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Mitigating Environmental Impacts Through Modal Shifts: A Life Cycle Assessment of India's Freight Transport Infrastructure

Krishna Murthy Inumula[1*], Misbah Hayat[2]

[1] Department of Supply Chain Management, Symbiosis Institute of International Business (SIIB), Symbiosis International (Deemed University) (SIU), Pune 411 057, India
[2] Department of Supply Chain Management, Asian Paints Ltd., Pune 411 057, India

Corresponding Author Email: dr.krishna@siib.ac.in

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ABSTRACT

This research emphasizes analyzing existing transport logistics systems of the state, detecting problems within every mode of transport, and proposing solutions for them to advance towards the sustainable development of multimodal logistics. It also looks into how the nation's logistic infrastructure can be optimized, and challenges associated with shifting from one mode of transport to another within the Indian transport system are considered as such changes are deemed necessary to remedy the structural imbalance. Ex-ante and ex-post evaluations of the funding strategies were carried out as life cycle assessments using OpenLCA. The software and eco-invent database concluded that the new modal infrastructure would be less damaging when utilized than the available one. Building rail shipments' share of the total to 45% would significantly mitigate the adverse effects on the environment that the current structure of the modalities of freight transport. In addition, it was found that, hence why the changes were made, the displacement of transportation brought down global warming impacts by a commendable 9%, as well as the effects of emissions in ecotoxicity in the land, ocean and freshwater by 20% on average. These results highlight the need to boost rail traffic and build railway infrastructure as the most efficient strategy towards positive outcomes. The research admits some data-sourced weaknesses, but it contributes to appreciating the need to put in place an appropriate transport system that is environmentally sound for the country's anticipated development.

1. INTRODUCTION

Multimodal transportation (MML) means the movement of goods between two places using different modes, such as road, rail, air, and water, under the management of one firm known as a Multimodal Transport Operator (MTO). The MTO then issues a single transport document for the entire journey, simplifying the procedures and providing end-to-end solutions. Looking at India's future, MML looks promising because manufacturing centres are inland, away from seaports. Besides, some key production centres are found in Uttar Pradesh, Haryana, Punjab (India), and the National Capital Region (Delhi), which are essential in exportation, while others like Gujarat, Maharashtra, and Tamil Nadu also play their part significantly. In this distribution pattern, there is a potential for both short and long-distance multi-model transport. This means that between 2013 and 2023, India's GDP has grown by a CAGR of 8.3%, with freight transport expected to rise by 9% on average [1]. However, the multimodal logistics industry has faced problems such as inadequate infrastructure and scattered transportation systems involving no common carriers or transshipment centres on roads and railways. Compliance is complicated, given the regulatory demands that differ from one area to another, making it difficult to comply. There are also revenue challenges due to the lack of skilled personnel because their mode can be compared economically and environmentally as far as their cost implications are concerned. In this regard, a modal shift from road to rail freight will be suggested by the study [1] to reduce emissions and enhance infrastructure and load capacity, hence supporting a net-zero-carbon emission campaign by 2070 [1]. These challenges are being addressed by the Gati Shakti National Master Plan and National Logistic Policy developed by the government.

India's logistics industry is set for significant transformation to improve infrastructure, increase efficiency, and reduce costs to enhance global competitiveness. Gati Shakti scheme seeks to eliminate bottlenecks for seamless multimodal connectivity by unifying ministries dealing with infrastructure. The national logistics policy stresses digitization, standardization, and regulatory reforms to streamline operations and reduce time spent during transit and overall transportation costs. Such measures will attract investments into logistics infrastructure and modern tracking technologies, spurring economic growth and easier integration in global value chains. This digitalization is expected to boost exports, creating new jobs to convert India into a $5 trillion economy.

This paper provides a critical examination of India's current logistics network. It makes recommendations for improvement through policy frameworks that align with those other developing countries use. India's transport sector is grappling with mobility issues that require swift solutions using green modes—those that support sustainability while making economic sense. This chapter identifies various challenges that bedevil India's transportation sector and proffers remedies for them. Moreover, it assesses modal shift impacts on transport policy and the environment through a case study.

2. LITERATURE REVIEW

The Indian economy has been one of the fastest-growing economies over the past decade, with a fragmented and unorganized logistics industry contributing about 5% to its Gross Domestic Product (GDP); it is therefore imperative that a solid multimodal logistics infrastructure should be available for any nation wanting to grow its economy [2]. Up to this point, many companies within such sectors seem uninterested in digital transformation, judging from their usual reluctance in such investments; however, some businesses have embraced this approach and are now leading the pack in terms of competitiveness [3]. One of the significant areas of focus regarding enhancing efficiency within logistics is multimodal logistics (MML), which also helps reduce operational costs, increasing efficiency while making them more competitive [4]. The demand for freight transportation comes from geographically dispersed producers and customers. So, due to global trade, conventional road transport is no longer always feasible, and consequently, alternative modes of transportation must be used [5]. According to the NITI Aayog report [6], 70% of India's freight logistics was handled by road, 18% by rail, 6% by water, and 6% by pipeline. Many industries have changed their operational methods after the pandemic in 2020, primarily based on cost reduction factors and improving performance by combining lean with agile approaches [7].

The transportation of goods industry has encountered several hindrances. As globalization takes place, it creates a lot more markets to be served while making them reach worldwide customers". Research looking at how different countries handle these new markets has shown that it is essential for governments to get involved in developing sophisticated and effective logistics parks, as is the case in Germany and China". Other studies examining the same issue have come up with similar findings, supporting the significance of government aid in logistics park development [8]. Moreover, an Italian case study focusing on intermodal growth found that port authorities playing a collaborative role with government backing and building partnerships were instrumental in policy prescription and infrastructure provision [9]. Researchers argue that cooperation among transportation authorities, including roads, railways, harbours and air transport, must be there if any headway is made in this sector. In 2022, India introduced the New Logistics Policy (NLP), which aims to establish a competitive logistics infrastructure to facilitate international trade [10]. The central theme of our paper is the development of government initiatives across different transport modes and sectors.

India has a bright future regarding multimodal logistics. The country is positioned in such a way that it will serve as the global hub for many commodities. Consequently, some long outstanding issues should be addressed for the industry to grow strategically. They include eliminating entry state taxes, improving infrastructure, developing new storage units and simplifying cumbersome formalities [11]. Additionally, to spur economic growth and ensure sustainable development, the Prime Minister's Gati Shakti (PMGS) scheme has shifted its focus towards capital expenditure on modern public goods [12]. Through the 'Gati-shakti' program, the government plans to invest over one hundred lakh crores (INR 100 lakh crore) in infrastructure in the next five years [13]. Compared to developed countries, where this is between 7 and 8%, India stands at 14-15% here, making investment costly due to higher logistics costs of 4.3 per cent of GDP (USD 45 billion annually) [14]. Therefore, Gati Shakti becomes an interactive platform where sixteen ministries, including the Ministry of Railways and the Ministry of Roads, can plan and implement various programmes to improve infrastructure connectivity [15]. This will reduce last-mile infrastructure connectivity and decrease transport time.

