FINAL RESEARCH SUBMISSION

European Hyperloop Competition 2025

Team Avishkar Hyperloop
Indian Institute of Technology Madras,
Tamil Nadu, India

Final Research Submission Socio - Economic Aspects of Hyperloop Development

Avishkar Hyperloop
Indian Institute of Technology Madras
Tamil Nadu, India June 2025

INTRODUCTION

About Avishkar Hyperloop

Avishkar Hyperloop is a diverse and dynamic student team from the Indian Institute of Technology Madras, Chennai, India, developing scalable technologies to make Hyperloop a reality in India and across the globe. Avishkar Hyperloop was founded in September 2017 by a group of students with the ambition of developing the first Hyperloop pod in India. We were selected for the final design round of the SpaceX Hyperloop Pod Competition'18. In 2019, we showcased our working prototype at the finale of the Competition at Hawthorne CA, where we were the only Asian team among 21 teams globally. The systems development and the design considerations here at Avishkar are planned keeping scalability at the forefront.
Sustainability, being the tentpole of manufacturing, poses the possibility of this disruptive transportation system integrating into our daily life.

AVAILABLE RESEARCH FACILITIES

The Centre for Innovation (CFI) at IIT Madras is a 24x7 student-run lab promoting informal learning and innovation. It offers a collaborative space, resources, and guidance, supporting large projects and creative, socially impactful ideas. Our main source of funding is CSR funds. CFI also houses tech clubs and collaborates on government initiatives.

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Fig. 1: Team Structure by System

Fig. 2

Cover Page

Title	Assessing Hyperloop's Viability in India's Freight Sector: A Multimodal Comparative and Socio-Economic Study with ML-Based Viability Analysis
Team Name	Avishkar Hyperloop
Submission	Full Scale - Socio-Economic Aspects
Word count	20000
To be published at	www.avishkarhyperloop.com

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TABLE 1: STATEMENT OF CONTRIBUTION

Assessing Hyperloop's Viability in India's Freight Sector: A Multimodal Comparative and Socio-Economic Study with ML-Based Viability Analysis

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Abstract— The concept of Hyperloop was proposed by Elon Musk in his paper Hyperloop Alpha in the year 2013. It was proposed that friction drag, aerodynamic drag can be reduced to a large extent. Since then, a lot of proposals have been put on table to check the feasibility of this mode of transportation. Recently, in India, a corridor spanning from Mumbai to Pune was proposed that could decrease the travel time to 25 minutes. In a democratic republic like India, when it comes to proposing a new mode of transportation, a lot of financial, political challenges are bound to occur. In addition to that, the diverse topography of India adds to those challenges. So, to study the feasibility of a Hyperloop corridor, these factors are to be kept in mind. Two metropolitan cities namely Chennai and Bangalore are a part of a potential corridor. Chennai, with it's automobile industry can be connected to Bangalore, the IT industry. This study aims to estimate a realistic ticket cost for a Hyperloop ride from Chennai to Bangalore, and aims to study the social implications of this ticket price and the shift it may create in society.

Keywords—Hyperloop, Ticket, Transport, Sustainability, Price, Cost, Vacuum, Energy, Social, Pod, Tube

1. Introduction

In the context of rapid urbanization, climate urgency, and expanding global trade, Hyperloop has emerged as a promising transportation innovation. Using magnetic levitation within low-pressure tubes, Hyperloop systems offer near-supersonic speeds with minimal energy consumption. While comparable to airline travel in terms of velocity, they present distinct environmental and operational advantages [1][2].
India, with its vast geography and evolving logistics demands, stands to benefit significantly from such innovation. The logistics sector contributes approximately 14% to the national GDP but continues to face structural fragmentation, high costs, congestion, and an overdependence on road transport [3]. These inefficiencies are particularly evident along major freight corridors such as the Golden Quadrilateral (GQ), a 5,846-kilometre highway network connecting Delhi, Mumbai, Chennai, and Kolkata. Although critical to national cargo movement, the GQ is constrained by congestion, air pollution, and outdated infrastructure [4].
In this context, Hyperloop technology presents a transformative opportunity to modernize freight mobility. Its ability to transport cargo at high speed with zero direct emissions has the potential to reshape supply chains, reduce warehousing needs, and improve regional economic integration [1]. With the GQ and the Western Dedicated Freight Corridor accounting for over 40% of India's freight traffic [5], even modest gains in speed, emissions reduction, and reliability could generate significant economic and social benefits—including improved access to essential goods, healthcare, and agricultural markets. This paper investigates the feasibility of integrating Hyperloop into India's freight logistics ecosystem. It evaluates economic, technological, and social dimensions through pricing model analysis, machine learning-based predictions, and scenario simulations.

2. Methodology

India, the study developed four distinct pricing scenarios based on route design, number of stops, directionality, and trip frequency. These cases reflect a range of real-world operating conditions across the Golden Quadrilateral corridor. Capital and operational expenditures (CAPEX and OPEX) were estimated using cost parameters from peer-reviewed research and feasibility studies, accounting for infrastructure, energy, maintenance, and labor. Case-wise evaluations were then conducted to determine unit economics and breakeven thresholds. To incorporate long-term financial realism, a Discounted Cash Flow (DCF) analysis and Net Present Value (NPV) calculations were applied, factoring in inflation and investment timelines. In parallel, a machine learning (ML) framework was used to predict the most suitable transport mode—road, rail, air, or Hyperloop—based on inputs like cost per kg-km, time, and shipment size. The model, trained on multimodal transport data, enabled objective scenario comparisons and helped identify where Hyperloop offers the greatest advantage. Finally, the study examined the broader societal impacts of Hyperloop, particularly along the Delhi–Mumbai corridor. Benefits considered included reduced emissions, enhanced healthcare and agriculture logistics, improved access, and alignment with national development goals. This integrated methodology offers a comprehensive basis for evaluating Hyperloop's role in India's freight future.

3. India's Logistics Sector: A Comprehensive Analysis of Transportation Modes and Sectoral Challenges

India's logistics sector stands as a cornerstone of the nation's economic infrastructure, representing a dynamic and rapidly evolving industry that plays a critical role in the country's growth trajectory. The sector has demonstrated remarkable expansion in recent years, with market valuations reflecting its increasing significance to the broader economy. Current estimates place the Indian logistics market at approximately USD 228.4 billion in 2024, with projections indicating substantial growth to USD 357.3 billion by 2030, representing a compound annual growth rate (CAGR) of 7.7% . Alternative assessments suggest even higher valuations, with some reports indicating the market reached USD 317.3 billion in 2024 and is expected to grow to USD 484 billion by 2029 at a CAGR of 8.8% [4] (Figure 3). These varying estimates collectively underscore the sector's robust growth trajectory and its pivotal role in supporting India's economic development objectives.

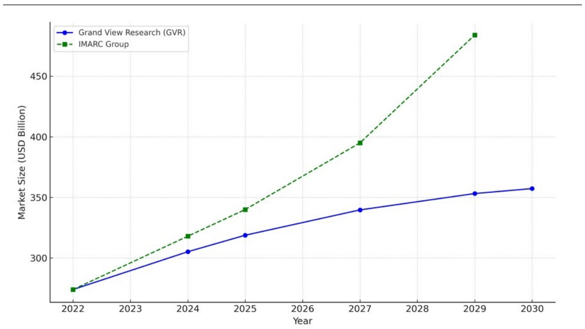

Fig. 3: Projected Growth of India's Logistics Market: GVR vs. IMARC Forecasts

This figure compares market size projections for India's logistics sector from Grand View Research (2022) and IMARC Group (2024). The GVR forecast assumes a 7.7% CAGR, projecting a value of USD 357.3 billion by 2030, while IMARC estimates USD 484 billion by 2029, factoring in accelerated growth driven by e-commerce expansion and infrastructure investments. Values are presented in USD billions.

Transportation services constitute the largest segment within India's logistics market, accounting for approximately 29.2% of revenue share in 2024, while warehousing and distribution services represent the fastest-growing segment [3]. The sector's growth trajectory has been supported by increasing demand from diverse industries, including manufacturing, consumer goods, retail, food and beverages, automotive, and healthcare sectors [60]. The COVID-19 pandemic has further accelerated the sector's transformation, driving increased adoption of digital technologies and highlighting the critical importance of resilient supply chain networks [61].

3.1. Historical Trends Of Transport in India

India's freight transportation landscape has undergone dramatic shifts since independence, reflecting broader economic priorities and infrastructure investments. The Table 2 below traces the evolution of modal shares from 1951 to 2024, contextualizing trends through policy interventions and institutional reforms.

Year	Road	Rail	Waterways	Air
1951	15%	85%	<1%	N/A
1991	60%	38%	2%	<0.1%
2022	71%	27%	2%	0.2%
2024	68.8%	29%	2%	0.2%

Table 2: Freight Transportation Modal Share (1951–2024)

The freight transportation landscape has undergone a profound transformation over the past seven decades. The historical modal share data illustrates how rail, road, waterways, and air transport have evolved in terms of their contribution to national logistics. This shift reflects a combination of infrastructure development, policy direction, economic liberalization, and growing demand for flexible freight services.

In 1951, railways accounted for approximately 85% of India's freight traffic, underlining the post-independence dependence on the colonial-era railway network [5] . However, over the ensuing decades, this dominance eroded steadily due to capacity limitations, increasing competition from road transport, and delays in modernization efforts. By 2022, the railway's share had dropped to 27%, marking a significant shift in modal preference [62]. Recent years, however, have seen modest recovery. In 2024, the rail share increased to 29%, owing to the commissioning of Dedicated Freight Corridors, which doubled the average freight train speed from 25 km/h to 50 km/h.

