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Carbon Footprint and Energy Trade-offs in Global Logistics Network

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Abstract: *The carbon footprint and energy trade-offs of global logistics networks are examined in this study. Emissions were computed based on carbon intensity, distance, and cargo weight using a simulated quantitative dataset of 200 international shipments via air, road, rail, and ocean transportation. According to the average modal data, air freight had the highest carbon intensity at roughly 500 gCO_2/ton-km, followed by rail at 30 gCO_2/ton-km, road transport at 100 gCO_2/ton-km, and sea transport at 20 gCO_2/ton-km. These averages support the idea that slower modes are more energy-efficient while faster modes are often more carbon-intensive. The link between delivery time, transportation cost, and carbon emissions was investigated using a multiple regression model. Transport costs had a significant positive impact on emissions, according to the regression results (coefficient = 0.0004, $p < 0.001$), whereas delivery time had a lesser but still beneficial impact (coefficient = 0.018, $p = 0.003$). The model described 97.5% of the variation in carbon emissions, with an intercept of 1.39 tCO_2 (R2 = 0.975). The study comes to the conclusion that cost, speed, and environmental responsibility must all be balanced for sustainable logistics. It suggests switching to rail and sea as a mode of transportation, pricing carbon, adopting renewable energy, electrification, AI-based routing, and more cooperation between logistics stakeholders.*

Keywords: carbon footprint, energy, trade-offs, global, logistics, network

INTRODUCTION

The need for quick, dependable, and economical logistic services has increased due to the globalization of supply chains. Fossil fuels play a major role in logistics operations, especially in shipping, aircraft, and trucking, which together form the foundation of international trade and significantly increase environmental carbon emissions. According to the International Energy Agency [IEA] (2023), freight transport alone accounts for around 8% of the transportation and logistics sector's nearly 14% contribution to global greenhouse gas emissions. Stakeholders are under increasing pressure to decarbonize their operations and increase energy efficiency in response to both climatic and economic concerns, making their operations more environmentally sustainable. This pressure stems from the sector's negative environmental impact and energy intensity.

Furthermore, energy is essential to logistical operations and activities, and fossil fuels are the most plentiful, reasonably priced, and hence most widely used energy source. However, because of the carbon footprint that results from their use, they have significant disadvantages. The difficulty of controlling carbon emissions in logistics networks has been further brought to light by recent empirical and modeling research. For example, that supply chain emissions originate from both direct and indirect sources across production, transportation, inventory, and procurement systems, necessitating a comprehensive network design approach (Comasň et al., 2015). According to the report, there are important trade-offs between environmental sustainability and supply chain responsiveness, such as quicker delivery via air transportation, since faster delivery frequently results in higher prices and carbon emissions. It also highlights how logistics network layout is significantly impacted by carbon management measures, such as carbon caps, levies, and emission regulations, and how these effects vary based on supply chain structure, demand uncertainty, and product characteristics.

The intrinsic trade-off between economic efficiency and sustainability is further reinforced by the fact that logistics network design choices, such as the choice of transportation mode, warehouse location, and inventory management, have a substantial impact on both operational costs and environmental outcomes (Ferdous, 2025). Businesses must intentionally strike a balance between environmental responsibility and competitiveness since sustainable logistics strategies, such as the adoption of green technologies and energy-efficient systems, assist minimize environmental effect but frequently increase operational costs. Furthermore, optimization-based research has broadened this conversation by including delivery performance as a critical component in logistics decision-making. This demonstrates that when designing carbon-efficient networks, the tri-objective trade-off between carbon emissions, transportation cost, and delivery time must be considered concurrently (Alamsyah & Purevdorj, 2021). The study shows that while adopting alternative fuels and intermodal transportation systems can reduce emissions, these strategies frequently introduce non-linear trade-offs, particularly between emissions reduction and delivery speed, especially for time-sensitive logistics operations.