The government is hurrying to increase logistics and infrastructure networks. It wants to involve the private sector to expand PPP to realize its goals despite its constraints [16]. One of the Research projects recently focused on setting up four interconnected multi-modal logistics parks (MMLPs) within BBIN, encompassing Bangladesh, Bhutan, India and Nepal. The study explored how water transport could enhance trade among these countries. These centres will be located in strategic areas identified by the researchers [17]. Various economic opportunities are expected by integrating inland waterways into multimodal supply chains [18, 19]. For instance, the World Bank has set aside $375 million towards improving the Ganges River to promote this program. The National Waterway 1 Project has proposed an initiative that would help develop the necessary infrastructure and services to make NW1 a remarkably efficient transportation corridor within this economically significant zone [20].

There is now equal importance attributed to environmental issues as it was before to the economy in the country's program. Policies shall be implemented, encouraging techniques that promote greenness within companies through measures to stimulate economic growth and innovation [21]. Businesses must recoup the costs by implementing efficient transportation options for transporting goods. Some things that can help achieve this include using multimodal freight transport that combines different modes of transport, thereby reducing emissions levels as much as possible while making full use of the available transport infrastructure [22, 23]. The other study considered the multimodal technique as the cheapest and most time-saving way to do so, and it has less harm to the surroundings in which we live so long as it exists. The law-abiding entrepreneurs in this industry are those service providers who still use greenhouse gas fuels and do not comply with the Kyoto Protocol. However, the transportation sector underwent a 375% increase from the industry's 1990 levels up until 2019 [24].

Flexible service can be activated and deactivated quickly by highly effective combined fleets, leading to optimal usage of vehicles; for example, trams with various compartments can integrate incoming and outgoing demands, thereby minimizing wastage through underutilized spaces. The increase in globalization has resulted in a need for multiple logistics services such as air, sea or land transport due to the demand for speedy product delivery, just-in-time manufacturing, and supply chain integration, among other factors. E-commerce and on-demand delivery have revolutionized the market in the last decade [25]. Multimodal transportation cuts across different forms of transport but has specific patterns that include using two or more modes, which are more efficient in their methodology. It is an advantage because they combine the best qualities of all these modes. From Traditional standalone to sophisticated modernized systems: It is possible that the logistics sector has undergone this transition recently, particularly regarding inventory management, stocks, and transportation. It is also worth noting that for specific sectors to transition from traditional to multimodal logistics systems, the existence and proper functioning of such facilities as multimodal logistic parks are required [26].

Based on the evidence available, many studies emphasize isolated sectors of transport. Despite this emphasis, they fail to provide an overarching view of India's transport system. Several studies concentrate on multimodal hubs but ignore problems faced by the whole transport system that are connected to these hubs [27]. Furthermore, there is limited discussion on future strategies. Even though several studies talk about government projects, there is no detail about these programs' specific issues. The mode change is often mentioned as a policy, yet previous studies do not exhaustively analyze its environmental impacts.

The current literature review on India's transportation system is dualistic, with the permissive emphasis on particular modes, such as roads or rails, to the neglect of the overall multimodal perspective. The main objective is to study the concept of logistics hubs without analyzing systemic inefficiencies that transcend all modes of transportation [28]. There is also a categorical discussion of modal shift policies but no "macro" impact assessment of the environment. Furthermore, although Gati Shakti and the National Logistics Policy have been discussed in the literature as directions prescribed by governments, most research has had their vision-myopic targeting of goals, overlooking possible challenges or practical bottlenecks [29, 30].

The study has filled this gap by examining India's freight transport infrastructure, where policy analysis works with comprehensive LCAs and, in practical terms, offers full-fledged multimodal logistics recommendations. Unlike most studies, this one addresses environmental assessments for shifting from road to rail with a critical conclusion that such a transition benefits the environment to the extent of a 9% reduction in global warming and up to a complete 20% in ecotoxicity. In addition to aligning policy evaluation with the sustainability metrics, the present study demonstrates viable improvements to the Indian Logistics network.

3. DATA AND METHODS

Given its rapidly growing economy and status as the most populous nation, India must now address the severe challenges of supply chain management by developing new ideas. Due to poor infrastructure, multiple modes of transport have not properly developed in India's freight transport field. In this study, we propose methods of integrating different means of transport for efficient working (Figure 1), increasing productivity, and promoting sustainable development, which can, in turn, spur upward economic growth.

The study acknowledges that secondary data sources, such as government reports, industry publications, and existing literature, may contain biases owing to outdated information, non-uniform reporting, or particular organizational views. For instance, government data might emphasize policy successes while downplaying challenges, and corporate reports may highlight favourable outcomes while omitting inefficiencies. To mitigate these biases, the research follows a structured approach: (1) Cross-verification of multiple sources to identify discrepancies and ensure data reliability; (2) Use of internationally recognized databases like Ecoinvent or OpenLCA for environmental impact assessment ensuring standardized methodologies; (3) Adoption of LCA methodologies [31], which require the inclusion of divergent data sets into an overall balanced view of environmental impacts; and (4) Use of case studies from other countries such as Germany for comparison against global best practices. By bringing together different perspectives, using validated data models, and employing standardized impact assessment techniques, this study eventually offers a relatively objective and comprehensive attempt to examine India's freight transportation system.

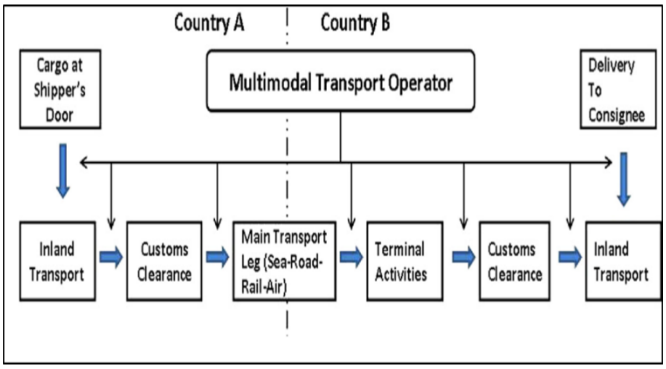

Figure 1. Movement of goods in a typical international multimodal transport chain

Transportation accounts for about 8% of global greenhouse gas emissions [32]. The study extends the existing body of knowledge by focusing on freight-related issues that affect Indian transport infrastructure and discussing recommendations covering different types of freight carriers. It emphasizes the need for a well-balanced approach to transport infrastructure and policy geared towards increasing the share of rail freight. In addition, it incorporates a case study and software-enabled Life Cycle Assessment (LCA) to pinpoint how changing transportation modelling affects the environment. Moreover, the long-term ecological consequences of shifting transport modes can be understood by applying dynamic LCA models, which allow for the progression of future technological and production processes. A comprehensive understanding of immediate and life cycle environmental impacts could be achieved when EIA results are used together with LCA results, though not solely. This type of program offers features like environmental load calculation, impact assessment, and sensitivity analysis using other software such as EMLCA or Open LCA. This study should also focus on different aspects, such as global warming potential, acidification, and human health effects, to address numerous impacts simultaneously. These LCA methodologies and tools will help determine all environmental damages caused by modal shifts in transport.

The methodology for the research's crucial findings is as mentioned:

1) Literature Review: 30 relevant industry reports, academic studies and existing literature on multi-modal logistics internationally and within India were reviewed comprehensively for this purpose.