In contrast, road transport has shown steady growth, rising from 15% in 1951 to 71% in 2022, establishing it as the dominant freight mode in India [63]. This rapid expansion is attributable to large-scale investments in highway infrastructure, particularly the construction of over 40,000 km of national highways under the Bharatmala Pariyojana [4]. Roads have also benefited from their inherent advantage in providing last-mile connectivity, which is essential for rural and peri-urban supply chains. However, by 2024, road transport's share slightly declined to 68.8%, indicating that government efforts to shift freight to more sustainable modes may be beginning to yield results.

Inland waterways have consistently held a 2% modal share over the decades, despite being recognized as a cost-effective and energy-efficient alternative [62]. Recent initiatives such as the Jal Marg Vikas Project have focused on improving navigability, particularly on National Waterway-1, which has been extended to 1,620 km [64]. In FY 2024–25, inland water transport moved 145.5 million tonnes of cargo, showing gradual but meaningful growth in volume if not in modal share.

Air freight, while still a niche segment, has gained traction over time. It emerged as a measurable mode by 1991 (at less than 0.1% share), and has since stabilized at 0.2% between 2022 and 2024. Despite the low share, air cargo saw a 13% year-over-year growth in 2024, handling 33.7 lakh tonnes of high-value, time-sensitive goods [65].
The modal shift trends are embedded in broader policy efforts to rebalance India's freight ecosystem. The National Logistics Policy (2022) sets a clear target of raising rail's freight share to 35–45% by 2030, supported by infrastructure modernization, pricing reforms, and digital integration [3]. These efforts are aligned with India's goals to reduce logistics costs, improve efficiency, and promote sustainability in freight transport.
In summary, the historical shift from a rail-centric to a road-dominant freight system reflects both the changing economic landscape and evolving logistics priorities. Recent trends, however, suggest a corrective trajectory led by multimodal infrastructure projects and strategic policymaking aimed at improving cost-effectiveness and reducing environmental impact. India's freight modal shifts reflect strategic policy realignments toward sustainable logistics, where Hyperloop technology can be a best fit . Even though automobile transportation still dominates, massive infrastructure initiatives are giving railroads and canals fresh attention. It will be necessary to overcome past capacity bottlenecks and encourage private sector participation in order to meet the 45 % rail target by 2030.

3.2. Transportation Infrastructure and Modal Distribution

India's logistics sector relies on a diverse array of transportation modes, each with distinct characteristics, capabilities, and challenges. Road transportation dominates the freight movement landscape, handling approximately 68.8 % of freight transportation and serving as the backbone of the country's logistics infrastructure [63] (Figure 4).
The freight transportation landscape in India is characterized by a pronounced reliance on road networks, which handle the majority of cargo movement across the country. Road transport accounts for 68.8 % of all freight transportation, representing more than two-thirds of the total modal share. This dominance reflects India's extensive road network development and the flexibility that road transport offers for door-to-door delivery services. The preference for road transport can be attributed to its accessibility to remote locations, faster transit times for short to medium distances, and the ability to provide last-mile connectivity that other modes cannot match.
The extensive road network provides comprehensive connectivity across urban and rural areas, enabling door-to-door delivery services and flexible routing options. However, this heavy dependence on road transport also contributes to increased logistics costs, environmental concerns, and infrastructure strain. The road logistics segment has benefited from significant government investments in highway development, with over 40,000 kilometers of highways constructed under the Bharatmala Pariyojana project by 2024 [66].

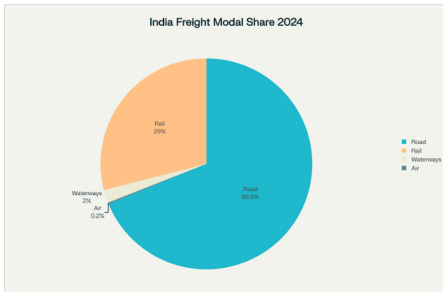

Fig. 4: Modal Share of Freight Transportation in India (2024)

Rail transport constitutes the second-largest share at 29.0 % of freight movement, serving as a crucial backbone for bulk cargo transportation across long distances. From Figure 4, the railway system's significant share underscores its importance in moving heavy commodities such as coal, iron ore, cement, and agricultural products efficiently across the vast Indian subcontinent. Despite facing competition from road transport, rail freight remains economically viable for high-volume, long-distance shipments due to its cost-effectiveness and environmental benefits.
Railway transportation represents a critical component of India's freight movement system, though its market share has experienced significant decline over the decades. Historical data reveals that railways' share in freight transport decreased from 85 % in 1951 to 60 % in 1991, reaching a low of 27 % in 2022 [67]. Recent efforts have shown modest improvements, with the rail freight share increasing to 29 % following targeted government initiatives [68]. The development of Dedicated Freight Corridors represents a transformative initiative in this regard, with the Eastern and Western corridors now operational and demonstrating significant improvements in transit times and capacity utilization [69].
Air cargo transportation has emerged as a dynamic growth segment within India's logistics ecosystem, demonstrating remarkable resilience and expansion. The sector has experienced substantial growth, with current international air cargo volumes reaching approximately 195,000 tonnes per month, representing a 13% increase compared to 2019 levels [70]. Domestic air cargo has also shown steady growth, with volumes reaching 113,662.9 tonnes in January 2025, representing a 6.9% increase year-over-year [71].
Inland waterways represent an underutilized but increasingly important component of India's transportation infrastructure. The Inland Waterways Authority of India reported record cargo movement of 145.5 million tonnes in fiscal year 2024-25, reflecting growing recognition of waterways' potential for cost-effective freight transportation [72]. The government has significantly expanded the waterway network, increasing the number of national waterways from 5 to 111, with operational length growing from 2,716 kilometers to 4,894 kilometers [73].

3.3. Sectoral Challenges and Structural Impediments

Despite its growth trajectory and economic importance, India's logistics sector faces numerous challenges that impede optimal efficiency and competitiveness. Infrastructure limitations represent perhaps the most significant constraint, encompassing inadequate transportation networks, insufficient warehousing capacity, and poor connectivity between different transportation modes [74]. While substantial investments have been made in highway development and port modernization, significant gaps remain in rural connectivity, multi-modal integration, and last-mile delivery infrastructure [75].

Cost competitiveness remains a persistent challenge for the Indian logistics sector, though recent assessments suggest improvements from previously assumed levels. While earlier estimates suggested logistics costs of 13-14% of GDP, more recent and methodologically rigorous studies indicate costs in the range of 7.8-8.9% of GDP [74]. Nevertheless, these costs remain substantially higher than the 8-9% observed in developed economies, indicating significant room for improvement [76].

Technology adoption and digital transformation represent both an opportunity and a challenge for the logistics sector. While leading logistics companies have embraced advanced technologies including artificial intelligence, Internet of Things, and blockchain applications, the broader sector remains characterized by fragmentation and limited technology penetration [60]. Approximately 90% of the logistics sector remains unorganized, with many smaller operators lacking access to modern technology solutions and digital platforms

Achieving a balanced and efficient freight modal mix in India remains a complex challenge due to a range of structural and operational constraints across transport modes. Road transport, which presently accounts for the majority of freight travel, is less viable for long-haul logistics due to its high emissions, chronic congestion, and fluctuating fuel prices. The industry is hampered by slow speeds, poor last-mile connectivity, and complicated pricing systems that lower its competitiveness, despite initiatives to promote a modal shift towards rail. Similarly, even though they are less expensive, inland waterways have limited use for regular freight operations due to seasonal navigability problems and poor port connections. Although it works well for valuable and urgent items, air cargo's wider use in national logistics is limited by high operating costs and infrastructural impediments.

The Government of India has set strategic modal share targets for 2030 in order to solve these issues, along with significant policy and infrastructural projects. By utilising investments in the PM Gati Shakti Master Plan and the Dedicated Freight Corridors, the goal is to move 35–55% of freight traffic to rail. With the help of the Jal Marg Vikas Project and the Sagarmala Programme, the goal is to increase the percentage of inland waterways to 5%. With the help of initiatives like Bharatmala and a national push for the use of electric vehicles (EVs) in commercial logistics, the proportion of road transport is anticipated to decrease to less than 50% at the same time. (Table 3) These programs are part of a larger movement towards multimodal, sustainable logistics that supports national objectives for infrastructure modernisation, cost reduction, and emission control.

Mode	Target Share	Key Initiatives
Rail	35–55%	Dedicated Freight Corridors, Gati Shakti Plan
Waterways	5%	Jal Marg Vikas Project, Sagarmala rs
Road	<50%	Bharatmala Pariyojana, EV adoption rs

TABLE 3: GOVERNMENT TARGETS TILL 2030

3.4. Recent Government Initiatives and Reforms

The Indian government has implemented comprehensive policy frameworks aimed at addressing structural challenges and promoting growth within the logistics sector. The National Logistics Policy, launched in September 2022, represents a landmark initiative designed to create an integrated, efficient, and cost-effective logistics ecosystem [67]. The policy's vision encompasses driving economic growth and business competitiveness through seamless, reliable, and sustainable logistics networks leveraging advanced technology and skilled workforce [69].

The PM Gati Shakti National Master Plan represents another transformative government initiative aimed at creating integrated multi-modal transport systems connecting rail, road, ports, and air transportation seamlessly [68]. This comprehensive approach addresses the historical problem of fragmented infrastructure planning and aims to reduce transportation time and costs while boosting supply chain efficiency [66]. Infrastructure development initiatives have received substantial government attention and investment, with projects such as Dedicated Freight Corridors achieving significant milestones. The Eastern and Western Dedicated Freight Corridors are now 96 percentage complete as of April 2024, with operational sections demonstrating substantial improvements in freight capacity and efficiency [72].