Adopting green logistics techniques has been empirically demonstrated to enhance supply chain performance in addition to network architecture concerns. Green logistics is said to have a positive impact on key performance indicators like logistics cost reduction, delivery efficiency, customer satisfaction, and environmental compliance through methods like eco-friendly transportation, sustainable packaging, energy-efficient warehousing, and carbon tracking (Parmar & Kushwah, 2025). The study also shows that companies that use green logistics strategies not only lessen their environmental impact but also improve their competitiveness and operational efficiency. However, obstacles like high initial costs and infrastructure constraints still exist, especially in developing nations. Furthermore, more comprehensive environmental evaluations of international logistics networks highlight how urgent it is to incorporate sustainability into supply chain management. Ilango and Sudha (2025), for instance, show that resource consumption, pollution, and greenhouse gas emissions from international logistics operations are major causes of environmental deterioration. According to their research, growing international trade and the need for quick delivery exacerbate these environmental effects, necessitating the use of sustainable solutions like intermodal logistics, electrified transportation, alternative fuels, and policy-driven decarbonization strategies.

Due to its substantial contribution to energy-related carbon emissions, decarbonizing the freight and logistics industry has emerged as a top priority at the international policy level. 10–11% of the world's energy-related CO_2 emissions are attributed to the freight and logistics industry, with freight transportation accounting for almost 88–90% of these emissions (Humphreys & Dumitrescu, 2021). The paper also emphasizes how the fast expansion of freight demand, which is expected to more than double by 2050, presents a significant obstacle to sustainability, especially in developing nations with inadequate infrastructure, legal frameworks, and technological adoption. In order to move the logistics industry toward a net-zero trajectory, it highlights the necessity of comprehensive decarbonization techniques including the Avoid–Shift–Improve framework, low-carbon fuel adoption, increased energy efficiency, and strengthened legislative interventions. The carbon footprint and energy trade-offs in international logistics networks are examined in this study. It specifically looks at how logistics stakeholders strike a balance between sustaining economic competitiveness and minimizing environmental consequences.

LITERATURE REVIEW

Carbon Footprint of Logistics

The "carbon footprint," which is the total amount of CO_2 and other greenhouse gases released into the atmosphere as a result of direct or indirect human activity, is a major concern in the modern world. They increase the average global temperature by trapping heat in the earth's atmosphere (Vinod, 2022). According to Ghosh et al. (2020), it is a significant contributor to global warming. Logistic operations are among the global value chain's biggest contributors to carbon emissions, according to numerous studies. Nearly 90% of emissions connected to logistics are caused by freight transportation and warehousing, according to Mckinnon (2018). Due to its reliance on diesel fuel, road transportation continues to be the most common mode and contributes disproportionately to carbon intensity. According to the Department for Transport (2006), road freight contributes about 6% of all domestic CO_2 emissions in the UK and 22% of all transportation-related CO_2 emissions. According to Piecyk & Mckinnon (2010), climate change and CO_2 emissions are becoming important considerations when making logistical decisions. According to their prediction, the UK's massive 18.6 million tons of CO_2 footprint in 2006 will decrease to 3.8 million tons by 2050 if the road freight industry follows the recommendations of its climate change committee and reduces emissions by 80%. According to Nagurney (2010) and Elkington (1994), logistics companies should not compromise upholding ethical and environmental principles in order to maximize profits.

Furthermore, Vinod (2022) noted that the logistics industry is essential to reducing carbon footprints and mitigating the consequences of climate change. Once more, Li et al. (2025) and Li et al. (2024) noted that road freight still contributes significantly to China's freight system despite the push for a change in the method of freight transit. According to Wu et al. (2017), China's fleet of heavy-duty trucks (HDTs) has grown by roughly 92% in the last ten years. According to the People's Republic of China's Ministry of Ecology and Environment (2023), this has resulted in an increase in fuel consumption and CO_2 emissions.

Researchers report that 77% and 76% of these emissions in the road transportation sector have been attributed to HDTs. More recent research highlights that logistics network design greatly influences carbon emission results, going beyond these conventional viewpoints. According to Comasň et al. (2015), an integrated network-level approach to carbon management is necessary because emissions are produced throughout the procurement, transportation, warehousing, and distribution processes. Ferdous (2025) found that choices like inventory rules, warehouse location, and method of transportation have a direct impact on cost and environmental performance, which reinforces the trade-off between sustainability and economic efficiency.