2) Alternatively, LC methodology may be used: it consists of four phases, which include goal definition and scope determination before proceeding to inventory analysis during the second stage, followed by evaluation in the third phase, and ending with interpretation. All these are meant to show how products or services affect the environment throughout their lifecycle process; one has first to identify system boundaries that incorporate all significant raw materials used besides energy consumed in the production process; in addition to this, there must also be the inclusion of loss materials as well as the final product. During the assessment phase, materials are attributed according to their environmental behaviour, and a summary impact analysis is done eventually before drawing conclusions and finding results. This entails four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. The first stage requires the researchers to define system boundaries that include all relevant raw materials, energy consumption in the production process, and waste in the air and the final product. In the second phase, materials are allocated based on their ecological implications, after which summarized effects are analyzed and evaluated to make conclusions and draw results.

Process Workflow for Life Cycle Assessment (LCA):

1. **Goal & Scope Definition**
- Define Objectives → Set System Boundaries → Select Functional Units.

2. **Life Cycle Inventory (LCI) Analysis**
- Data Collection (Fuel, Emissions, Infrastructure) → Identify Transport Modes (Road, Rail, Water) → Use EcoInvent Database.

3. **Life Cycle Impact Assessment (LCIA)**
- Apply Recipe 2016 Method → Assess 18 Environmental Categories → Use OpenLCA Software.

4. **Interpretation & Decision Making**
- Compare Scenarios (Before & After Shift) → Identify Key Impacts (CO2, Ecotoxicity, Energy) → Recommend Sustainable Policy Changes.

3.1 Parameters and assumptions under freight transport analysis (Scenarios under Open LCA)

To carry out the LCA study using Open LCA software through the Ecoinvent3.2 database, the outcome was an assessment of the environmental impacts of modal ship transitions in the period-specific to India's freight transport system. The analysis focused on transport modes, i.e., mainly roads, rails, and inland water-shipping. The modulation is primarily to ramp up rail freight to 45% of the total cargo handling quantity. The methodology followed was ISO 14040 and 14044; the methodology utilized ReCiPe 2016 as the midpoint (H) method to appraise 18 impacting environmental categories.

3.1.1 Key parameters and assumptions

1) Transport modes considered:

- Road Freight: Assumed EURO5-equivalent to BS VI emissions standard.
- Rail Freight: Global average emissions for freight trains (GLO dataset).
- Inland Waterways: GLO dataset used for barges and inland vessels.

2) Equivalence of BS VI to EURO5:

BS VI standards in India are in alignment with EURO6 in the case of light-duty vehicles; however, for heavy-duty diesel vehicles, it more closely matches EURO5 in terms of PM and NOx emissions.

The study applied EURO5 assumptions to estimate the emissions from freight trucks as India's BS-VI regulations are specific in their challenges for fleet transitions and fuel demands more or less in line with EURO5.

3) Scenarios modelled:

- Before Modal Shift: 66% road, 31% rail, 3% inland waterways.
- After Modal Shift: Targetive: 45% rail freight, Obstruction: reduced dependency on road transport.

4) Impact categories assessed:

- Global Warming Potential (GWP);
- Ecotoxicity: terrestrial, freshwater, marine;
- Ozone Formation & Eutrophication;
- Human Health & Non-carcinogenic Toxicity.

3.1.2 Findings

Raising the proportion of rail freight to 45% results in a 9% decrease in global warming impacts and a possible 20% reduction in the average ecotoxicity. Shifting to rail-based freight is an environmentally superior move as it saves fuel, lowers CO_2 emissions, and effectively uses infrastructure.

Justification for Equating BS-VI with EURO5 in Open LCA Analysis

Comparison of BS VI and EURO Emission Standards for Heavy-Duty Vehicles.

BS VI stipulations, being in force from 1 April 2020 in India, substantially derive from the EURO6 regulations for light diesel vehicles. However, BS VI regulations for heavy-duty diesel vehicles (HDVs) are closest to those of EURO5.

Table 1. Emission limits comparison (g/kWh)

Pollutant	BS VI (India)	EURO5 (EU, 2008)	EURO6 (EU, 2014)
NOx (Nitrogen Oxides)	2	2	0.4
PM (Particulate Matter)	0.02	0.02	0.01
HC (Hydrocarbons)	0.46	0.46	0.13
CO (Carbon Monoxide)	1.5	1.5	1.5

3.1.3 Key observation

NOx and PM limit values are the same for BS VI and EURO5 standards, confirming that EURO5 standards (Table 1) are a reliable data source for LCA. EURO6 allows shorter NOx limits (0.4 g/kWh), yet India is still not cooperating with such measures for FREVs.

3.1.4 Fuel quality and real-world implementation constraints

1) Sulfur Content in Diesel:

BS VI has mandated ultra-low sulfur diesel (10 ppm) just like EURO6 for a long.

Compliance for the entire fleet of trucks in India have been relatively slow to the extent of ageing vehicles and poor maintenance, starkly reminiscent of similar market trends for EURO5 in Europe.

2) Vehicle Technology Adoption:

BS VI introduced Selective Catalytic Reduction (SCR) and Diesel Particulate Filters (DPF), similar to EURO5.

Meanwhile, EURO6 has advanced online real-time emissions monitoring with AdBlue injection systems, which have not been wholly mandated for India's freight transportation industry.

3) Fleet Transition Challenges:

A large percentage of Indian freight trucks will be around BS IV or older by 2023, closely aligning Indian freight truck emissions performance with the EURO5-no longer EURO6.

EURO6 standards also require more sophisticated onboard diagnostics (OBD-II) and real-time emission monitoring, which had not yet been implemented for India's commercial vehicles to their full extent.

3.1.5 Applicability to OpenLCA freight transport modeling

1) Why EURO5?

EURO5 truck emissions were used in the study because they best represent India's heavy-duty fleet's operational average emissions profile after implementing BS VI rules.

EURO6, as claimed, shall lead to emissions substantially underestimated, and the LCA results may be based on an awkwardly upbeat expectation.

2) Implication of the Modal Shift Scenarios

Using EURO5-like emissions, the study's global warming impact reduction of 9% and the ecotoxicity-20% decrease is better reflected since they consider gradual improvements than the ideal later-day scenarios.

The decision to equate BS-VI with EURO5:

a. ABS and PM limits do not differ for heavy-duty vehicles.

b. Fuel quality and vehicle technology constraints in India.

c. Time-restricted transition trends, reminiscent somewhat of Europe's cutoff of EURO5.

d. More realistic emissions modelling in OpenLCA, excluding overly optimistic projections using EURO6.

Case studies: A German study on the environmental impacts of higher-capacity vehicles (HCVs) compared to normal trucks will be utilized as a case study to understand how much modal shift might affect ecology within India. It also seeks to establish whether an increased percentage of rail freight can impact the entire cargo transport segment. The study has been structured in such a way that every chapter addresses specific research questions concerning the life cycle assessment of HCVs, their influence on public road infrastructure, the environmental issues associated with GHG emissions from freight transportation, and the implications of increasing volume of market for freight transport.

