve as key inputs for emissions modeling and infrastructure planning, particularly in aligning future logistics needs with decarbonization objectives.

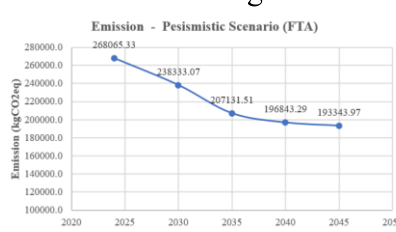
9. Potential Emission Reduction from Modal Shift

Under both pessimistic and optimistic scenarios, only a portion of total demand growth is feasible for rail transition. These volumes, when multiplied by route distance and adjusted for train fuel efficiency and carbon intensity, yield the estimated GHG reduction potential. This analysis provides a quantitative basis for evaluating the environmental benefit of partial modal shifts in the rice freight supply chain.

10. Decarbonization Analysis of Freight Trip Attraction (FTA)

This analysis quantifies the impact of modal shift interventions on greenhouse gas (GHG) emissions from inbound freight flows (Freight Trip Attraction) to Pasar Induk Beras Cipinang (PIBC). Without any intervention, emissions are projected to rise from 268,065.33 $kgCO_2e$/day in 2024 to 746,819.99 $kgCO_2e$/day by 2045, primarily driven by the growing volume of medium-duty trucks (particularly Vehicle Class 6b), which alone account for over 250,000 $kgCO_2e$/day at the end of the forecast period. This sharp increase reflects the compounding effects of demand growth and the continued reliance on high-emission road freight modes.





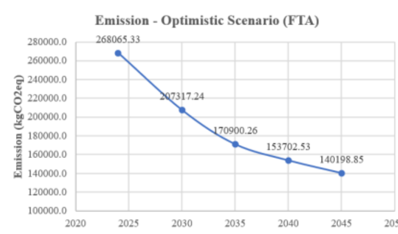


Figure 14. BAU Emission
Source: Simulation of emissions without modal shift interventions, 2024

Figure 15. Pessimistic Scenario Emission
Source: Emissions simulation with limited rail adoption, 2024

Figure 16. Optimistic Scenario Emission
Source: Emissions simulation with intensive rail adoption, 2024

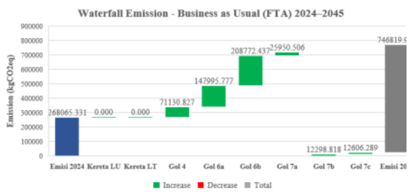


Figure 17. BAU Waterfall Emission

Source: Decomposition of emission contribution per vehicle, 2024

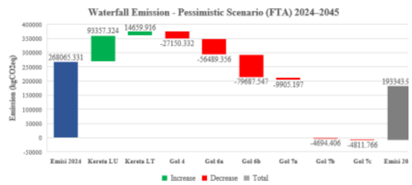


Figure 18. Pessimistic Scenario Waterfall Emission

Source: Decomposition of emission reductions from partial interventions, 2024

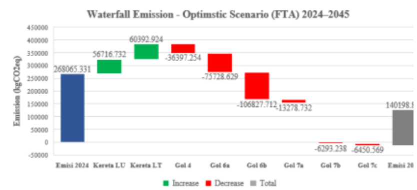


Figure 19. Optimistic Scenario Waterfall Emission

Source: Decomposition of emissions reductions from intensive interventions, 2024

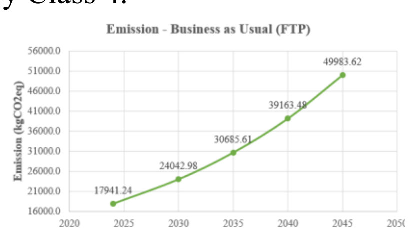
Two modal shift scenarios were simulated to assess the potential for emission reductions. Under the pessimistic scenario, where adoption of rail logistics remains limited, emissions are reduced to 193,343.97 kgCO_2e/day by 2045—representing a 28% decrease from the 2024 baseline. In contrast, the optimistic scenario, which assumes more aggressive integration of rail freight systems, yields a reduction to 140,198.85 kgCO_2e/day, corresponding to a 48% decrease from baseline levels.