3.5. Emerging Technologies and Future Prospects

India's logistics sector is increasingly embracing emerging technologies that promise to revolutionize transportation and supply chain management. The development of hyperloop technology represents one of the most ambitious technological initiatives, with India planning to develop the world's longest hyperloop test track spanning 40-50 kilometers [3]. Electric vehicle adoption and smart charging infrastructure development represent critical areas of technological advancement within the logistics sector [4]

India's transportation infrastructure, anchored by a 6.6-million-kilometer road network, facilitates 71% of freight and 85% of passenger traffic, serving as the na-

Policy/Initiative	Objective	Key Components	Reference
National Logistics Policy (2022)	Reduce logistics costs from 14–18% to 8% of GDP by 2030; improve global LPI ranking.	- Unified Logistics Interface Platform (ULIP) - Ease of Logistics (ELOG) portal - Comprehensive Logistics Action Plan (CLAP)	Invest India, PIB
PM GatiShakti National Master Plan	planning across 16 ministries via GIS-based platform.Integrate infrastructure .	- Multimodal connectivity (road, rail, ports, air) - Synchronization of Bharatmala, Sagarmala, and UDAN projects	India.gov
Sagarmala Programme	Promote port-led development and reduce EXIM logistics costs.	- 272/839 projects completed (INR 1.41 lakh crore investment) - Coastal shipping growth (118 percentage since 2015)	Sagarmala.gov
UDAN Regional Connectivity Scheme)	Improve air connectivity to underserved regions.	- 149 operational airports (2023) - Krishi UDAN for agricultural freight - Lifeline UDAN for medical cargo	DD News
Parvatmala Ropeway Initiative	Provide sustainable transport in hilly/urban areas.	- 200+ projects (INR 1.25 lakh crore investment) - Kedarnath (12.9 km) and Hemkund Sahib (12.4 km) ropeways	NHAI Report
National Waterways Development	Boost inland water transport for cost-effective freight movement.	- 111 operational waterways (e.g., Ganga, Brahmaputra) - 700% cargo growth (2015–2025)	IWAI
Bharatmala Pariyojana	Develop economic corridors and improve road connectivity.	- 34,800 km highway network - Focus on North-East and border roads	India.gov
FASTag Expansion	Streamline toll collection and reduce congestion.	- 98% penetration in toll collection - New rules (2025) for blacklisted tags and penalties	Financial Express
Green Logistics Initiatives	Promote sustainable logistics through decarbonization.	- Coal Logistics Plan (shift 90% coal transport to rail) - Hydrogen-powered freight trials	PIB

TABLE 4: LIST OF GOVERNMENT POLICIES / INITIATIVES

tion's economic backbone [4]. This network, the world's second-largest, includes 151,000 km of National Highways like NH-44 (Srinagar–Kanyakumari) and NH-48 (Delhi–Chennai), which connect strategic locations and form the Golden Quadrilateral linking major metros [77]. Expressways, though only 0.09% of total roads, are transformative: the 1,386 km Delhi–Mumbai Expressway reduces travel time to 12 hours, while ongoing projects like the Varanasi–Kolkata corridor aim to enhance regional connectivity [78].

State highways (186,528 km) and rural roads under initiatives like Pradhan Mantri Gram Sadak Yojana ensure last-mile access, bridging 25,000 remote habitations [62]. Border Roads Organisation projects, such as the 2,445 km of strategic roads built in 2020–23, bolster defense logistics [62]. Internationally, the India–Myanmar–Thailand Trilateral Highway exemplifies cross-border trade ambitions, projected to boost GDP by $70 billion by 2025 [79].

Despite progress, challenges persist. National Highways witness 33% of India's 423,000 annual road accidents, necessitating improved safety protocols [63]. Investments under Bharatmala Pariyojana target reducing logistics costs from 12% to 9% of GDP by 2030 through 34,800 km of new economic corridors [4]. This infrastructure evolution, blending scale and innovation, remains pivotal to India's goal of a $5 trillion economy, ensuring mobility and equity across its diverse geography.

3.5.1. *The golden quadrilateral*

The Golden Quadrilateral (GQ), India's flagship national highway project, forms a 5,846 km loop connecting the country's four major metropolitan hubs—Delhi, Mumbai, Chennai, and Kolkata. Initiated in 2001 and substantially completed by 2006, it is one of the largest highway infrastructure projects in the developing world. The GQ links 13 major cities, traverses high-density industrial corridors, and facilitates a significant portion of India's domestic freight traffic, accounting for nearly 40% of total road freight volumes [4].

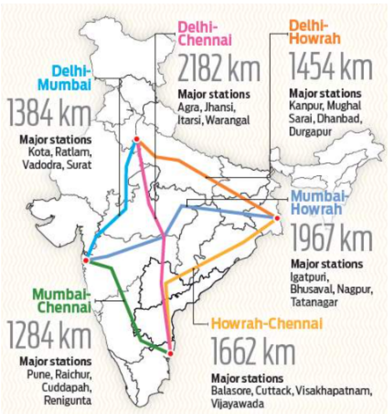

Fig. 5: Golden quadrilateral

3.6. Trade Volume and Economic Importance

The GQ supports an annual freight movement exceeding 550 million tonnes, largely consisting of industrial goods, agricultural produce, electronics, automotive parts, and fast-moving consumer goods (FMCG)[92]. The corridor catalyzed a 2.7% increase in real income in the manufacturing sector and up to 18% improvement in allocative efficiency in some Indian states, by optimizing firm-level productivity and reducing intranational trade costs [91]. The welfare gains from the GQ are estimated at $4.2 billion annually, effectively recovering the initial construction cost of $5.6 billion in under two years [92].

3.7. Goods Transported

The corridor handles a diverse range of commodities, including automotive components and finished vehicles, pharmaceuticals and medical supplies, agricultural produce, and consumer electronics and textiles.

The Golden Quadrilateral (GQ) corridor, being India's most critical freight artery, facilitates the movement of a wide spectrum of goods essential to the country's economic infrastructure. The corridor connects industrial, agricultural, and consumption hubs across Delhi, Mumbai, Chennai, and Kolkata, enabling efficient east–west and north–south trade. Among the most frequently transported commodities are grains (rice, wheat, maize, pulses) from northern and eastern states to urban centers; fruits and vegetables such as onions, tomatoes, and bananas from Maharashtra, Andhra Pradesh, and Tamil Nadu; and dairy products and packaged foods to meet the urban demand in metros [4].

The GQ also serves as a backbone for India's automobile and electronics supply chains, particularly between Chennai, Pune, and the NCR region, with significant volumes of automobile components, consumer electronics, and durables moving in both raw and finished forms. The construction sector relies heavily on GQ for the transportation of cement, steel, bricks, sand, and aggregates, supporting India's growing infrastructure and urban housing needs. Bulk commodities such as coal, petroleum products (LPG, diesel), and fertilizers are commonly routed via GQ in coordination with rail and port-based terminals, especially along the western and eastern coasts.

Additionally, high-value, temperature-sensitive goods like pharmaceuticals, vaccines, and meat and seafood are increasingly using time-bound express logistics services across this corridor. The emerging demand for faster delivery of e-commerce parcels and FMCG goods has led to the proliferation of third-party logistics and multimodal hubs along the GQ. These trends collectively position the Golden Quadrilateral as the spinal column of India's domestic freight ecosystem, with its multimodal flexibility offering robust support to a diverse and dynamic range of cargo types [88].

3.8. Key Stakeholders

Several entities have vested interests in the GQ freight corridor: Central Government Ministries (e.g., Ministry of Commerce, Railways, Road Transport), State Governments and Urban Planning Agencies, Public and Private Logistics Operators (e.g., CONCOR, Delhivery, Amazon India), Rail Freight Corporations like DFCCIL, Port Authorities and Airport Cargo Terminals, and Local SMEs and MSMEs. Amazon India, for example, has signed MoUs with Indian Railways to create hub-and-spoke logistics models across these high-traffic routes [62].

Fig. 6: Key Stakeholders

3.9. Time Taken by Different Modes

To understand the operational advantages of Hyperloop in India's freight sector, a comparison of average transit times between Delhi and Mumbai was conducted across key transportation modes: road, rail (DFC), air, and Hyperloop. These estimates reflect typical conditions under current infrastructure capabilities, providing a benchmark to assess potential time savings.

Transport Route	Freight Volume/Share	Key Goods Transported	Hyperloop Integration Potential
National Highways	40% of road freight traffic	Manufacturing goods (39%), mining products (39%), agricultural commodities (22%)	Limited; hyperloop prioritizes high-value/time-sensitive cargo incompatible with bulk NH freight
State Highways	~20% of road freight (estimated)	Regional agricultural produce, small-scale manufacturing, local minerals	Minimal; serves as feeder network to NHs rather than long-haul corridors
Expressways	25% of intercity freight	Electronics, automotive parts, perishables, e-commerce parcels	High potential for time-critical shipments via proposed multimodal logistics parks
Railways	927 MMT (2023–24)	Coal (44%), iron ore (15%), cement (8%), containers (6%)	Complementary role through proposed transshipment hubs at hyperloop terminals
Coastal Shipping	12.8 MMT (2023–24)	POL products (35%), iron ore (28%), coal (19%)	Possible integration through port-connected hyperloop corridors under Sagarmala program

TABLE 5: FREIGHT CHARACTERISTICS AND HYPERLOOP INTEGRATION POTENTIAL BY ROAD TYPE

As shown in Table 30, road transport, the most widely used mode in India, takes approximately 3 to 4 days to move freight between Delhi and Mumbai—primarily due to traffic congestion, toll delays, and regulatory stops. Rail transport via the Dedicated Freight Corridor (DFC) offers a significant improvement, reducing this time to 16–27 hours owing to electrified lines, double-stacked trains, and reduced congestion. Air cargo, while much faster at around 2 hours, is constrained by high costs, limited cargo volumes, and infrastructure bottlenecks at airports.