3.2 Justification for selecting the German HCV study as a comparative framework

Due to a comprehensive analysis of modal shift, ecological impact, and infrastructure utility, the study of Germany's HCV can be a reference point for India's transport system. German transportation is touted as a model for multimodal logistics, with extremely well-connected linear infrastructure systems and the ultimate operating philosophy, which India can consider in its move to modernize transport. The study's methodology is based on lifecycle assessment (LCA) of consequences on ecology and infrastructure from transferring freight from road to rail. This goes hand in glove with the transition on the Indian side to increase the share of rail freight from 31 to 45 per cent to clean up emissions and logistics efficiencies.

Similarities and Differences Between German and Indian Transport Systems

1) Maturity of Infrastructure

• Germany has a highly integrated transport system with well-maintained roads, uniformly efficient rail traction networks, and multimodal logistics infrastructure.

• India suffers from an issue of significant infrastructure gaps, enforced by the heavy, overreliant road transport sector (66 percent of all freight movement), limited rail shadow networks (31 percent), and infant inland waterways (3 percent).

2) Modal Share and Environmental Concerns

• Germany has optimised its rail movement sector significantly, which can be seen by its modal share structures that are far more advanced vis-a-vis India's efforts, among others, to reduce emissions either by regulatory actions or intensified investments in infrastructure.

• India: The development of this concept is highly miscible since the most significant share of freight sent by rail is sent by diesel trucks that emit a great deal of carbon dioxide.

3) Regulatory Framework

• Germany: Lays down well-string emission standards and promotes high-capacity vehicles (HCVs) for better use of transportation systems, and has port HUB lines.

• India: Though India is witnessing legions of regulations varying from state to state, thereby complicating multimodal logistics, recent narratives backed by policy regimes such as the Gati Shakti and the National Logistics Policy are all used to streamline the transport framework.

With the help of the research conducted by the German study, India will manage and improve its transport belief in fostering modal shift, and following suit from herein, India will actively promote sustainability and mechanisms for governance.

4. ANALYSIS AND FINDINGS

To aid in addressing the research questions, we have gathered secondary data from a range of sources, including government websites and reputable non-governmental websites, explicitly focusing on these three sections:

• Current logistics infrastructure of India;

• Essential logistics infrastructure strategy for India's future;

• Shifting towards balanced infrastructure.

4.1 Current logistics infrastructure of India

1) Road: The data is from the Ministry of Road Transport and Highways, and it shows that the total road length (Figure 2) in India has increased from 4,676,838 km in 2011 to 63 73,000 km in 2022. This is an increase of over 36.26%.

2) Railway: By the fiscal year 2022, India had more than 68,000 kilometres (Figure 3) of railway tracks. India has one of the most significant railway systems globally. Every day,

Indian Railways operates more than 12,000 passenger trains and over 7,000 freight trains.

3) Water: In the financial year 2022, India possessed a cumulative count of 229 ports. After a dormant period of five years, there was an increase in port numbers in 2019 (Figure 4), marked by the inclusion of five additional non-major ports. As of 2022, this distribution included 12 major and 217 non-major ports nationwide.

4) Air: The number of national operational airports (Figure 5) has increased twice, from 74 in 2014 to 148 in 2023. This expansion results from the government's continuous endeavours to enhance airport and aviation infrastructure.

5) Support Infrastructure: In FY 2022, India has 129 Inland container depots (ICD), 168 container freight stations (CFS), one multi-modal logistics park under construction, and about 300 million sq ft of warehouse space to support the logistics network, as shown in Table 2.

Table 2. India's support infrastructure in 2022

ICD	CFS	Multi-Modal Logistics Park	Warehouse Space
129	168	1	300 million sq ft

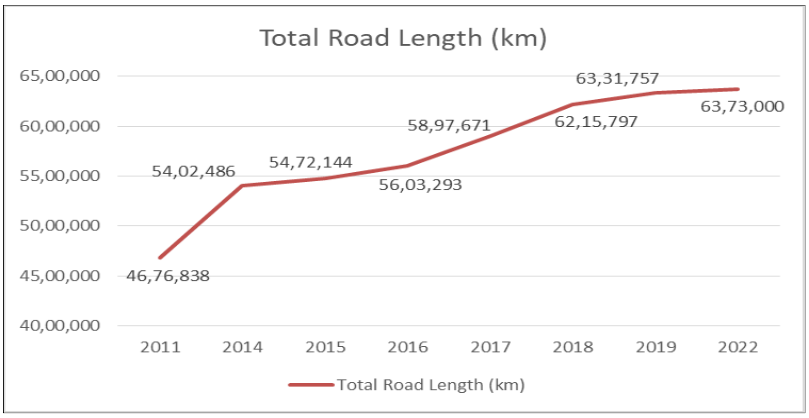

Figure 2. Total road length in India from the financial year 2011 to 2022 (in kilometers)

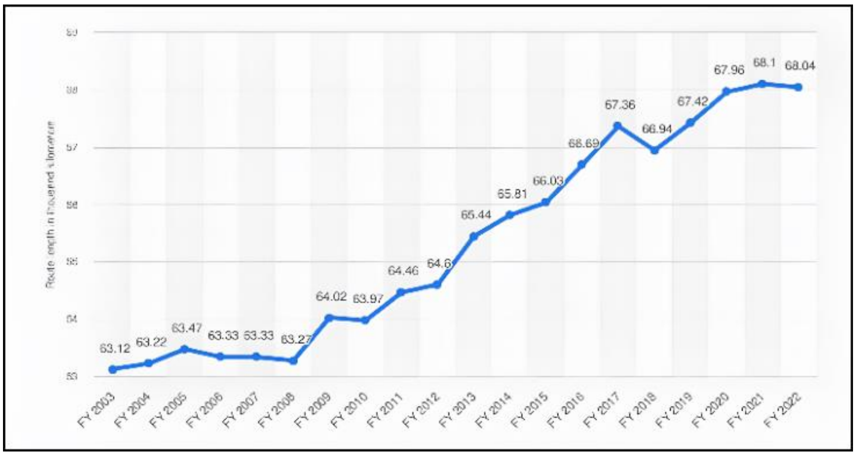

Figure 3. Total route length of railways across India from 2003 to 2022 (in 1,000 kilometres)