Global logistics operations have also been found to be significant causes of environmental deterioration, including pollution and overuse of resources, in addition to carbon emissions. According to Ilango and Sudha (2025), growing international trade and the need for quick delivery greatly increase greenhouse gas emissions, air pollution, and environmental deterioration. Humphreys and Dumitrescu (2021) highlighted that the freight and logistics industry accounts for 10–11% of the world's energy-related CO_2 emissions at the global policy level, with freight movement alone responsible for over 90% of these emissions. This emphasizes how urgent it is to decarbonize logistics infrastructure, especially in developing nations where the need for freight is rising quickly. Furthermore, it has been demonstrated that implementing green logistics techniques greatly lowers carbon footprints. Eco-friendly transportation, sustainable packaging, energy-efficient warehousing, and carbon tracking all contribute to lower emissions and better supply chain performance, as Parmar and Kushwah (2025) showed. Their results support the claim that logistics systems can concurrently attain operational efficiency and sustainability.

Energy Trade-offs

There are trade-offs between sustainability and efficiency when it comes to energy use in logistics. Although maritime transportation uses less energy per ton-kilometer than air or road transportation, it is linked to particulate matter and sulfur oxide emissions (Notteboom & Rodriguez, 2020). Although air freight is the fastest, it is not a sustainable alternative for bulk products due to its high carbon intensity. Green supply chain management (GrSCM) is driven by a number of factors, including optimizing profit and minimizing waste as well as reducing energy usage throughout the logistics and supply chain (Jain et al., 2023). Energy consumption is one of the key indicators of relevance for assessing environmental factors in supply chains and logistics.

While Cholette & Venkat (2009) found that supply chain and logistics practices in the wine sector can significantly affect carbon emissions through energy usage, Sundarakain et al. (2010) identify energy as a main driver of green supply chain and logistics. By highlighting the relationship between cost, delivery performance, and environmental impact, recent studies contribute to a deeper understanding of energy trade-offs. Logistics systems must balance a tri-objective trade-off between carbon emissions, transportation cost, and delivery time, as Alamsyah and Purevdorj (2021) showed. According to their findings, lower-emission delivery choices frequently result in longer delivery times and increased operational complexity, whereas faster delivery options, such air freight, considerably increase energy consumption and emissions. Similarly, given the anticipated rise in freight demand, Humphreys and Dumitrescu (2021) pointed out that the logistics industry confronts a significant challenge in shifting from reliance on fossil fuels to low-carbon energy sources. The trade-offs between cost, environmental sustainability, and operational efficiency are made more difficult by the continued reliance on fossil fuels.

Mitigation Strategies

According to research, there are three main ways to reduce emissions from logistics: (i) switching from road to rail or waterway (Cullinane & Bergqvist, 2014); (ii) improving operational efficiency through load consolidation and routing optimization (Janjevic & Ndiaye, 2014); and (iii) technological advancements like electrification, hydrogen fuel, and digital platforms (IEA, 2023). Recent research highlights a more comprehensive and multifaceted strategy to emission reduction, extending these tactics. The Avoid–Shift–Improve (ASI) framework was put forth by Humphreys and Dumitrescu (2021) and includes energy efficiency, enhanced asset utilization, modal shift, demand reduction, and switching to low-carbon fuels as important decarbonization strategies. Green logistics techniques have also become essential mitigation tactics. According to Parmar and Kushwah (2025), eco-friendly transportation, energy-efficient warehousing, and carbon monitoring systems are examples of sustainable logistics techniques that greatly enhance operational and environmental performance. In a similar vein, Ilango and Sudha (2025) highlighted the importance of electrification, multimodal transportation, alternative fuels, and policy interventions in attaining sustainable logistics operations. Another important factor in reducing emissions is technological innovation.

Route optimization, real-time tracking, and better resource use are made possible by digitalization, artificial intelligence, and smart logistics systems, which lower emissions and wasteful fuel use. Adoption of hydrogen fuel, renewable energy sources, and electrified transportation systems is also becoming more widely acknowledged as a long-term way to achieve net-zero logistics systems.