By contrast, the Hyperloop system, once deployed, is projected to complete the same journey in under 2 hours, combining the speed of air travel with the scalability of rail. This capability introduces the possibility of same-day intercity freight delivery, offering transformative benefits for time-sensitive industries such as pharmaceuticals, perishables, and e-commerce. The significant reduction in transit time also improves logistics reliability, reduces inventory holding costs, and supports just-in-time delivery models.

3.10. Carbon Footprint and Sustainability

India's freight transport sector is a major contributor to the nation's carbon dioxide (CO_2) emissions, reflecting both the scale of economic activity and the heavy reliance on fossil-fuel-based road transport. As of 2020, the transport sector accounted for approximately 14% of India's total energy-related CO_2 emissions, with road transport alone responsible for over 90% of these emissions [80] [82] [81]. Trucks, which dominate freight movement across the country, are particularly significant: they consume the most energy in the freight sector and are the largest single source of freight-related emissions, largely due to their prevalence, low fuel efficiency, and dependence on diesel fuel [80] [81][89].

Traditional freight systems contribute significantly to emissions. Road freight in India emits approximately 275 gCO_2/ton-km, while rail emits around 30–40 gCO_2/ton-km depending on electrification [87]. Air cargo exceeds 500 gCO_2/ton-km.

In contrast, the Hyperloop, when powered by solar or wind, can achieve emissions as low as 4–10 gCO_2/ton-km, with potential 90% reductions in lifecycle emissions compared to air freight [1] [83]. Moreover, the Hyperloop's closed-tube, low-friction design supports regenerative braking, zero tailpipe emissions, and solar power integration, making it a promising alternative for green logistics [90]. This comparison is shown in Table 6 below

Mode	Carbon Footprint on DMIC (gCO_2/ton-km)
Road	~260–300
Rail (DFC)	~30–40
Air Cargo	~500–600
Hyperloop	<10 (if powered by renewables)

TABLE 6: MODAL COMPARISON OF CARBON FOOTPRINT IN DELHI MUMBAI CORRIDOR

3.11. Further analysing the Carbon Emissions the full breakdown

The Golden Quadrilateral (GQ) highway network, connecting Delhi, Mumbai, Chennai and Kolkata, exemplifies these challenges. Road freight along the GQ emits approximately 260–300 grams of CO_2 per ton-kilometer, while rail freight is considerably more efficient, emitting only 30–40 grams per ton-kilometer [87]. Air cargo, though less common for bulk freight, has the highest emissions at over 500 grams per ton-kilometer [1]. The total daily CO_2 emissions from all vehicles on the GQ corridor are estimated between 298,800 and 366,800 tons, with trucks alone accounting for 189,000 to 229,000 tons per day. This data is shown in Table 7

Table 8 presents a concise summary of the total daily carbon dioxide (CO_2) emissions generated by various vehicle types operating along India's Golden Quadrilateral

Segment	Approx. Distance (km)	Major Cities Covered	Estimated Emissions (tons/day)
Delhi – Mumbai	~1,400	Jaipur, Ahmedabad	25,000 – 30,000
Mumbai – Chennai	~1,300	Pune, Bangalore	22,000 – 28,000
Chennai – Kolkata	~1,680	Visakhapatnam, Bhubaneswar	26,000 – 32,000
Kolkata – Delhi	~1,530	Varanasi, Kanpur	24,000 – 29,000
Total (GQ Network)	~5,900	All major metros	**97,000 – 119,000**

TABLE 7: FULL BREAKDOWN OF CARBON FOOTPRINT IN GQ CORRIDOR

Vehicle Type	Total CO_2 Emissions (tons/day)
Trucks (HCV & LCV)	189,000 – 229,000
Passenger Cars	63,000 – 79,000
Buses	16,800 – 20,800
Two-Wheelers	30,000 – 38,000
Total (All Vehicles)	**298,800 – 366,800**

TABLE 8: SUMMARY OF TOTAL CO_2 EMISSIONS BY VEHICLE TYPE (TONS/DAY)

(GQ) highway network. The GQ, which connects major metropolitan cities such as Delhi, Mumbai, Chennai, and Kolkata, is a critical artery for the country's freight and passenger transport. The data in Table bb highlights the disproportionate contribution of different vehicle categories to India's overall transport-related emissions, emphasizing the environmental challenges posed by road-based logistics.
According to the table 8, trucks—including both heavy and light commercial vehicles—are the dominant source of emissions, producing between 189,000 and 229,000 tons of CO_2 per day. This figure underscores the central role of trucks in India's freight movement and their reliance on diesel fuel, which is less efficient and more carbon-intensive compared to other modes of transport [80] [82] [81]. Passenger cars are the next largest contributors, emitting 63,000 to 79,000 tons of CO_2 daily, followed by two-wheelers (30,000–38,000 tons/day) and buses (16,800–20,800 tons/day). Collectively, all vehicle types on the GQ corridor emit between 298,800 and 366,800 tons of CO_2 each day, illustrating the substantial carbon footprint of India's road transport sector
The figures in Table 8 reflect the broader national trend, where road transport accounts for over 90% of logistics sector emissions, with trucks alone responsible for nearly 38% of the sector's CO_2 output [85] [84]. These emissions are driven by the high volume of freight and passenger movement on the GQ, the predominance of fossil-fuel-powered vehicles, and the limited modal shift to lower-emission alternatives such as rail or inland waterways.In summary, Table 8 provides a clear snapshot of the environmental impact of India's logistics sector, particularly the outsized role of trucks and road transport in driving CO_2 emissions.

3.12. CO_2 Emissions from Rail Transport Along the Golden Quadrilateral (GQ)

Indian Railways plays a pivotal role in both freight and passenger transport along the Golden Quadrilateral (GQ), which connects India's major metropolitan cities. The data presented in tables cc and dd offers a detailed account of the carbon dioxide (CO_2) emissions associated with these railway operations, highlighting the environmental advantages of rail transport over road-based alternatives.
Table 9 provides a segment-wise breakdown of CO_2 emissions from freight trains operating on the GQ. For each major corridor—Delhi-Mumbai, Mumbai-Chennai, Chennai-Kolkata, and Kolkata-Delhi—the table lists the average number of daily trains, the volume of freight moved (in million tons per day), and the estimated CO_2 emissions (in tons per day). These figures illustrate that rail freight is substantially more energy-efficient than road freight, emitting only about 30–40 grams of CO_2 per ton-kilometer compared to approximately 260–300 grams for trucks. This efficiency is further underscored by the fact that rail freight emits roughly 75% less CO_2 per ton-kilometer than road freight, making it a critical component of India's strategy to decarbonize its transport sector.
Table 10 shifts focus to passenger trains, presenting similar data: the number of daily trains, the number of passengers carried (in millions per day), and the corresponding CO_2 emissions (in tons per day) for each segment of the GQ. The table reveals that passenger rail is also highly efficient, producing only 30–50 grams of CO_2 per passenger-kilometer, while passenger cars emit 120–180 grams per passenger-kilometer. This means rail emits 60–70% less CO_2 per passenger-kilometer compared to road transport, a difference driven by higher occupancy rates and more efficient energy use
The summary section of table 10 aggregates the total daily CO_2 emissions from both freight and passenger trains across the entire GQ network. It shows that, despite the high volume of goods and people moved, the total emissions from rail remain significantly lower than those from road transport. For instance, total daily rail emissions (freight plus passenger) are estimated at 30,000–40,100 tons, whereas road vehicles on the same network emit between 298,800 and 366,800 tons per day
In essence, these tables provide clear and quantifiable evidence of the environmental benefits of rail transport on the Golden Quadrilateral. They demonstrate that Indian Railways, by virtue of its energy efficiency and lower emissions intensity, is a vital solution for reducing the carbon footprint of India's logistics and passenger mobility. This

data supports national and international policy goals aimed at shifting more freight and passenger traffic from road to rail, thereby advancing India's commitments to climate change mitigation and sustainable development [86].

3.13. To Summarise

India's freight ecosystem along the Golden Quadrilateral (GQ) is primarily served by conventional transport modes—road and rail—which together account for more than 95% of total domestic freight movement. Road transport, with its flexibility and reach, has become the dominant mode, especially for last-mile delivery and FMCG goods, despite challenges such as high fuel costs, congestion, and vehicle emissions. Rail transport, on the other hand, remains the backbone for long-haul and bulk commodities such as cement, coal, steel, and fertilizer. However, it suffers from last-mile disconnects, speed limitations, and capacity constraints, which limit its competitiveness for high-value or time-sensitive cargo [4]
Air cargo has gained importance for e-commerce, medical supplies, and electronics, particularly between Delhi and Mumbai, but remains expensive and infrastructure-dependent, suitable mainly for premium freight. Meanwhile, inland waterways, though energy-efficient, have not reached full potential due to seasonal limitations, slow speeds, and limited port-link integration. Despite the infrastructural investments across all these modes, the current logistics network still struggles to deliver cost-effective, fast, and sustainable freight solutions, especially for temperature-sensitive, time-critical, or intermodal cargo.
The Golden Quadrilateral has already proven its value in reducing transit times, boosting productivity, and lowering intranational trade barriers. Yet, challenges remain in addressing environmental concerns and last-mile connectivity. With India aiming to double its freight movement capacity by 2030, incorporating next-generation logistics solutions like the Hyperloop into this network could offer unprecedented gains in efficiency, speed, and sustainability. However, the full potential will depend on cost viability, policy integration, and renewable energy adoption, which will determine whether the Hyperloop can evolve from a technological aspiration into a scalable, inclusive, and transformative freight backbone for India.