These reductions are primarily achieved through modal substitution of freight currently served by Class 6a and 6b trucks, which dominate the inbound rice logistics chain. While emissions from rail freight do increase over time due to higher transported volumes—reaching 56,716.73 kgCO_2e/day (long-distance) and 60,392.92 kgCO_2e/day (medium-distance) by 2045—they remain substantially lower than the emissions they displace, resulting in a net decarbonization benefit.

The results affirm that shifting inbound logistics from road to rail presents a robust strategy for mitigating emissions growth in urban freight corridors. The magnitude of reduction—ranging from 28% to 48% depending on implementation scenario—demonstrates the critical role of rail mode readiness and policy support in achieving long-term emission mitigation targets.

11. Decarbonization Analysis of Freight Trip Production (FTP)

This section analyzes greenhouse gas (GHG) emissions from outbound freight (FTP) from PIBC, assuming continued use of road transport. Emissions are projected to increase from 17,941.24 kgCO_2e/day in 2024 to 49,983.62 kgCO_2e/day by 2045. Although smaller than inbound (FTA) emissions, FTP growth follows a similar trend and remains a significant contributor to overall logistics emissions. The primary sources are trucks in Vehicle Classes 6a and 6b, followed by Class 4.



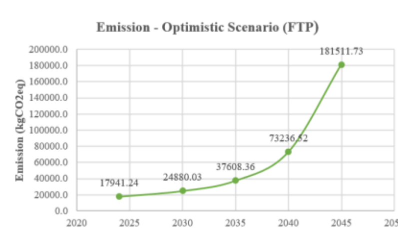


Figure 20. BAU Emission
Source: Projected outbound emissions without intervention, 2024

Figure 21. Pessimistic Scenario Emission
Source: Projected outbound emissions with limited interventions, 2024

Figure 22. Optimistic Scenario Emission
Source: Projected outbound emissions with maximum intervention, 2024

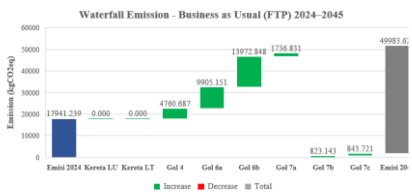


Figure 23. BAU Waterfall Emission
Source: Contribution of outbound emissions per vehicle, 2024

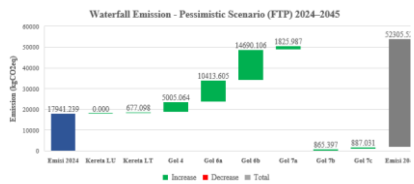


Figure 24. Pessimistic Scenario Waterfall Emission
Source: Partial outbound emission reduction, 2024

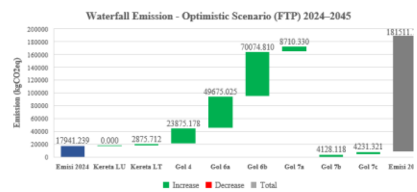


Figure 25. Optimistic Scenario Waterfall Emission
Source: Intensive outbound emission reduction, 2024

Only a limited portion of outbound freight is shifted to rail—mostly to long-distance services (LT)—starting in 2025, contributing about 677.10 $kgCO_2e$/day, which remains constant until 2045. This reduction is modest compared to the increase in truck emissions, particularly from Classes 6a and 6b, which reach 22,513.81 $kgCO_2e$/day each by the end of the projection.

Under a business-as-usual scenario, emissions rise by over 167,000 $kgCO_2e$/year by 2045, equal to a 912% increase from baseline. This spike is primarily driven by growing freight demand that far exceeds the available capacity of rail infrastructure. Even with rail in use, its emission share remains minor—around 733.44 $kgCO_2e$/day—while emissions from trucks dominate, contributing up to 87,030.33 $kgCO_2e$/day at their peak.

