Planning Electrified Highway Systems for Low-Carbon Freight Transport and Environmental Sustainability on Routes Connecting Major Ports in Western India

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Abstract. India's freight transport sector is a major contributor to national CO_2 emissions, with road-based heavy-duty vehicles handling 83% of cargo and consuming 50% of the country's diesel. This study conducts a comprehensive feasibility analysis of implementing an Electrified Highway (E-Highway) system, utilizing overhead pantograph catenary wires, to decarbonize freight trucks servicing key western Indian ports: Mundra, Kandla (Deendayal), Hazira, and Jawaharlal Nehru Port Trust. The estimated baseline CO_2 emissions revealed huge emissions of 11.43 million tonnes annually from the port cargo data of these ports. Huge reductions in carbon emissions is possible after integration of E-highway. However, challenges such as grid unreliability and regulatory hurdles are main bottlenecks. A phased implementation timeline for E-Highway is proposed, alongside synergies with India's 500 GW renewable target by 2030 and near-zero goals by 2070, to reduce carbon emissions.

Keywords: CO2 emissions, E-highway, Freight trucks, Renewable energy.

1 Introduction

India's ports are backbone for international trade, processing over 90% of the nation's cargo volume along its 7500 km coastline. The western ports: Mundra, Kandla (Deendayal), Hazira, and Jawaharlal Nehru Port Trust (JNPT), are particularly critical, handling diverse commodities including containers, oil, coal, chemicals, textiles, and automobiles. The Mundra Port alone processed 200.7 million metric tons (MMT) with 8 million TEUs (Twenty-foot Equivalent) of cargo in financial year 2024-25. Additionally, Kandla Port handled 132 MMT (primarily oil and chemicals), Hazira 25 MMT, and JNPT 7.1 million TEUs, representing over half of India's container trade [1]. These ports connect to northern and northwestern hinterlands (e.g., Delhi NCR, Rajasthan, Punjab, Haryana, Uttar Pradesh) via national highways and expressways like the Jamnagar-Amritsar and Delhi-Mumbai corridors (Fig. 1). However, the connectivity from these ports to destination hinterlands is mainly through diesel-powered heavy-duty vehicles (HDVs), with road freight accounting for 83% of India's total cargo movement, and rail only 17% [2]. This causes huge environmental carbon emissions, as road freight contributes 14% to national CO_2 emissions along-with other pollutants (PM2.5, NOx etc.), and accounts for 50% of net diesel consumption [3]. Besides, freight demand in India is projected to grow at an annual pace of 8–10%, driven by the rapid growth of e-commerce, manufacturing, and government initiatives such as Make in India. In the absence of decisive policy measures to promote

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sustainable freight transport, the emissions from HDVs will remain unchecked, posing significant environmental and health risks. The Government of India's vision for sustainable freight transport is gaining momentum through initiatives spearheaded by NITI Aayog and the Ministry of Road Transport and Highways (MoRTH), complemented by policy frameworks such as FAME-III and the PM E-Drive program [4]. Thus, there is an urgent need to decarbonize the freight sector in line with India's national target of achieving net-zero emissions by 2070. Accordingly, the present study is designed with the following objectives: (1) To estimate baseline CO_2 emissions from freight trucks operating on major western ports. (2) To assess potential emission reductions through the adoption of green E-Highway systems. (3) To analyse route-specific characteristics, infrastructure requirements, and cost–benefit implications. (4) to estimate the long-term financial benefits of switching to hybrid trucks from conventional diesel trucks.

2 Methodology

This study investigates the environmental merits of planning E-Highway system on major western Indian ports linking Mundra and Kandla to Jamnagar-Amritsar Expressway (via Samkhiyali); and Hazira and JNPT to Delhi-Mumbai Expressway. In terms of port connectivity, Mundra is connected via State Highway (SH)-41 and National Highway (NH)-27, Kandla via NH41 and NH27, Hazira via NH48, and JNPT through NH48 with dedicated six-lane access. Routes are illustrated in Fig. 1. Route 1 connects Mundra and Kandla to Amritsar, while Route 2 links Hazira and JNPT to Delhi (see Fig. 1). The weighted average distances travelled by freight trucks to these ports were estimated considering cargo distribution from local, regional, and distant sources. The estimated average distances were 882 km for Mundra, 680 km for Kandla, 842 km for Hazira, and 734 km for JNPT. Furthermore, using port capacity and the annual cargo volume handled [1], the corresponding freight truck requirements were determined (Table 1).