4. Assumptions and The Model

4.1. Pod Model

- The pods are designed to be 15 meters long
- Taking the average pod diameter as 2.8 meters, the resulting blockage ratio is calculated to be 0.49.
- For the purposes of this study, a cruising velocity of 0.6 Mach, equivalent to 205.8 m/s, has been considered.
- The acceleration and deceleration of the pod are assumed to be 4.5 m/s².
- Since the objective is to analyze a minimal Hyperloop system, we have considered an upscaled version of our current pod, adapted for cargo transport. As a result, no compressor is included in the system.
- The total weight of the pod is taken as 56,727 kg, out of which:
  - 31,727 kg accounts for the dead weight, including the chassis, battery, and onboard systems
  - 25,000 kg is considered the payload
- The internal volume of the pod has been calculated to be 86 cubic meters, and with a payload capacity of 25 tons, the configuration closely resembles that of an ISO 45-foot High Cube container, commonly used in standardized freight operations.

4.2. On Pod Systems

- **Levitation**: The pod utilizes Electromagnetic Suspension (EMS) for levitation, with all supporting electrical systems and the power source located onboard the pod. This enables efficient levitation independent of external infrastructure.
- **Braking**: The pod is brought to rest using eddy current magnetic brakes. While this system currently ensures reliable deceleration, regenerative braking will be evaluated in future iterations of this document once relevant numerical data is collected and analyzed.
- **Propulsion** is achieved through onboard Linear Induction Motors (LIMs). These motors are powered via an inverter and controlled using voltage-to-frequency (V/f) control strategies to ensure smooth and efficient operation.
- **Aerodynamic Shell**: The outer structure of the pod functions as an aerodynamic shell, integrating all subsystems under a unified design. It is optimized to maintain aerodynamic efficiency without compromising the modularity of internal systems.
- **Suspension**: The pod includes a dedicated suspension system responsible for maintaining the stability and precise clearances required during travel. It ensures smooth operation and structural integrity even under dynamic disturbances.
- **Thermal Management**: Key onboard components such as the LIMs, EMS units, and battery systems are thermally managed to prevent operation beyond safe temperature thresholds. For this purpose, immersion cooling, microchannel heat exchangers, and Phase Change Chambers (PCCs) are being considered as potential solutions.

4.3. Design Rationale

Avishkar Hyperloop has proposed a 5,864 km-long Hyperloop corridor interlinking the four major metropolitan cities along India's Golden Quadrilateral. The infrastructure

Segment	Distance (km)	Daily Freight Trains (avg.)	Freight (Million Tons/Day)	CO_2 Emissions (tons/day)
Delhi – Mumbai	~1,400	150	5.5	5,500 – 7,000
Mumbai – Chennai	~1,300	130	4.8	5,000 – 6,500
Chennai – Kolkata	~1,680	140	5.2	5,500 – 7,000
Kolkata – Delhi	~1,530	135	5.0	5,200 – 6,800
Total (GQ Network)	~5,900	**555 Freight Trains**	**20.5 Million Tons**	**21,200 – 27,300**

TABLE 9: CO_2 EMISSIONS FROM FREIGHT TRAINS

- Assumption: Diesel locomotives emit 4–6 grams CO_2 per ton-km, while electric ones are cleaner.
- Rail freight emits 75% less CO_2 per ton-km than road freight.

Segment	Distance (km)	Daily Passenger Trains (avg.)	Passengers (Million/Day)	CO_2 Emissions (tons/day)
Delhi – Mumbai	~1,400	200	2.5	2,500 – 3,500
Mumbai – Chennai	~1,300	180	2.2	2,200 – 3,200
Chennai – Kolkata	~1,680	160	2.0	2,000 – 3,000
Kolkata – Delhi	~1,530	170	2.1	2,100 – 3,100
Total (GQ Network)	~5,900	**710 Passenger Trains**	**8.8 Million Passengers**	**8,800 – 12,800**

TABLE 10: CO_2 EMISSIONS FROM PASSENGER TRAINS

- Assumption: Trains emit 30–50 g CO_2 per passenger-km, while cars emit 120–180 g CO_2 per passenger-km.
- Rail emits 60–70% less CO_2 per passenger-km compared to road transport.

design prioritizes structural efficiency, vacuum integrity, and operational safety, with the following key considerations:

- The system comprises two parallel vacuum tubes, each 4 meters in diameter, constructed from mild steel. The wall thickness of each tube is maintained at 18 mm to balance structural strength and material optimization.
- To prevent buckling of the relatively thin tube walls under low internal pressure (approximately 1,000 Pa), internal stiffeners made of mild steel are integrated at regular intervals along the length of the tube.
- The tubes incorporate interconnecting ducts every 20 meters, running between the two tubes. These ducts play a critical role in mitigating the piston effect generated by high-speed pod movement, thus maintaining pressure equilibrium and minimizing resistance.
- Structurally, the tube is segmented into 20-meter sections, each fabricated using spiral welding techniques to enhance dimensional tolerance. Adjacent 20-meter sections are further joined by peripheral welds along their rims. All welds in the system are assumed to be flawless and leak-proof.
- Vacuum pumps are attached via flexible bellows located at every 10 km along the tube. These bellows not only enable a secure interface for pressure management but also serve to absorb mechanical vibrations generated during pump operation.
- At either end of the tube system, a 47-meter long airlock section is installed. These are connected to the main tube via bellows, acting as transition chambers between atmospheric pressure and the low-pressure environment of the main vacuum tube, thus ensuring safe pod entry and exit.
- The entire tube structure is elevated above ground level, necessitating robust support. For this purpose, reinforced concrete pylons are deployed at 12-meter intervals, each mounted on dedicated concrete foundations. This pylon design ensures structural stability and load distribution throughout the corridor.
- The track is an upscaled version of the team's most recent prototype and is constructed using a combination of Mild Steel, Aluminium, and concrete for cost-effective strength. The two horizontal mild steel sections located at the ends of the track are designed to support Electromagnetic Suspension (EMS) by maintaining a precise air gap between the pod and the track. At the center, an inverted T-section made of Aluminium serves as the propulsion guide, interacting with the Linear Induction Motor (LIM) mounted on the pod. These components are supported by concrete structures, ensuring structural stability and economic feasibility.
- The mild steel sections are mounted on individual concrete blocks such that the EMS-supporting surfaces protrude outwards, while the remaining portion remains embedded within the concrete for anchoring. Both these end blocks, along with the central inverted Aluminium T-section, are mounted on a trapezium-shaped concrete base. This entire assembly is housed within the vacuum tube. All track components and their dimensions are meticulously designed to ensure that the blockage ratio of the pod remains within optimal limits, balancing aerodynamic performance and system efficiency.

Details	Time (Mins)
Airlock Time	8.2115
Loading Time	10
Unloading time	10
U - Turn Time	3
Speed Headway Time	5

TABLE 11: ASSUMED OPERATIONAL TIMINGS

Cases	Headway time (Mins)
Case 1	33.2115
Case 2	33.2115
Case 3	36.2115
Case 4	36.2115

TABLE 12: HEADWAY TIME FOR ALL CASES

4.4. Time Calculations

The assumed operational timings for the tubes are presented in Table 11, based on which the headway times for each case have been calculated and are detailed in Table 12.

4.5. Route Design and Case Categorization

To systematically evaluate the technical, economic, and environmental feasibility of Hyperloop implementation in India, this study identifies and compares four distinct route scenarios—or cases—along the Golden Quadrilateral (GQ). The GQ is India's most critical freight and passenger corridor, linking the nation's four principal metropolitan centers: Delhi, Mumbai, Kolkata, and Chennai. Together, these cities account for a substantial proportion of India's GDP, freight traffic, and intercity passenger volume [4].

The case design strategy was intended to reflect real-world logistics patterns and scalable transport demand scenarios, while also accounting for infrastructure limitations, stop requirements, and energy consumption. The following four cases were developed for analysis the full route is shown in Figure a below

Fig. 7: Proposed route for Hyperloop in India

4.5.1. *Case 1: Baseline Scenario (Direct Point-to-Point Without Stops)*

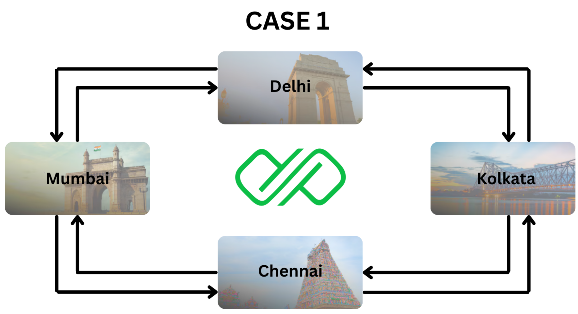

Fig. 8: Visualisation for Route case 1

In this baseline scenario, high-speed Hyperloop lines are modeled directly between the four metro cities of the Golden Quadrilateral without any intermediate stops. The routes include:

- Delhi $\rightarrow$ Mumbai $\rightarrow$ Kolkata $\rightarrow$ Chennai $\rightarrow$ Delhi

This scenario assumes non-stop intercity travel, optimizing for speed and energy efficiency. It serves as a benchmark to estimate minimum carbon emissions, shortest travel time, and ideal economic cost for high-priority cargo and passenger movement between key metro regions.

4.5.2. *Case 2: Scenario with Intermediate Stops*

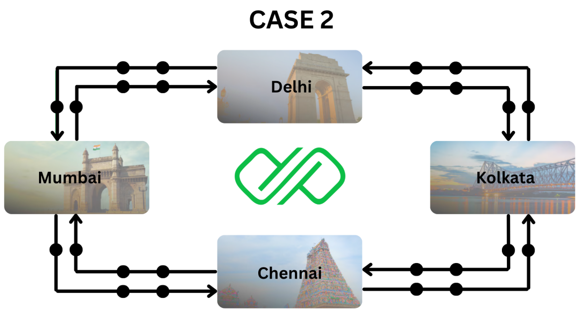

Fig. 9: Visualisation for Route case 2

In Case 2, the same four metro connections are modeled but with the inclusion of three major intermediate cities per leg, chosen based on freight volume, geographic centrality, and regional economic importance. The updated corridors include:

- Delhi → Jaipur → Ahmedabad → Surat → Mumbai
- Mumbai → Pune → Hubli → Bangalore → Chennai
- Chennai → Vijayawada → Visakhapatnam → Bhubaneswar → Kolkota
- Kolkota → Patna → Varanasi → Lucknow → Delhi

This scenario represents a hub-and-spoke model, better aligned with logistics decentralization, passenger accessibility, and regional integration. It allows for a more granular understanding of load-unload cycles, operational complexity, and energy variability due to frequent acceleration and deceleration.