METHODOLOGY

Using a simulated dataset of 200 international logistics shipments spread over four modes of transportation—air, road, rail, and maritime—this study takes a quantitative analytical approach. Important operational factors are captured in the dataset, such as shipping distances between 100 and 5000 km, cargo weights between 1 and 50 tons, and modal characteristics like average delivery speed, average cost per ton-kilometer, and carbon intensity. Each shipment's carbon emissions (CO_2) were calculated using the standard emission model, which is presented as follows:

$$Emission\ (tCO_2) = \frac{carbon\ intensity(gCO_2/t\text{−}km) \times Distance(km) \times Tons}{1000} \qquad (i)$$

A multiple regression model was developed with carbon emissions as the dependent variable and transportation cost (USD) and delivery time (hours) as independent variables in order to investigate the trade-offs between environmental and operational performance. This method makes it possible to evaluate how time-related and cost-effective logistics choices affect carbon footprint results across various modes of transportation.

RESULTS AND DISCUSSION

Modal Comparisons

The simulated results in figure 1 show distinct variations in the operational and environmental performance of transport modes and are in line with previous research. With an average carbon intensity of roughly 500 gCO_2/ton-km, air freight is the most expensive and has the quickest travel time. Road transport comes next, with an average of roughly 100 gCO_2/ton-km. Although it provides accessibility and flexibility, its reliance on fossil fuels makes it comparatively carbon-intensive. Although its use is frequently limited by physical constraints, rail transport has a far lower carbon intensity of about 30 gCO_2/ton-km, making it more energy-efficient and reasonably cost-effective.

With an average of roughly 20 gCO_2/ton-km, maritime transportation is the most carbon-efficient option; nevertheless, it has the slowest delivery times, which makes it less appropriate for shipments that must arrive on time.