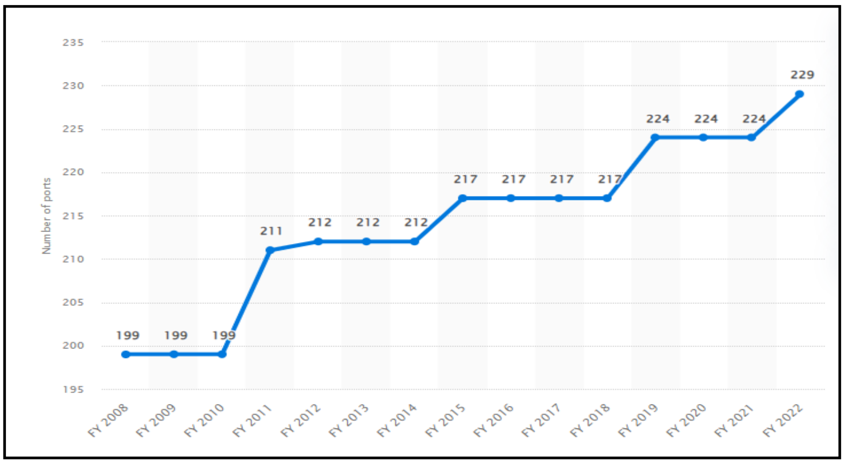

Figure 4. Total number of ports in India from 2008 to 2022

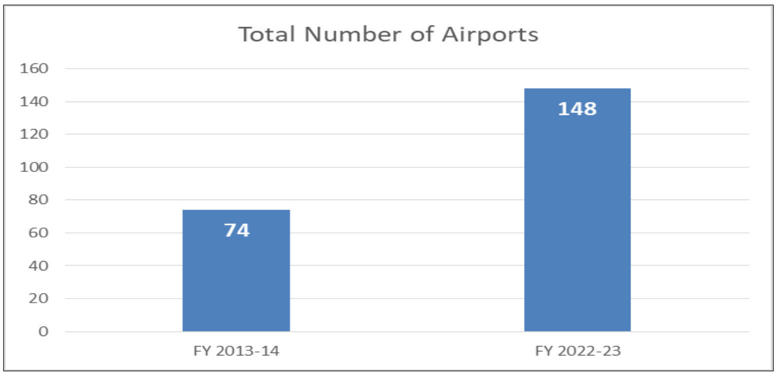

Figure 5. Total number of airports in India

4.2 Shifting towards balanced infrastructure

Referring to the provided chart, roads emerge as the predominant mode of freight transport in India, representing 66% of the total, trailed by railways at 31%, water at 3%, and air at the lowest, 1%. To achieve a more balanced infrastructure, systematic and efficient development of logistics infrastructure necessitates a substantial shift along four crucial dimensions: directing flows through the appropriate mode, constructing facilitative elements, enhancing asset efficiency, and reallocating investments. The proposed change is presented in Figure 6.

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Given the emerging status of water and air modes, freight movement by rail is the sole practical alternative to road transport in the short term. Consequently, elevating the share of railways from 31% to 45% of the total freight traffic signifies a crucial and balanced shift in the logistics infrastructure.

4.3 Projection of growth for rail freight

In alignment with the NITI Aayog's goal of achieving a 45% mode share for rail freight in the total freight movement by 2050, we have analysed the present growth (Figure 7) in rail freight and projected future growth trends to meet the target specified by NITI Aayog [1].

The provided graph reveals a substantial disparity between road and rail freight movement. Additionally, the Compound Annual Growth Rate (CAGR) for road freight surpasses rail freight at 7% and 5%, respectively.

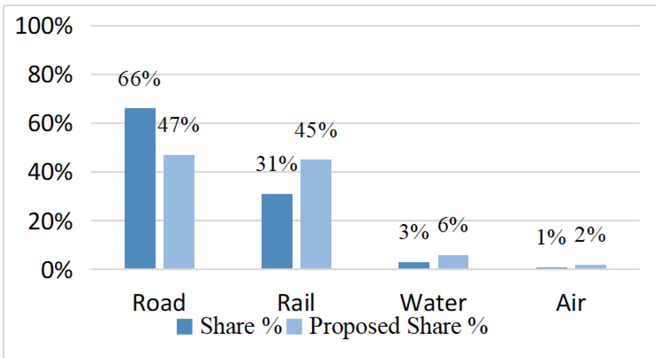

Figure 6. Modal distribution of freight movement in India for the year 2022

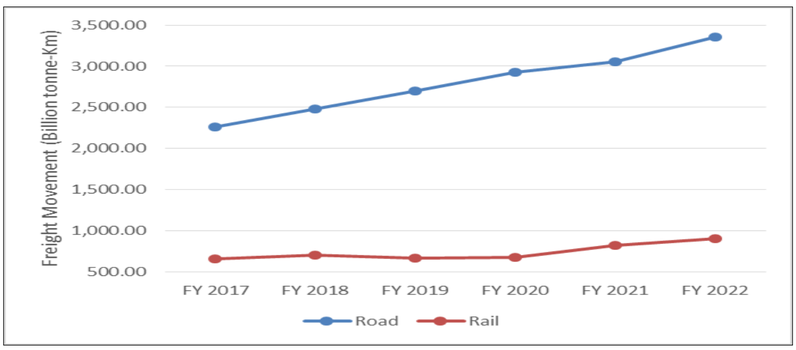

Figure 7. Current trend of freight movement in India

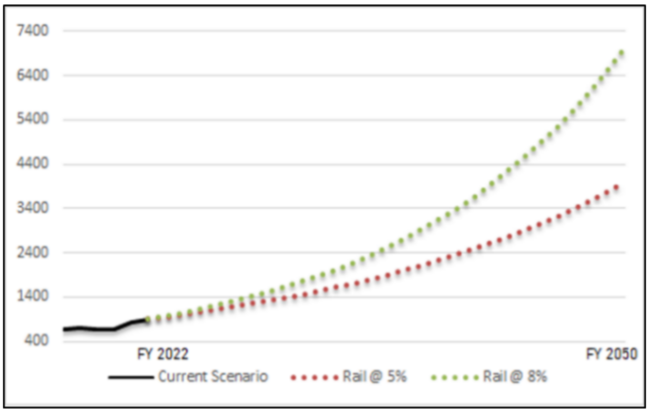

Figure 8. Growth of rail freight over the years from FY 2022 to FY 2050

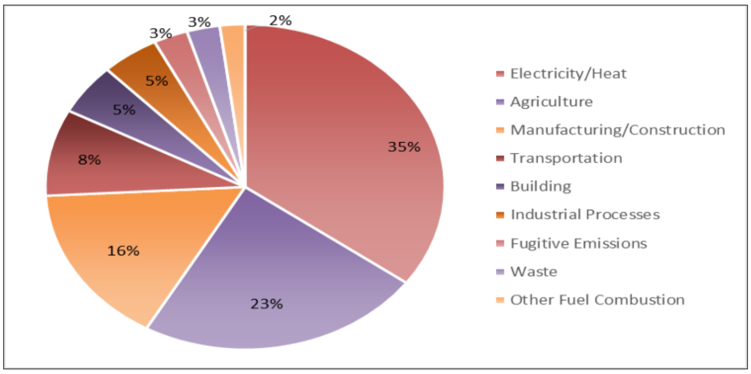

Figure 9. Greenhouse gas emissions in India across different sectors in 2020

Considering the projections from the graph (Figure 8), the growth trajectory of rail freight unfolds with two distinct scenarios. The first projection maintains the current growth rate of 5%, while the second envisions a growth rate of 8%. The latter aims to elevate rail freight's share to 45%, aligning with the anticipated expansion of the country's economy. Consequently, the volume of goods moved is anticipated to reach 15.6 trillion tonne-km by 2050.

4.4 Trade-offs in rail expansion: Economic costs vs. environmental benefits

Expanding rail infrastructure in India shows a drastic trade-off between short-term economic costs and long-term environmental benefits. By transitioning freight transportation from road to rail with a target of 45% rail, the global warming index would be reduced by 9%, and ecotoxicity would be lessened over land, fresh water, and marine environments by an average of 20%. This transformation strides India toward net zero carbon emissions by 2070. Conversely, the cost incurred to expand the rail system is very substantial because the government's take, thus Gati Shakti National Master Plan, requires a significant capital expenditure of over $100 Lakh crore for infrastructure development. High carriage costs, including investment in the Dedicated Freight Corridors (DFC), will, therefore, hold up this project and pressure both public authorities and companies. Furthermore, the rail system is believed to be more energy-efficient than highways by ton-kilometre, thereby reducing greenhouse gas emissions (Figure 9). The application of digital tracking and logistics parks is also seen as adding an extra edge for long-term efficiency and cost-effectiveness. However, the viability of economic assessments depends on the pockets of those companies that might benefit from it, an encouraging regulatory milieu, and private sector involvement to carry out the project. This study reveals that, though the construction cost for the railway may be very high, the sustainability, environmental, and logistical implications tip the scales in favour of the departments involved.