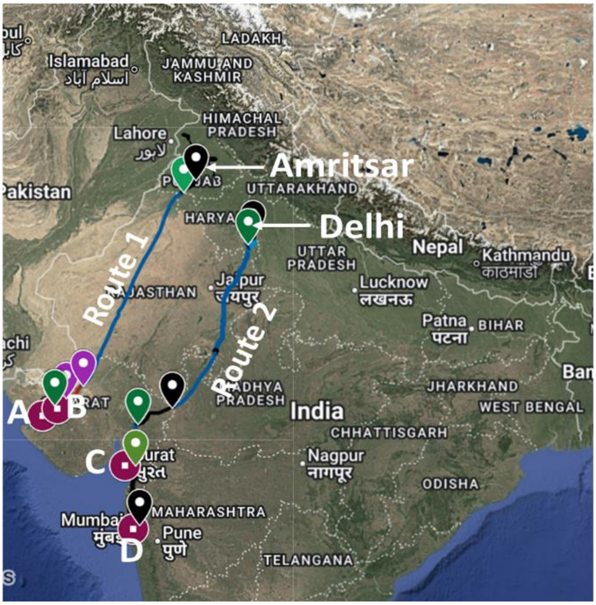

Fig.1. The map illustrates the routes connecting the major western ports under study (Mundra, Kandla, Hazira, and Jawaharlal Nehru Port Trust (JNPT)) to mainland India through existing highways.

The use of hybrid freight trucks equipped with pantographs is proposed for zero-emission operation along electrified corridors. For off-corridor operations, these trucks switch to battery or diesel-hybrid systems, ensuring operational flexibility.

2.1 Emission Modelling

The diesel HDVs emit ~1.04 kg CO2 /km [5]. Annual CO2 emissions in million tons (MT) from freight transport via diesel HDVs was calculated using Eqn. 1.

$$CO_2\ emissions\ (MT) = Daily\ Trucks \times Distance\ (km) \times 1.04 \times \frac{365}{10^6} \quad (1)$$

The energy requirement for hybrid freight trucks operating on E-highways was estimated based on electricity consumption. Previous study suggests that electric trucks require approximately 1.5 kWh of electricity to travel 1 km. The annual electricity consumption was calculated in Eqn. 2, followed by calculation of CO2 emissions in Eqn. 3.

$$\text{Annual Electricity Consumption} = Daily\ Trucks \times Distance\ (km) \times 1.5 \times 365 \quad (2)$$

$$CO_2\ emissions\ (MT) = \text{Annual Electricity Consumption} \times \frac{CE}{10^6} \quad (3)$$

Here, CE denotes the carbon emission factor (in kg CO_2/kWh) during electricity generation, which varies depending on the mode by which electricity is generated. The electricity supply is expected from Gujarat's electricity grid, which currently derives ~64% of its capacity from renewables (predominantly solar and wind) and ~36% from fossil fuels. The estimated carbon intensity was ~0.38 kg CO_2/kWh (assuming 1kg CO_2/kWh from fossil-fuel based thermal plants). By contrast, the national electricity grid has a significantly higher emission factor of ~0.82 kg CO_2/kWh. A complete transition to renewables would reduce this intensity to ~0.04 kg CO_2/kWh. Integrating additional renewable energy sources into Gujarat's grid could therefore markedly reduce carbon intensity. International pilot projects provide strong evidence for this transition: Germany's ELISA project (2019) demonstrated emission levels of 0.02–0.05 kg CO_2/km, while Sweden's 2 km Siemens e-highway trial (2016) achieved near-zero emissions with a grid intensity of 0.02 kg CO_2/kWh [6].

3 Results

3.1 Baseline CO_2 Emissions

Baseline CO_2 emissions from diesel-powered freight trucks servicing the four ports were estimated using a daily truck count of 36,700, and weighted average distances derived from cargo distribution (Table 1). For example Mundra Port, with 20,000 daily trucks traveling an average distance of 882 km, the annual CO_2 emissions are estimated at 6.69 MT from diesel HDV. Kandla Port, handling 400 daily trucks with an average distance of 680 km, contributes 0.11 MT. Hazira Port, with 2,300 daily trucks covering an average of 842 km, accounts for 0.73 MT, while JNPT Port, servicing 14,000 daily trucks over 733.5 km, produces 3.89 MT. Collectively, these four ports generate 11.43 MT of CO_2 emissions annually in FY 2024–25 (refer Table 1). This highlights the significant environmental burden of diesel-based road freight, which contributes nearly 14% of India's total CO_2 emissions [7].

Table 1. The estimated CO_2 emissions (in metric tonnes) from freight transport through the ports under different scenarios.