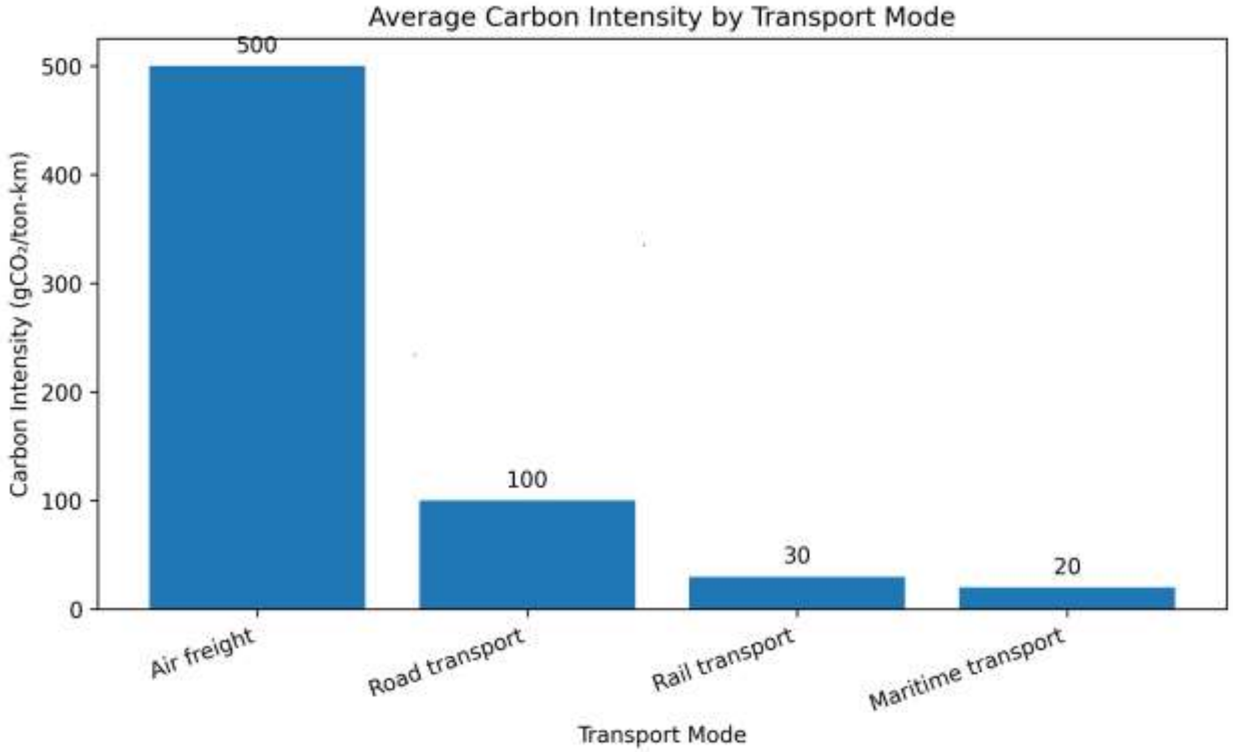

Figure 1. Average Emissions by Transport Mode

Regression Analysis

The logistical performance indicators and carbon emissions have a robust and statistically significant association, according to the regression results as shown in table 1. Transport cost and delivery time together account for 97.5% of the variation in emissions, according to the model's strong coefficient of determination ($R^2 = 0.975$). Transport cost (coef ≈ 0.0004, $p < 0.001$) shows a strong positive and statistically significant relationship with emissions, indicating that more expensive transportation options usually linked to carbon-intensive modes like air freight—contribute significantly to greater emissions. Delivery time (coef = 0.018, $p < 0.003$) also exhibits a positive correlation with emissions, suggesting that longer transit times are linked to a little increase in emissions, perhaps due to the cumulative energy cost of extended logistics operations. Baseline emissions are shown by the intercept (≈ 1.39 tCO_2), which emphasizes that even small shipments produce emissions that cannot be avoided because of handling procedures and underlying energy needs.

Table 1. Regression Results

Variable	Coefficient	Std. Error	t-Statistic	p-Value
Constant	1.39	0.40	3.49	0.001
Cost_USD	0.0004	0.000005	83.0	<0.001
Time_hours	0.018	0.006	3.01	0.003

Model Statistic	**Value**
Dependent Variable	Carbon Emissions
Independent Variables	Transport Cost; Delivery Time
R^2	0.975
Explained Variation	97.5%
Model Interpretation	The model explains a very high proportion of the variation in carbon emissions, indicating a strong association between logistical performance indicators and environmental outcomes.

Interpretation of Trade-offs

The results draw attention to important trade-offs that are present in logistics decision-making. In particular, using quicker modes of transportation like air and road greatly shortens delivery times, but it also dramatically raises operating expenses and carbon emissions. On the other hand, slower modes of transportation, like rail and sea, offer significant reductions in emissions, but at the cost of longer delivery times. Furthermore, even while warehousing automation can increase operational effectiveness and lower some energy losses, it frequently raises electricity demand, which could counteract environmental benefits unless it is backed by renewable energy sources.

Additionally, last-mile electrification offers a workable plan for cutting urban emissions, but putting it into practice necessitates a large infrastructure investment, especially in developing nations.

Policy and Managerial Implications

The study offers the following management and policy suggestions for creating a robust, low-carbon logistics system based on the previously mentioned findings and the identified trade-offs:

1. Through carbon price, fuel efficiency regulations, and investments in low-carbon infrastructure, policymakers should encourage modal transitions to rail and sea.
2. Logistics managers should balance delivery speed, expenses, and carbon footprints by including sustainability measures into performance reviews.
3. To facilitate systemic decarburization, supply chain partnerships must involve carriers, shippers, and regulators in addition to individual businesses.
4. Given the infrastructure limitations in emerging regions, technology adoption (AI-driven routing, electrification, hydrogen fuels) should be scaled strategically.

CONCLUSION

Energy efficiency and carbon reduction must be balanced in global logistics networks. Due to the energy trade-offs present in global supply chains, this study has empirically shown that emissions are strongly correlated with transportation costs and somewhat influenced by delivery periods. There are still trade-offs between cost, speed, and sustainability even while modal transformations, technical innovation, and the incorporation of renewable energy provide potential possibilities. Achieving robust, low-carbon logistics systems would require a systemic strategy that incorporates digital optimization, regulatory incentives, and cooperative planning.

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