4.5.3. *Case 3: U-Turn Adjustment and Variable Route-Based Pricing*

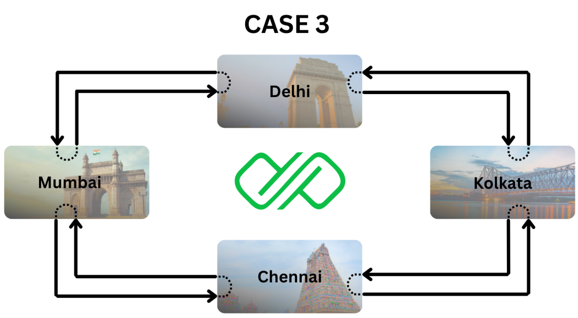

Fig. 10: Visualisation for Route Case 3

In Case 3, each leg of the GQ is modeled as a dedicated round-trip corridor, emphasizing bidirectional operations without stops. The routes include:

- Delhi ⇌ Mumbai
- Mumbai ⇌ Kolkata
- Kolkata ⇌ Chennai
- Chennai ⇌ Mumbai

The focus here is on evaluating network elasticity, vehicle turnaround efficiency, and segment-based carbon emissions. This case reflects the real-world logistics structure of dedicated freight and express passenger services, and how Hyperloop can be operated independently in major commercial corridors.

4.5.4. *Case 4: Variable Pricing with Intermediate Stops and Lower Trip Frequency*

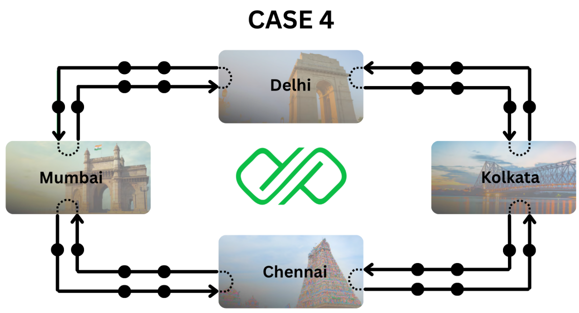

Fig. 11: Visualization of Route Case 4

The final case expands Case 3 by incorporating strategic intermediate cities along each leg. This design combines the operational realism of Case 3 with the regional inclusivity of Case 2, forming a more comprehensive and implementable network model. The detailed routes are:

- Delhi ⇌ Mumbai
  - Intermediate Stops: Jaipur → Ahmedabad → Surat
- Mumbai ⇌ Chennai
  - Intermediate Stops: Pune → Hubli → Bangalore
- Chennai ⇌ Kolkata
  - Intermediate Stops: Vijayawada → Visakhapatnam → Bhubaneswar
- Kolkota ⇌ Delhi
  - Intermediate Stops: → Patna → Varnasi → Lucknow

Case 4 allows the most accurate estimation of total system-wide energy requirements, carbon mitigation potential, and infrastructure demands, while also examining the

5. Feasibility and Competitiveness Analysis of Hyperloop-Based Cargo Transport in the Indian Logistics Sector

To assess the viability and competitiveness of Hyperloop-based cargo transportation within India's evolving logistics ecosystem, a comprehensive pricing model was developed. This model accounts for both capital and operational expenditures, integrates region-specific logistics parameters, and captures dynamic market behavior through four case scenarios representing distinct economic outlooks.

5.1. Capital Expenditure Components

As with any infrastructure-intensive project, substantial capital expenditure (CAPEX) is a prerequisite. The following cost categories were identified and quantified as critical to the establishment of a Hyperloop system, as outlined in the table case-wise:

5.1.1. Tube Construction

The Hyperloop tube infrastructure is envisioned as a combination of mild steel and concrete, extending over a total distance of 5,846 kilometers. The cost of mild steel is considered at INR 37 per kilogram, with a density of 7,800 kg/m³. For the supporting infrastructure, concrete is employed, with a cost of INR 15,000 per cubic meter. The excavation cost is estimated at INR 250 per cubic meter. A construction index of 2 was applied to both steel and concrete costs to reflect implementation complexities.

5.1.2. Track Infrastructure

The track comprises a composite structure of concrete, aluminum, and mild steel. The construction index for concrete remains at 2, while for aluminum and mild steel, a higher construction index of 2.89 is applied, reflecting their processing and assembly requirements.

5.1.3. Land Acquisition

Land acquisition represents the most significant component of capital costs. The project necessitates the acquisition of land spanning 5,864 kilometers in length and 15 meters in width to accommodate two parallel tubes. This allocation includes room for tubes, stations, ingress and egress points, and safety buffer zones. Land costs were assessed at INR 1,650 per square meter.

5.1.4. Structure Compensation

Prior to initiating land development, compensation for existing private buildings, commercial establishments, and privately held land must be addressed. This involves negotiations, purchase agreements, and resettlement processes. The cost structure includes rehabilitation expenses for displaced residents. Drawing parallels with high-speed rail (HSR) projects, a structure compensation rate of INR 0.5 crore per kilometer was assumed, yielding a total structure compensation cost of INR 2,923 crore for the 5,864 km stretch.

5.1.5. Terrain Leveling

Following land acquisition, the terrain must be leveled and prepared for construction. This process includes excavation, land clearing, and surveying. The foundation is based on a tube diameter of 1.6 meters and a depth of 12.5 meters. Using a safety excavation factor of 1.5, the total excavation volume was calculated to be 37.7 m³ per meter of track. The unit excavation cost is INR 250 per cubic meter.

5.1.6. Labor Costs

Labor costs encompass the wages, benefits, and overheads associated with employing the required workforce. A 3:1 skilled-to-unskilled labor ratio was assumed, with daily wage rates of INR 750 for skilled workers and INR 400 for unskilled workers. These values were used to compute total labor expenses based on workforce requirements and construction timelines.

5.1.7. Signaling and Telecommunication

The signaling and telecommunication systems ensure the safe and efficient operation of the Hyperloop. Drawing parallels from metro corridor infrastructure, an estimated cost of INR 5 crores per kilometer was applied. For the full 5,864-kilometer stretch, the total signaling and telecommunication cost was computed accordingly.

5.1.8. Stations

Hyperloop stations serve as the primary interface between cargo handlers and the transportation network. Drawing comparisons with metro infrastructure, the main station cost was assumed to be INR 60 crores, while substations were estimated at INR 40 crores each. Cases 1 and 3 incorporated four main stations, while Cases 2 and 4 included an additional nine substations, reflecting increased network complexity and reach.

5.1.9. Paint and Coatings

Painting and protective coatings are essential for long-term structural integrity and corrosion resistance. Concrete pylons and mild steel tubes are subject to different application requirements. Coating costs for concrete surfaces (210 microns thickness) were taken at INR 290 per unit area, and for steel surfaces (230 microns thickness), at INR 230 per unit area.

5.1.10. Pods

Each cargo pod is estimated to cost INR 40 crores. The number of pods required was determined using the formula: total time divided by headway time. Based on Case 1, considered the baseline scenario, a total of 22 pods was deemed necessary.

To account for unforeseen or miscellaneous expenses, a 15% project margin was added to the total capital expenditure. Consequently, the total CAPEX was estimated at INR 1,797,849.421 crores for Cases 1 and 3, and INR 1,798,263.421 crores for Cases 2 and 4.The breakdown can be referenced from Table 16 and Table 17

5.2. Operational Expenditure Components

Operational expenditures (OPEX) were derived based on Avishkar's proprietary technologies, performance assumptions, safety standards, and energy consumption models. The cost per unit of electrical energy (kWh) is INR 10.81 or 0.26 USD according to [93].

5.2.1. *Levitation Energy Cost*

Levitation is achieved through an onboard Electromagnetic Suspension (EMS) system that eliminates ground friction. Based on Transrapid-derived equations and Avishkar's experimental validations, total drag-related energy losses were evaluated. The EMS system requires 2 kW/ton for levitation and guidance. For a 56.727-ton pod, the energy consumption per journey was found to be approximately 822.29 kWh, corresponding to an expenditure of INR 8,889.01.

5.2.2. *Propulsion Energy Cost*

Propulsion is driven by a Linear Induction Motor (LIM). The total energy demand includes:
a)Aerodynamic drag: 3,454 N at 205.8 m/s cruise speed
b)Levitation drag due to electromagnetic resistance
c)Kinetic energy to accelerate the 56.727-ton pod
Considering a LIM efficiency of 60 percent, the total energy requirement for propulsion per trip was estimated to be 25,014.78 kWh, leading to a cost of INR 270,409.82.

5.2.3. *Thermal Energy Cost*

Thermal management is vital for maintaining safe operating temperatures. Phase Change Composites (PCCs) were used for battery cooling, and immersion cooling was used for other systems. Using the Darcy-Weisbach equation and standard pump power models, the total thermal energy demand was computed as 0.8119 kWh per trip, costing INR 8.78.

5.2.4. *Cabin Energy Cost*

Although the Hyperloop cargo pods do not require extensive lighting or heating, some energy is consumed for air conditioning and monitoring systems to preserve temperature-sensitive cargo. Total cabin energy consumption per trip was 851.84 kWh, corresponding to a cost of INR 9,208.35.