Port	Daily Trucks	Distance* (km)	CO_2 Emission (MT)			
			Diesel	National Grid	Gujarat Grid	Renewable Energy
Mundra	20,000	882	6.69	7.92	3.66	0.41

Kandla	400	680	0.10	0.12	0.06	0.01
Hazira	2,300	842	0.74	0.87	0.40	0.04
JNPT	14,000	733.5	3.89	4.61	2.13	0.24
Total	36,700	3137.5	11.43	13.52	6.25	0.71

* Distances have been calculated from Port Mundra and Kandla to Amritsar, and from Hazira and JNPT to Delhi, considering the most accessible route for cargo movement (refer Fig. 1).

3.2 Reduction Potential in CO_2 Emissions

The potential for CO_2 emission reductions through the E-Highway system was assessed. The annual CO_2 emissions and corresponding percentage reductions for each port were evaluated under the baseline diesel scenario and three alternative electrification scenarios (Table 1). For Mundra Port, current emissions of 6.69 MT are projected to decrease to 3.66 MT with electricity sourced from the Gujarat Grid and further to 0.41 MT under a fully renewable scenario. Similarly, for JNPT Port, emissions of 4.61 MT are expected to decline to 2.13 MT and 0.24 MT, respectively. The emission reductions for Kandla and Hazira Ports are provided in Table 1. Total emissions across these ports are projected to decrease from 11.43 MT to 6.25 MT with electricity from the Gujarat Grid, and further to 0.71 MT under a fully renewable scenario—representing reductions of ~45% and ~94%, respectively. These results further highlight the transformative potential of renewable energy integration in the E-Highway system, aligning with India's 500 GW renewable energy target by 2030 [8]. It should be noted that, due to the high carbon intensity of electricity from the national grid, utilizing it would increase CO_2 emissions (Table 1); therefore, cleaner energy sources should be prioritized for E-highways.

3.3 Techno-feasibility Analysis

As mentioned earlier, hybrid freight trucks equipped with pantographs are proposed to operate in zero-emission mode along electrified highway corridors, while switching to battery-hybrid operation off-corridor to maintain routing flexibility. The core system elements include overhead contact lines for external power supply, pantographs for current collection, electric drive systems in trucks, and grid-connected rectifier substations. This configuration enables continuous and flexible charging during motion, making it particularly suitable for busy freight corridors. Figure 2 shows the images of pantographs equipped hybrid trucks in panel 1, and conventional diesel trucks in panel 2.

Field trials in Germany — including the ELISA demonstrations on high-traffic motorways — have confirmed technical feasibility and reliable logistics integration under real-world conditions [6]. These studies also indicate potential reductions in local noise and air pollution. Seamless transitions between electric and hybrid drive modes have been consistently achieved, demonstrating system robustness for daily freight operations.

In the Indian context, pilots on port–expressway routes could validate performance under domestic traffic density, terrain variability, and climatic conditions. Partial route electrification could be combined with battery operation in segments where infrastructure deployment is costly or impractical. Early market penetration may remain modest (10–20% in targeted corridors), but with scaling of infrastructure, cost-offsetting fiscal measures, and evolving logistics business models, adoption rates could realistically approach 50% by mid-century on major freight routes.