4.5 Environmental impact analysis of modal shifts in India's freight transport

The present study focuses on the environmental implications of a switch from road to rail for freight transport in India through LCA methodology. The findings show meaningful reductions in GWPs up to 9% and ecotoxicity (across, but not restricted to, terrestrial, marine, and freshwater media) up to 20% for a projected transport spearing of 45%. However, a few categories, such as freshwater eutrophication, ozone formation on terrestrial ecosystems, human health, and human non-carcinogenic toxicity, still showed slight improvement. This might explain why the ability to undertake this shift is entirely bounded by fossil fuels or the challenges on the rail side in terms of inefficiencies and fuel mix regarding railyard operations. Indeed, Indian rail transport still relies significantly on diesel locomotives for its traction, whereas electrification is considered to have different statuses across regions in India. The environmental dividends for converting to rail will result from a rocket, so to speak, of the modal share with increasing cleaner and alternative energy into the rails. For instance, a shift to rail may not be meaningful regarding reduced carbon emissions when freight marginally shifts to steel-dependent electricity (brown power). Likewise, construction works have reduced the long-term environmental burdens of the rail freight infrastructure. Such challenges will form part of an integrated approach that envisions decarbonising rail energy sources, increasing the efficiency of multimodal logistics parks, and growth in infrastructure tailored based on a circular economy. Future research could focus on the effects of energy and electricity mixes utilised in a section of the globe on management projects.

4.6 Sensitivity analysis of modal shift in Indian freight transport infrastructure

1) The sensitivity analysis studies the effect of variations in the selected key assumptions on the model output of the study where LCA modelling and Open LCA were applied. Therefore, the possible robustness evaluation of the environmentally related reduction is the target for analysis under various assumptions.

2) Principal assumptions and variables

The principal assumptions include:

• Increase in rail freight share from 31 to 45%.

• Reduction in road freight proportion leading to lower emissions.

• Life Cycle Emissions Data from the Ecoinvent 3.2 database.

• Economic growth projections aligning with NITI Aayog's logistics targets.

3) Sensitivity scenarios

a. Scenario 1: Variation in rate of increase in rail freight

• Low-Growth Case: Rail freight increases to only 38% instead of 45%.

• High-Growth Case: Rail freight increases to 50% in 2050.

• Impact: The low-growth case resulted in a global warming potential reduction of only 6%; the high-growth scenario also intensified the reductions to beyond 10%.

b. Scenario 2: Change in Emission Factors

• Baseline: Emission factors remain unchanged.

• Optimistic: Rail technology advances reduce emissions by 15%.

• Pessimistic: Delays in infrastructure lead to a slower promotion of low-emission rail, reducing overall benefits by 5%.

c. Scenario 3: Road freight efficiency improvements

• Assumption: Fuel efficiency and electric truck adoption reduce road freight emissions by 10%.

• Impact: Impact from the modal shift reduces slightly, with an 8% reduction in global warming potential instead of 9%.

4) Findings and robustness of results

In all scenarios, one uniformly performs exceptionally well in the environmental outcomes-positive modal shifts from road to railways. The conclusions varied amplitude-wise but essentially hold good:

• It is touted that expanding rail freight leads to significant emissions reduction.

• When investment in rail infrastructure occurs, the magnitude of benefits is contingent on that timing.

• The road freight efficiency improvements largely dampen the benefits contemplated.

Conclusions: The analysis favours the effectiveness of modal shifts to reduce environmental consequences. However, considerable variation concerning the extent of benefits is merely due to external factors like technology and the implementation of infrastructure.

5. CASE STUDY: TRANSPORT POLICY

5.1 Background

In India, the transportation sector is one of the significant contributors to greenhouse gas emissions, with around 270 million tonnes of CO_2 equivalents emitted in 2020 [28]. Road freight transportation is responsible for a larger share of emissions due to the extensive use of diesel oil as a fossil fuel, due to its cheaper rate. As of 2022, road transport of goods carried more than 66% of metric-ton kilometres of freight in India, followed by rail transport at 31% and waterway transport at 3%, and the rest is air. As per the modal shift by 2050, the target is to increase the percentage of rail freight and reach 45% of metric-ton kilometres of cargo in the country. With the adoption of a balanced infrastructure, there will be significant improvement in energy efficiency as well as in GHG emissions.

5.2 The LCA methodology

As described in international standards ISO 14040 and 14044, the life cycle assessment is a standardised method to assess comprehensively the potential environmental impact. For this study, Open LCA version 2.0.3 software is being used. This helps provide in-depth insights into assessment results, enabling the identification of critical drivers across the life cycle. Integrated life cycle costing and social assessment ensure comprehensive analysis. Eco Invent 3.2 databases used for this analysis are globally recognised resources commonly used for LCA studies [31].

5.3 Goal and scope

To compare the impact of modal shifts in the Indian Transportation System on the environment regarding air, soil, and water emissions. This assessment aims to analyse two scenarios and compare the final results on whether the increase in rail freight transportation has a positive or negative impact on the environment.

5.4 Data and life cycle inventory analysis in open LCA

The input data includes the following components:

• Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Cut-off (Assuming EURO5 equivalent to BS VI to apply in India market context, also lorry 16-32 metric ton has a more significant share in road freight transportation [29], so consider it as a component for representing the road freight transportation.)

• Transport, freight train {GLO}| market group for | Cut-off

• Transport, freight, inland waterways, barge {GLO}| market for | Cut-off

GLO - Global standard is considered an Indian standard to calculate the impact of train freight, inland waterways, and air freight on the environment [29].

5.5 Impact assessment method

Under the Recipe 2016 Midpoint (H) LCIA method, 18 impact categories are broadly classified under ecosystem, human health, and resources.

5.6 System modelling

For this study, a system boundary has been drawn (Figure 10) to examine all upstream resources considered to study the impact.

5.7 Inventory analysis

To investigate the impact caused before and after the modal shift on the environment, this analysis of input and output (Figure 11 and Figure 12) is carried out as shown below in the model graph.