These results suggest that, unlike FTA, FTP emissions continue to rise sharply due to high outbound demand and limited modal shift. Emissions increase from 49,984 $kgCO_2e$ (BAU) to 52,306 $kgCO_2e$ (pessimistic, +192%) and 181,512 $kgCO_2e$ (optimistic, +912%).

12. External Cost Analysis: Carbon Tax Valuation

The analysis of external costs is based on the carbon emissions resulting from freight transport activities related to Pasar Induk Beras Cipinang (PIBC), as quantified in previous sections. Using projected emission values under various demand scenarios, this section estimates the potential economic burden imposed by logistics-related GHG emissions in monetary terms (Rp/day).

Table 5. presents the projected external costs across three scenarios—Business as Usual (BAU), Pessimistic, and Optimistic—for both inbound (Freight Trip Attraction/FTA) and outbound (Freight Trip Production/FTP) logistics. The cost estimates increase significantly over time, especially under the BAU scenario, where no major intervention is applied to reduce emission intensity.

Table 5. Externality Cost Reduction

Freight Trip	Scenario	Externality Cost Reduction (Rp)				
		2024	2025-2030	2031-2035	2036-2040	2041-2045
FTA	Pessimistic	Rp -	-Rp 4,860,532	-Rp 12,896,874	-Rp 25,428,942	-Rp 46,258,904
	Optimistic	Rp -	-Rp 6,107,457	-Rp 14,755,906	-Rp 28,254,068	-Rp 50,700,713
FTP	Pessimistic	Rp -	-Rp 124,402	-Rp 280,712	-Rp 361,727	Rp 194,062
	Optimistic	Rp -	Rp 33,652	Rp 355,208	Rp 2,231,316	Rp 10,992,972

Source: Calculation of carbon costs based on Law No. 7/2021 and projected emissions, 2024

These figures underscore the financial implications of environmental degradation associated with road-based freight transport. The externalities include indirect societal costs arising from air quality degradation, global warming, and public health risks—further justifying the urgency of implementing lower-carbon logistics solutions.

Conclusion

This study investigates the environmental and economic impacts of freight transportation to and from *Pasar Induk Beras Cipinang* (*PIBC*), focusing on greenhouse gas (GHG) emissions and the potential for a modal shift to rail. It aims to assess baseline emissions and logistics demand growth, and evaluate decarbonization and externality cost reductions from shifting freight modes. Key findings indicate that logistics activities generate approximately 268 tCO_2e/day from *Freight Trip Attraction* (*FTA*) and 36 tCO_2e/day from *Freight Trip Production* (*FTP*), with major emissions from *Surakarta*, *Tegal*, and *Cirebon* for inbound logistics and *Bandung* for outbound trips, peaking in the evening hours from high-emission truck classes. Projected demand growth is expected to be 5% annually under *Business-as-Usual* (*BAU*) and Pessimistic scenarios, while an Optimistic scenario suggests a 10% growth, leading to total demand of 56 kt/day (FTA) and 28 kt/day (FTP) by 2045, with up to 11.3 kt/day (FTA) and 5.7 kt/day (FTP) potentially shiftable to rail. *FTA* shows significant decarbonization potential, with GHG reductions projected between 28% and 48% compared to 2024, while *FTP* emissions may rise due to increased outbound demand. Daily carbon externalities for *FTA* could drop from Rp26.4 million to Rp16.2 million or Rp11.7 million, while *FTP*-related externalities may increase significantly. Targeted interventions for *FTA*, particularly high-emission vehicles and nighttime operations, offer substantial decarbonization opportunities, supporting the need for mode-shifting policies and carbon cost integration in freight planning to mitigate environmental impacts in Indonesia's logistics sector.

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