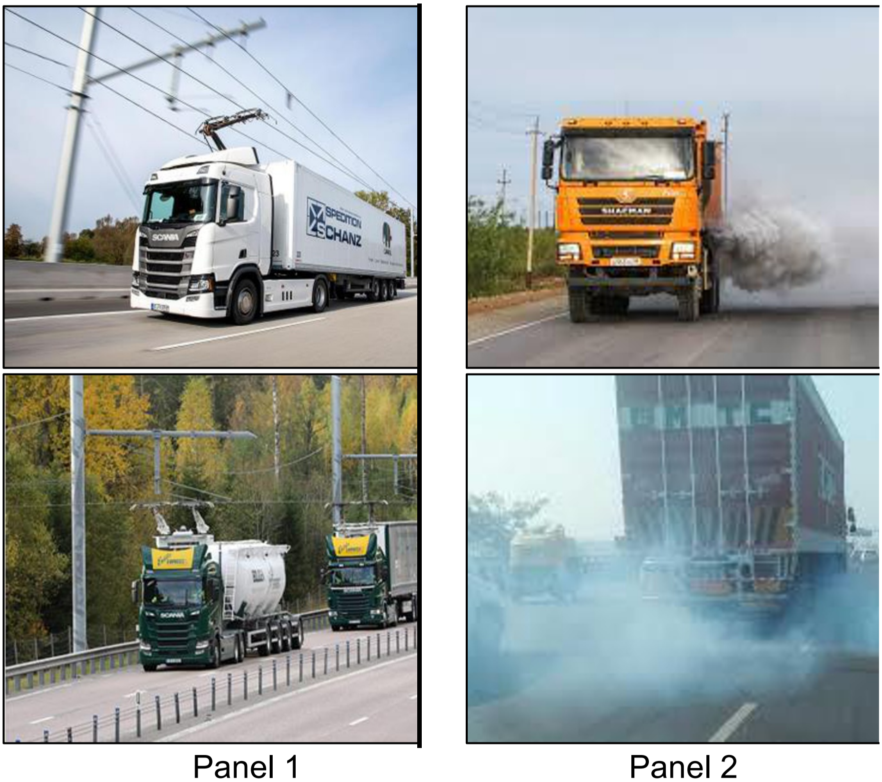

Fig.2. Panel 1 (left) illustrates hybrid e-trucks equipped with pantographs operating in zero-emission mode along an electrified corridor. Panel 2 (right) shows conventional diesel trucks emitting pollutants from the tailpipe during freight transport.

3.4 Cost Analysis

The construction cost for the E-Highway system is estimated approximately ₹4 crores/ km, encompassing catenary poles, substations, and transformers, adapted from pilot projects from European estimates [6]. These estimates account for poles spaced every 50 meters, substation costs estimated at ~₹1crore/ km, and transformers cost at ₹50–80 lakh per MV-ampere. These costs can be further reduced by leveraging India's manufacturing efficiencies and lower labour costs, making the E-Highway system economically competitive relative to global benchmarks. For the proposed routes connecting western ports with mainland India, total infrastructure construction costs are offset by long-term fuel savings and emission reductions. Further with additional support from government incentives such as the ₹500 crore e-truck subsidy scheme for 2025–26 [4], these costs can be further reduced. Table 2 presents a brief comparison of the cost structures of the two transport modes.

Table 2. The estimated cost of freight transportation using diesel trucks versus electric trucks across different ports.

Port	Distance (km)	Diesel Consumption (Litre/trip)	Diesel Cost (₹/trip)	Electric Consumption (kWh/trip)	Electric Cost (₹/trip)
Mundra	882	198.5	17,861	1,323	9,949
Kandla	680	153	13,770	1,020	7,671
Hazira	842	189.5	17,051	1,263	9,498
JNPT	733.5	165	14,854	1,100.25	8,274
Total	3137.5	706	63,535	4706.25	35,391

In Table 2, the diesel consumption is assumed, with an average of 0.225 L/km, derived as the midpoint from documented values for different truck models on company websites: Tata (0.202 L/km), Ashok (0.254 L/km), and Eicher (0.225 L/km) — representing loaded conditions. The diesel cost is assumed to be ₹90 per litre, reflecting current market conditions. For the E-highway system, the electricity consumption is considered as 1.5 kWh/km, with an electricity cost of ₹7.52 per kWh, assuming the general commercial tariff applicable in Gujarat. The distances are calculated as weighted averages for all four ports. The percentage savings in fuel consumptions from electrification was 44.3% computed using the equation 4:

$$\text{Savings (\%)} = [(\text{Diesel Cost} - \text{Electric Cost}) / \text{Diesel Cost}] \times 100 \quad (4)$$

Financial Comparison of Diesel vs Electric Trucks

The lifecycle financial analysis pertaining to Cost-Benefit Ratio (CBR), Net Present Value (NPV), and Internal Rate of Return (IRR) is carried out in Equations 5, 6 and 7.

Towards this analysis, the following assumptions have been considered. The annual mileage of the HDV is taken as 100,000 km, with a vehicle lifespan of 10 years. The initial cost of a diesel truck is assumed to be ₹40 lakh, while that of an electric truck is ₹90 lakh, implying an additional investment of ₹50 lakh for the electric alternative. A discount rate (r) of 12% has been applied for financial evaluation. Based on the per-kilometre savings of ₹8.97/km (as derived from the previous table), the annual savings amount to ₹8,97,000 for 100,000 km of operation per truck. The cash flow assumptions therefore consist of an initial extra outflow of ₹50,00,000, followed by annual inflows of ₹8,97,000 at the end of each year for a period of 10 years.