5.2.5. *Vacuum Leakage*

Maintaining a vacuum environment is essential to minimize aerodynamic drag. Leakage occurs at interfaces such as:

- Gate valves (every 1 km, 4 m dia): 111.28 m³/hr
- Emergency exits (every 1 km, 1 m dia): 27.82 m³/hr
- Pump flanges (2 per bellow): 31.07 m³/hr
- Bellow joints (4 m dia): 111.28 m³/hr

Three vacuum pumps rated at 671.4 kW each operate 24/7, with two active and one on standby. For a dual-tube system, the total daily energy consumption was estimated at 25,002.51 kWh, amounting to INR 270,277.10.

5.2.6. *Salaries*

Despite automation, human oversight is required at both terminals. A lean team of technical personnel, safety officers, and logistics coordinators ensures round-the-clock operations. For Case 1 and 3, salary cost per trip was INR 3,389.53. For Case 2 and 4, including the additional 9 substations, the cost increased to INR 16,947.65.

5.2.7. *Airlocks Energy*

Airlocks are necessary for maintaining tube pressure integrity during pod entry and exit. Based on calculated volume and vacuum pump specifications (32,000 m³/hr, 671.4 kW), energy consumption per trip was 698.24 kWh.
This translated to INR 7,547.97 for Cases 1 and 3. For Cases 2 and 4, the increased complexity due to more substations led to a cost of INR 18,869.94. Refer Table 13 and Table 14 for full breakdown.

Category	**Cost (INR)**
Levitation Energy	8,889.0129
Propulsion (LIM) Energy	270,409.8236
Thermal Energy	8.7762
Cabin Energy	9,208.3528
Vacuum and Leakage Energy	270,277.0991
Airlock Energy	7,547.9744
Salaries	3,389.5302
Total Cost	**569,730.5692**

TABLE 13: OPERATIONAL EXPENDITURE BREAKDOWN - CASE 1 AND 3

5.3. Hyperloop Cargo Pricing Model – Case-Wise Analysis

Following the establishment of capital and operational expenditure, we evaluated the cargo pricing structure under four distinct scenarios, each designed to reflect different operational and infrastructure conditions. The fundamental

Category	Cost (INR)
Levitation Energy	8889.01293
Propulsion (LIM) Energy	270409.8236
Thermal Energy	8.776170952
Cabin Energy	9208.352763
Vacuum and Leakage Energy	270,277.0991
Airlock Energy	18869.936
Salaries	16947.65102
Total Cost	**594610.6516**

TABLE 14: OPERATIONAL EXPENDITURE BREAKDOWN - CASE 2 AND 4

pricing strategy assumes that the operational cost is recovered through ticket pricing, while capital expenditure is recovered through long-term profits

To support the financial feasibility of capital-intensive green infrastructure such as Hyperloop, this study incorporates the assumption of Viability Gap Funding (VGF)—a fiscal mechanism wherein the government or funding body provides a capital subsidy of up to 20 percent to bridge the gap between project cost and projected revenues. VGF is particularly important for early-stage infrastructure with high upfront costs and long gestation periods, where economic benefits (e.g., emissions reduction, time savings) exceed direct financial returns.

In the case of Hyperloop, which offers significant environmental benefits—including near-zero operational emissions, low land footprint, and alignment with India's Net Zero by 2070 target—VGF provides a strategic tool to unlock private sector participation [48].

The environmental orientation of Hyperloop aligns it with the investment mandates of global financial institutions such as the World Bank, International Finance Corporation (IFC), and the Asian Development Bank (ADB), all of which offer concessional climate finance for low-carbon transport infrastructure. Specifically, the IFC's Green Bond Program and the World Bank's Climate Investment Funds (CIF) support transit projects that significantly reduce greenhouse gas (GHG) emissions while promoting sustainable development [49] [50].

Nationally, India's Department of Economic Affairs administers the VGF Scheme for Public–Private Partnerships (PPPs) in infrastructure, which has been extended to include environmentally sustainable projects in the transport sector under the National Infrastructure Pipeline (NIP) [51]. Given these opportunities, a 20% VGF assumption has been included in the cost analysis of this study, reflecting the potential for carbon-conscious infrastructure like Hyperloop to secure partial capital support from both domestic and international green finance mechanisms.

5.3.1. *Inflation :*

For the economic assumptions to account for the impact of inflation and future value of money in this study, a Discounted Cash Flow (DCF) approach was employed. The Net Present Value (NPV) formula was applied to project costs and benefits over time, adjusting them to present-day values.

The calculations followed the general formula:

$$\text{NPV} = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} - \text{Initial Investment}$$

where:

- R_t = Net cash flow (inflows minus outflows) at time t
- i = Discount rate (reflecting inflation, risk, and opportunity cost)
- t = Time period (e.g., years, months)
- n = Total number of periods.

This method enables more accurate financial evaluation by incorporating a discount rate that reflects inflation, opportunity cost, and capital risk. By discounting future cash flows, the analysis ensures that investment decisions for infrastructure options like Hyperloop are based on realistic, time-adjusted economic projection Below is the detailed analysis for each case:

5.3.2. *Case 1:Baseline Scenario (Direct Point-to-Point Without Stops)*

In this scenario, the headway time is calculated as 33.2115 minutes. With a total of 1,440 operational minutes in a day (24 hours), this results in approximately 52 trips per day. Factoring in a 20% increase in trip frequency due to the presence of two parallel tubes and a fixed number of pods, the system is expected to transport 3902.26 tonnes of cargo per day, assuming each platoon carries 75 tons.

The base operational cost per kilogram for a full 5,864 km journey was calculated to be INR 7.60 by the below formula:

$$C = \frac{O \times N}{Q}$$

where:

C = Base operational cost per kg per trip for 5864 km
O = OPEX cost (one-way)
N = Number of trips per day
Q = Total cargo shifted per day (kg)

By dividing this cost by the total distance, the cost per kilometer per kilogram was derived as INR 0.0013.

Considering a standard average speed of 65 km/h for road and rail freight, the total time required to cover a distance of 5,864 km is approximately 90.22 hours. In contrast, the proposed Hyperloop model completes the same journey in just 7.91 hours, resulting in a time savings of 82.31 hours. As per NITI Aayog estimates, the value of time for freight is INR 200 per tonne per hour [38]. Based on this, the time savings translate to an additional value of INR 16.46 per kilogram, which can be factored into the pricing structure.

Time value is included to account for the economic benefits of faster delivery. For time-sensitive goods, reduced transit time lowers inventory and spoilage costs. As per NITI

Aayog, valuing time saved at INR 200 per tonne per hour allows us to reflect these gains in pricing, making Hyperloop's speed advantage economically meaningful.
To determine the total transportation cost between any two stations, the following formula was applied:

$$C_{\text{total}} = \left(\frac{C_{\text{base}} \cdot D}{5,864}\right) + \left(C_{\text{per km}} \cdot D\right) + \left(\frac{C_{\text{Value of hyperloop}} \cdot D}{5,864}\right)$$

where:

- C_{total} = Total Cost per kilogram between two stations.
- C_{base} = Base Operational cost oer kilogram for 5,864 km (INR 7.60) .
- $C_{\text{per km}}$ = Cost per kilometer per kilogram.
- $C_{\text{Value of hyperloop}}$ = Cost Charged per kilogram for time savings (INR 16.46).
- D = Distance between two stations.

A profit margin of 15% was assumed to this base cost to arrive at the final price charged.

$$P_{\text{Final}} = C_{\text{total}} + P \cdot C_{\text{total}}$$

where:

- P_{total} = Price per kilogram between two stations.
- C_{Final} = Final cost per kilogram between two stations.
- P = Profit Percentage

Under this scenario of case 1:

- The total annual profit was estimated at INR 1,46,539.02 crores.
- The total annual revenue generated was INR 2,51,803.70 crores.
- The capital expenditure recovery (break even) period without inflation was calculated to be 9.81 years and with inflation it came to be around 13 years.

Cost between all the stations can be refered from Table 18

5.3.3. *Case 2:Scenario with Intermediate Stops*

Case 2 builds directly upon the structure of Case 1 but incorporates multiple intermediate stops. The headway time remains the same at 33.2115 minutes, resulting in 52 daily trips (including the 20% increase due to dual-tube operations). The daily cargo volume remains consistent at 3,902.26277 tons. The base operational cost per kilogram for the full journey of 5,864 km is INR 7.93.This results in a cost per kilometer per kilogram of INR 0.00136. Using the same cost calculation formula and maintaining a 15% profit margin:

- The annual profit was estimated at INR 1,46,638.42 crores.
- The total annual revenue was calculated at INR 2,52,565.78 crores.
- The break even period for capital expenditure recovery without inflation was determined to be 9.81 years and with inflation is 13 years.

Cost between stations can be refered from Table 19

5.3.4. *Case 3:U-Turn Adjustment and Variable Route-Based Pricing*

In Case 3, the operational structure changes due to an additional 3 minutes allocated for pod U-turns, increasing the headway time to 36.2115 minutes. Consequently, the system completes approximately 48 trips per day, shifting an estimated cargo volume of 3578.97 tonnes. The base operational cost per kilogram for the full route remains at INR 7.60. However, unlike previous cases, the cost per kilometer per kilogram varies based on the distance between individual main stations. These values were obtained via interpolation of the earlier calculated average cost per km per kg. The pricing model follows the same equation as before, and a 15% profit margin was added to the base cost.

- The annual revenue was INR 2,52,565.78crores and profit values were computed to be INR 1,18,299.29 crores based on station-specific pricing.
- The breakeven years for this case were determined to be 12.16 years without inflation and with inflation it was around 16 years.

Refer to Table 20

5.3.5. *Case 4:Variable Pricing with Intermediate Stops and Lower Trip Frequency*

Case 4 extends the logic of Case 3 by incorporating intermediate stations along with variable pricing and a reduced number of trips. The headway time is again 36.2115 minutes, leading to 48 trips per day. The expected daily cargo volume is 3,578.98 tonnes. The base operational cost per kilogram for the full 5,864 km route is INR 7.93. Similar to Case 3, the cost per kilometer per kilogram was interpolated for each route segment between stations, reflecting more granular pricing based on distance.