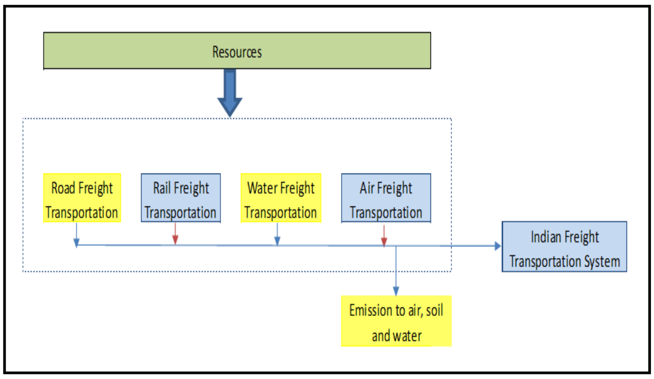

Figure 10. System boundary of the Indian goods transportation system

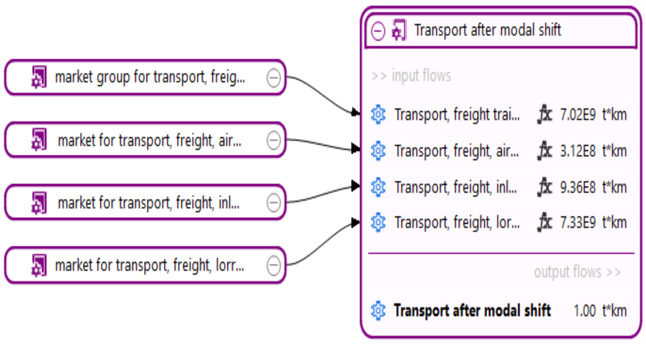

Figure 11. Model graph depicting the input-output data for India's goods transport system before a modal shift

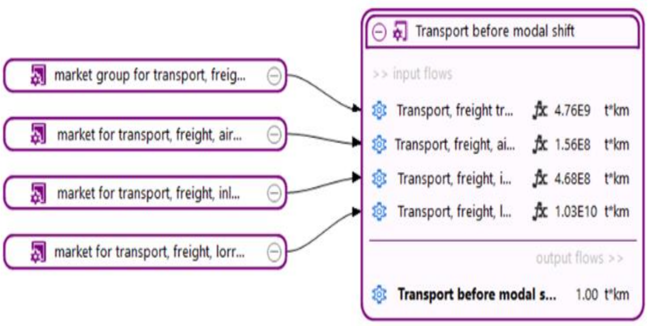

Figure 12. Model graph depicting the input-output data for India's goods transport system after modal shift

5.8 Evaluation result

With the help of open LCA, the result of the impact analysis was obtained. The absolute impact values under 18 different impact categories are in the table below (Table 3), where the cell highlighted in green indicates the lowest impact, and the pink indicates the highest impact when comparing the scenario before and after the modal shift.

Table 3. Result of the impact assessment of the simple model, before modal shift vs. after modal shift

	Impact Categories	Unit	Transport Before Modal Shift	Transport After Modal Shift
Ecosystem Impacts	Fine particulate matter formation	kg PM2.5 eq	2.67E+06	2.58E+06
	Freshwater ecotoxicity	kg 1,4-DCB	3.24E+07	2.76E+07
	Freshwater eutrophicatio n	kg P eq	2.08E+05	2.08E+05
	Global warming	kg CO2 eq	2.16E+09	1.97E+09
	Ionising radiation	kBq Co-60 eq	4.83E+07	4.71E+07
	Marine ecotoxicity	kg 1,4-DCB	6.06E+07	4.98E+07
	Marine eutrophicatio n	kg N eq	2.12E+04	1.99E+04
	Ozone formation, terrestrial ecosystems	kg NOx eq	8.69E+06	9.09E+06
	Stratospheric ozone depletion	kg CFC11 eq	1.43E+03	1.20E+03
	Terrestrial acidification	kg SO2 eq	6.19E+06	6.12E+06
	Terrestrial ecotoxicity	kg 1,4-DCB	3.05E+10	2.24E+10
Human Health Impacts	Ozone formation, human health	kg NOx eq	8.50E+06	8.92E+06
	Human carcinogenic toxicity	kg 1,4-DCB	5.69E+07	5.73E+07
	Human non-carcinogenic toxicity	kg 1,4-DCB	1.48E+09	1.24E+09
Resources Impacts	Fossil resource scarcity	kg oil eq	7.25E+08	6.48E+08
	Land use	m2a crop eq	8.17E+07	6.73E+07
	Mineral resource scarcity	kg Cu eq	4.78E+06	4.57E+06
	Water consumption	m3	6.24E+06	5.81E+06

Figure 13 presents the comparative analysis of the life cycle impacts of Indian freight transportation, compared to the scenario before and after the modal shift. The above analysis shows that increasing rail freight has lower impacts than the current dominant road freight transport. From the analysis, the modal shifts yield an incredible 9% reduction in global warming effects, and ecotoxicity across terrestrial, marine, and freshwater gets reduced by an average of 20%.

From the result, the modal shift has a low impact compared to the current scenario, where road freight dominates Indian transportation. However, the impact categories (i.e., freshwater eutrophication, ozone formation, terrestrial ecosystems, ozone formation, human health, and human non-carcinogenic toxicity) are less influenced by increasing the share of rail freight. This impact analysis shows that the increase in rail freight, up to 45% of total freight in India, positively impacts variables such as fuel consumption, CO_2 emissions, logistics infrastructure, and land use.

The study conducted in this present investigation intends to study India's freight transport system and the environmental impacts that could be observed (Table 3) by switching from road transport to rail transport. By focusing on LCA conducted through Open LCA software and the Ecoinvent database, it was discovered that enhancing freight transportation by rail to 45% can cut global warming by 9% and ecotoxicity of about 20% on land, oceans, and freshwater bodies. This work is to be fitted into the National Master Plan on Gati Shakti and the National Logistics Policy of India, aspiring to augment multimodal connectivity and decrease transit times and logistics costs. The study helps indicate that road transport is seen to reign in the Indian freight sector even while being the major contributor to greenhouse gas emissions. The best way to balance logistics networks, reduce emissions, and support sustainable economic operations would be to enhance rail infrastructure in the country.

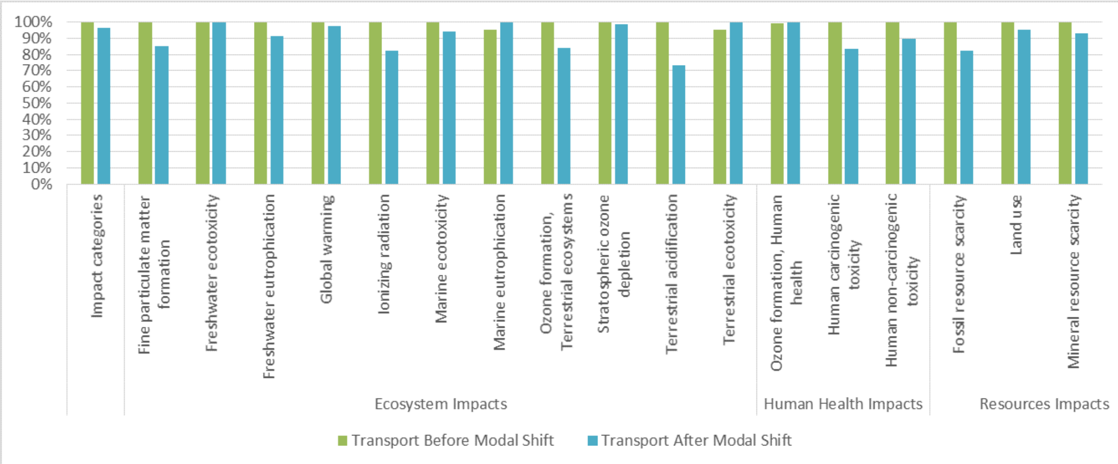

Figure 13. Relative impacts comparison between India's goods transport system before and after the modal shift

6. IMPLICATIONS

This research suggests that transforming the share of freight transportation in India from roads to railways would lead to 45% by 2050. This will significantly reduce India's environmental footprint, contributing to a 9% reduction in global warming and a 20% reduction in ecotoxicity across terrestrial, marine, and surface water environments. Consequently, according to these results, India expects to achieve net zero in 2070 by attacking logistics, one of the most significant GHG emitters. Progressing toward a more sustainable logistics infrastructure would allow India to diminish its carbon footprint, optimise energy use, and enhance resource efficiency.