A) Cost-Benefit Ratio

$$CBR = \frac{\sum_{t=1}^{t=10} \frac{Annual\ Savings}{(1+r)^t}}{Extra\ Initial\ Cost} \tag{5}$$

B) Net Present Value

$$NPV = \sum_{t=1}^{t=10} \frac{Annual\ Savings}{(1+r)^t} - Extra\ Initial\ Cost \tag{6}$$

C) Internal Rate of Return

$$\sum_{t=1}^{t=10} \frac{Annual\ Savings}{(1+IRR)^t} - Extra\ Initial\ Cost0 = 0 \tag{7}$$

Table 3. The financial parameters CBR, NPV and IPR highlighting the economic benefits of transitioning to e-trucks.

Parameter	Value	Remark
CBR	1.014	> 1 Favourable
NPV	₹68,250	Positive NPV, Favourable
IRR	12.33%	IRR > Discount rate (12%)

As in Table 3, the analysis reveals that the CBR indicates benefits just exceeding the costs, making the project viable but sensitive to key assumptions. The NPV is positive, suggesting that switching to electric trucks yields a small net gain. Additionally, the IRR is slightly higher than the 12% discount rate, implying a moderately acceptable return on investment. Furthermore, these estimates are on the conservative side, as various government schemes and subsidies related to green energy have not been considered. Overall, the financial analysis indicates higher benefits for the electric vehicle option compared to conventional HDVs, even under present case scenario.

4 Discussion

With an estimated 36,700 daily trucks servicing the four ports, electrification could reduce CO_2 emissions of ~11.5 MT annually to 54%, Gujarat Grid, and 0.06% under renewable energy integration. The system reduces reliance on diesel, which accounts for 50% of India's fuel consumption, potentially lowering fuel import costs. Construction and operation are projected to create jobs, driven by demand for infrastructure development and maintenance. Indian adaptations, such as weather-resistant designs for monsoon conditions and Vehicle-to-Grid integration, enhance system resilience and grid stability by using e-trucks as energy storage. Additionally, logistics efficiency gains are expected due to reduced fuel costs and improved operational reliability. Further, a phased implementation is recommended: pilot projects covering 100 km of port-to-expressway routes (e.g., Mundra to Jamnagar-Amritsar, Hazira/JNPT to Delhi-Mumbai) for period 2025–2030, followed by scaling up, covering major western, southern, and eastern port corridors within the Golden Quadrilateral. Further, electrification will result in a 44.3% reduction in fuel consumption cost. The cost–benefit ratio (CBR) shows that the benefits marginally outweigh the costs, indicating that the project is feasible but remains sensitive to the underlying assumptions. The net present value (NPV) is positive, suggesting that transitioning to electric trucks offers a modest net economic advantage. Furthermore, the internal rate of return (IRR) is slightly above the 12% discount rate, indicating a moderately acceptable return on investment.

However, implementing the E-Highway system has several challenges. Grid unreliability, particularly in rural areas, necessitates upgrades for the network to ensure a stable power supply for electrified trucks. Monsoon-related weather conditions are expected to increase maintenance costs by 10–20%, requiring robust infrastructure designs. Regulatory hurdles, including permitting processes under the Ministry of Road Transport and Highways (MoRTH), pose barriers to rapid deployment. Adoption challenges, such as high upfront costs for hybrid trucks, are significant but can be mitigated through government subsidies and toll exemptions under the FAME-III and PM E-Drive programs [4]. These incentives, combined with e-truck subsidy scheme, may reduce financial barriers and encourage fleet electrification. Strategic planning, including phased implementation and public-private partnerships, can further address regulatory and infrastructural challenges, ensuring scalability and operational

5 Conclusion

In summary, electrified highways present a promising pathway for decarbonizing long-haul freight transport in India. The technology offers substantial environmental benefits by enabling heavy-duty trucks to operate with near-zero emissions along electrified corridors, significantly reducing dependence on diesel and contributing to national climate goals. Economic advantages are also compelling, as dynamic charging can lower operational energy costs by 40–50%, reduce oil imports, and stimulate domestic EV-related manufacturing and green infrastructure investments. Furthermore, integration with renewable energy sources, particularly solar, enhances system efficiency and enables energy synergies along major freight corridors, potentially reducing the need for large on-board batteries while strengthening EV adoption.

However, these benefits must be weighed against critical challenges. The initial capital costs of electrified highway infrastructure remain high, posing financial barriers in a resource-constrained developing country like India. Additionally, reliable grid capacity and stable power supply are essential, yet uneven across regions, raising concerns about system resilience, especially during extreme weather. Regulatory coordination, technical standards, and slow fleet conversion rates may also delay large-scale adoption. Therefore, while electrified highways are technically feasible and strategically aligned with India's long-term sustainability vision, phased deployment, focused pilots, renewable integration, and policy harmonization will be crucial to realizing their full potential.

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