1) Policymakers have to find a way to encourage the private sector to invest in rail infrastructure:

• Subsidies or rebates may be granted on income tax to the private investment in railway freight corridors;

• Enter public-private partnerships to construct railside and roadside multimodal logistics parks;

• Find funds through the private sector for expanding DFCs and ensure they are on time and ready before they are due.

2) Freight tariffs need to be adjusted to strengthen rail competitiveness:

• Adjust freight tariffs to an optimal level for bulk commodities to induce a switch of goods transportation from roadways to railways.

• Newly designed, good-looking price-mix systems should be worked out according to demand behaviour.

• Build an atmosphere where there is no profit from the road on one side and a toll from the freight on the other. That may add costs to the cargo as it moves.

3) Coordination of state taxes and regulations:

The state tax works very well if it is comparable across states and does not pass hurdles in the delivery.

• Compliance could be made easy if a single-window clearance system is utilised.

• Aligning the state transport policy with the National Logistics Policy needs to be done.

4) Expand multimodal connectivity:

• Ex Pan India, expand Gati Shakti to concur with pot-holed infrastructure.

• Develop a well-interconnected rail, road, inland waterway, and air-cargo terminals.

• Establish and operationalise logistic hubs with real-time traceability and appropriate tech infrastructure.

5) Promote sustainability and clean green logistics:

• Target 45% share of railways freight from 31% as a quick measure for reducing emissions.

• Design and implement schemes fostering electrification of the transport systems and providing subsidies for alternative fuels.

• Ensure there are strict regulations in place for emissions from road freight transport.

Such strategies will help India achieve cost-effective, environment-friendly, and globally competitive freight transport modes. I can elucidate these points if you would like further details.

This article provides a comprehensive look at India's transportation infrastructure and significant barriers to intermodal logistics in India. This serves as a point from which state policies for different types of freight transport can be examined along with strategic vision development. In terms of promoting the idea of balanced infrastructure and achieving it using modal shifts, the article contributes to shaping future directions of the policy-making process. With the help of software of this kind, it becomes possible to analyse the change in environmental footprints due to switching modes. This implies one can determine if there's a net decrease in greenhouse gases upon increasing railway freight before and after rail freight is increased. This means that all forms of transport may experience similar simulation results.

7. STUDY HIGHLIGHTS

1) India's Logistics sector is expected to go through substantial changes in its focus on enhancing overall export competitiveness.

2) Improved multimodal connectivity focuses on the Gati Shakti scheme, eradicating bottlenecks.

3) This study also suggests ways of integrating different modes of transport to improve the system response.

4) For the aim of this research, LCA has been used to focus on symptoms of environmental change, specifically transport planning.

5) In India, the transportation of goods by road is advanced. This is because road transportation occupies 66% of the total space.

6) Changing the transportation mode from 31% to 45% is a significant transformation of logistics infrastructure.

7) The effects of modal shifts are a reduction of 20% in ecotoxicity and 9% in global warming effects.

8. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

This study provides secondary data on India's freight transport efficiency compared to the benefits of moving from the standard highway mode to rails for a more sustainable method. The increased rail freight range of around 45% could help cut global warming impacts by an average of 9% and ecotoxicity by 20%. Secondary data has been complemented with accurate metrics for measuring freight efficiency in practice, like Direct Performance Freight Data, Field Surveys, Sensor-Based Tracking, and Modal Comparisons. Still, due to the limitations in the present paper, it must be addressed as a future research direction.

The study raises several limitations for the freight assessment in India, mainly excluding air and water transport impacts due to low modal share (1% and 3%, respectively). The omission does not entirely contribute to understanding the environmental impact of multimodal logistics. Further, the study makes an elaborate analysis of material on the benefits of transfer from road to rail. Still, it does not consider specific possible measures, including potential improvements in road transport, fueled by technology on the one hand and some alternative fuels on the other. This study lays bare data challenges, especially for assessing instant environmental impacts using LCA models. The ambiguity surrounding emission rates, the inconsistency of data sets, and projections sustained by technological assumptions embarrass its precision even more.

In the future, it is recommended to consider the integration of renewable energy sources into railway networks for sustainability in India, which could be mainly focused on more significant renewable usage in the Indian railway networks, thus opening up the road to solar and wind power in electrification, fueling cells by hydrogen and battery-operated freight trains, and taking advantage of these. Further examining water transport, especially inland waterways, for freight logistics compared with LCA studies could help better understand the environmental benefits. Future opportunities lie in artificial intelligence (AI) and Internet of Things (IoT) applications in optimising multimodal logistics by decreasing inefficiency in transshipment and interlinkage with the last mile. Research-oriented policy is very scalable in amalgamating the regulatory incentives, public-private partnerships, and investment frameworks for India's decarbonisation in the freight sector. All are stepping stones to bridge the concept of net-zero emissions by 2070.

9. CONCLUSION

Investigating various elements of contemporary logistics infrastructure in India unveils incongruities and disparities. It provides strategies to redress these challenges due to their reliance on a well-founded, complete perspective. This research also evaluates the environmental implications of changing modes of transport, which is a critical point as it requires extensive infrastructure.

Utilising OpenLCA software and the Ecoinvent database for comprehensive LCAs, the study suggests increasing rail's proportion in freight transportation to 45%. This change could result in a remarkable 9% decrease in global warming effects and an average 20% reduction in ecotoxicity across terrestrial, marine, and freshwater environments. By underscoring the crucial role of railways and advocating for eco-friendly rail transport development, the report presents a compelling case for implementing innovative solutions in India's logistics sector.

The study's findings best link to the Gati Shakti National Master Plan, which aims at fostering integration, efficiency, and sustainability within transportation networks. Expanding the share of rail freight complements the objectives related to integrated multimodal connectivity and infrastructure for seamless trade. Thus, embracing digitalisation, exercising investments in DFC, and allowing policy-induced model shifts in India will enhance logistics efficiency, reduce production costs, and increase global trade competitiveness, simultaneously enhancing climate commitments.

The shift will also promote global sustainability frameworks, especially the UN's SDGs, which directly target SDG 9 for more robust and resilient infrastructure, SDG 11 for developing sustainable cities and communities a cleaner environment by reducing urban pollution and traffic, and SDG 13 in effective climate action by curbing emissions and improving environmental sustainability. Investing at the lowest point of the freight chain through the provision of a well-structured logistics and sustainable transport system will make India grow itself, fostering a global example of progress in sustainable development. Future strategies must focus on the growth of rail networks, renewable energy integration in transport operations, and public-private partnerships. This way, India will be forging a logistics ecosystem that is greener and more efficient.

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