The total cost between stations was computed using the established formula, and a profit margin of 70% was assumed as before.

- Annual profits came to be INR 1,16,906.77 crores and revenues were calculated to be INR 1,63,068.933 crores.
- The break even period was calculated to be 12.31 years without inflation and with inflation it was around 17 years.

The cost between stations can be refered from Table 21
The Summary table of all the cases talked before with the break even years without inflation and with inflation can be refered from Table 22.

Based on the breakeven analysis, Case 1 and Case 2, with shorter recovery periods, are better suited for private investment due to quicker returns and lower risk. In contrast, Case 3 and Case 4, with longer payback periods, are more appropriate for public sector funding, where broader economic or social impact justifies delayed profitability. This allocation strategy is discussed further in the next section.

To conduct a more realistic analysis, we performed a demand sensitivity study by maintaining a constant ticket price and varying the demand levels (e.g., 50%, 60%, etc.). For each demand scenario, we computed the breakeven years both without accounting for inflation and with inflation, as shown in Table 23 and Table 24, respectively. Recognizing that inflation rates are not fixed, we further analyzed the breakeven periods using three different discount factors to assess the sensitivity of results under varying economic assumptions. This analysis is presented in Table 25.

5.4. Key Results from the Pricing Model:

5.4.1. *Operational Performance :*

- Headway times ranged from 33.21 to 36.21 minutes, depending on stop configurations and turnaround assumptions.
- With two tubes and fixed pods, daily trip capacities ranged from 48 to 52 trips, allowing for substantial daily cargo movement.
- Total daily cargo throughout ranged from 3578 to 3902 tonnes, depending on headway and platoon assumptions.

5.4.2. *Cost Breakdown (Per Kg per Km) :*

- Base operational cost (without variable components) across 5864 km: INR 7.59/kg (Case 1 & 3) and INR 7.93/kg (Case 2 & 4). Effective cost per km per tonne varied from INR 1.30–1.36.
- Variable cost interpolations were added for realistic station-to-station pricing in Cases 3 and 4.
- Time savings: 82.31 hours (compared to 90.22 hours by road/rail at 65 km/h)
- Time value gain: INR 16.46/kg, factored into total cost using NITI Aayog's valuation of INR 200/tonne/hr.

5.4.3. *Profitability Assumptions :*

- Profit margins assumed 15 percentage in all cases
- Annual profit estimates ranged from:
  Case 1 : INR 1,46,539.02 crores
  Case 2 : INR 1,46,638.42 crores
  Case 3 : INR 1,18,299.29 crores
  Case 4 : INR 1,16,906.77 crores

5.4.4. *Demand and Sensitivity Analysis*

- Breakeven is strongly influenced by demand levels—higher utilization significantly shortens payback time.This means the project is very sensitive to underutilization — consistent demand is essential.
- Once inflation and the time value of money are considered, breakeven years increase by 5–13 years across all cases.
- Sensitivity analysis reveals that even modest increases in inflation can substantially delay returns—a critical input for investors and policymakers.This confirms the project is highly sensitive to macroeconomic volatility.
- To evaluate the breakeven dynamics under both fluctuating demand and varying economic conditions, a Monte Carlo simulation was performed over 1,000 iterations for Case 4. In each iteration, demand levels were randomly selected between 50% and 100%, and a random discount rate—either 1%, 3%, or 5%—was applied independently for each year to reflect uncertainty in inflation and capital cost. This approach captures a more realistic financial environment where both revenue and macroeconomic parameters vary unpredictably over time. The resulting distribution of breakeven years is summarized in Table 15.
- The results indicate that breakeven most commonly occurs between years 29 and 32, suggesting a later recovery period compared to fixed-rate models. Very few cases reached breakeven significantly earlier or later, indicating a reasonably consistent long-term return profile despite annual financial volatility. These insights highlight the importance of robust financial planning and long-term commitment when operating in uncertain macroeconomic landscapes.

Breakeven Year	Frequency
24	2
25	8
26	31
27	48
28	77
29	122
30	142
31	140
32	132
33	86
34	79
35	62
36	37
37	14
38	12
39	6
>40	2

TABLE 15: BREAKEVEN YEAR FREQUENCY WITH RANDOM DISCOUNT RATES

Expenditure	Cost (INR)	Rates
Steel for tube	3318821748324	37 INR/Kg
Concrete for tube	1703607031339	15000 INR/m^3
Track expenditure	2122098000000	-
Land acquisition	7234425000000	1650 INR/m^2
Structure Compensation	29230000000	0.5 Cr INR/Km
Terrain leveling	5508602286	250 INR/m^3
Labour	891620228000	400 INR - Unskilled 750 INR - Skilled
Signalling	292300000000	5 Cr INR/Km
Main stations (4)	2400000000	60 Cr INR/Station
Paint coatings	10506097143	290 INR - con (210 microns) 230 INR- steel (230 microns)
Project margin (0.15)	2341577506064	15%
Pods (22)	26400000000	40 Cr INR/Pod
Total (INR)	**17978494213156**	-
Total (Crs INR)	**1797849.421**	-

TABLE 16: CAPITAL EXPENDITURE FOR CASE 1 AND CASE 3

Expenditure	Cost (INR)	Rates
Steel for tube	3318821748324	37 INR/Kg
Concrete for tube	1703607031339	15000 INR/m^3
Track expenditure	2122098000000	-
Land acquisition	7234425000000	1650 INR/m^2
Structure compensation	29230000000	0.5 Cr INR/Km
Terrain leveling	5508602286	250 INR/m^3
Labour	891620228000	400 Rs - Unskilled 750 INR - Skilled
Signalling	292300000000	5 Cr INR/Km
Main stations (4)	2400000000	60 Cr INR/Station
Stations in between (9)	3600000000	40 Cr INR/Station
Paint coatings	10506097143	290 INR - con (210 microns) 230 INR- steel (230 microns)
Project margin	2341577506064	15
Pods (22)	26400000000	40 Cr INR/Pod
Total (INR)	**17982634213156**	-
Total (Crs INR)	**1798263.421**	-

TABLE 17: CAPITAL EXPEDITURE OF CASE 2 AND CASE 4

Route	Distance (Km)	OPEX cost (INR)	Value of Hyperloop (INR)	Profits (INR)	Price (INR)
Delhi - Mumbai	1419	3.68775312	3.983095861	1.150627347	8.821476328
Mumbai - Chennai	1290	3.352502836	3.620996237	1.046024861	8.019523935
Chennai - Kolkata	1684	4.376445563	4.726943925	4.376445563	10.46889791
Kolkata - Delhi	1453	3.77611366	4.078532971	3.77611366	7.854646631

TABLE 18: COST BREAKDOWN OF CASE 1

Routes	Distance (km)	Opex cost (INR)	Value of Hyperloop (INR)	Profits (INR)	Price (INR)
Chennai - Bangalore	350	0.9153200094	0.9824408396	0.2846641273	2.182424976
Bangalore - Hubli	350	0.9153200094	0.9824408396	0.2846641273	2.182424976
Hubli - Pune	440	1.150688012	1.235068484	0.3578634744	2.74361997
Pune - Mumbai	150	0.392280004	0.4210460741	0.1219989117	0.9353249898
Chennai - Mumbai					**8.043794913**
Mumbai - Surat	199	0.5204248053	0.5585877916	0.1618518895	1.240864487
Surat - Ahmedabad	270	0.7061040072	0.7578829334	0.2195980411	1.683584982
Ahmedabad - Jaipur	670	1.752184018	1.880672464	0.5449284723	4.177784955
Jaipur - Delhi	280	0.7322560075	0.7859526717	0.2277313019	1.745939981
Mumbai - Delhi					**8.848174404**
Delhi - Lucknow	323	0.8447096087	0.9066525462	0.2627043232	2.014066478
Lucknow - Varanasi	280	0.7322560075	0.7859526717	0.2277313019	1.745939981
Varanasi - Patna	260	0.679952007	0.7298131951	0.2114647803	1.621229982
Patna - Kolkata	590	1.542968016	1.656114558	0.4798623861	3.67894496
Delhi - Kolkata					**9.060181402**
Kolkata - Bhubaneswar	439	1.148072812	1.23226151	0.3570501483	2.73738447
Bhubaneswar - Visakhapatnam	4407	1.150688012	1.235068484	0.3578634744	2.74361997
Visakhapatnam - Vijayawada	350	0.9153200094	0.9824408396	0.2846641273	2.182424976
Vijayawada - Chennai	455	1.189916012	1.277173091	0.3700633655	2.837152469
Kolkata - Chennai					**10.50058189**

TABLE 19: COST BREAKDOWN OF CASE 2

Routes	Distance (km)	Cost per km-kg (INR)	OPEX cost (INR)	Value of Hyperloop (INR)	Profits (INR)	Price (INR)
Delhi - Mumbai	1419	0.0003154	2.29144085	3.983095861	0.9411805066	7.215717218
Mumbai - Chennai	1290	0.0002867	2.046139261	3.620996237	0.8500703247	6.517205823
Chennai - Kolkata	1684	0.0003743	2.8185627	4.726943925	1.131825994	8.677332619
Kolkata - Delhi	1453	0.0003229	2.35732583	4.726943925	0.9653788202	7.401237621

TABLE 20: COST BREAKDOWN OF CASE 3

Routes	Distance (Kms)	Cost per km-kg (INR)	OPEX Cost (INR)	Time Savings (INR)	Profits (INR)	Price (INR)
Chennai - Bangalore	350	0.00008119	0.46908	0.98244	0.21773	1.66925
Bangalore - Hubli	350	0.00008119	0.46908	0.98244	0.21773	1.66925
Hubli - Pune	440	0.00010207	0.59889	1.23507	0.27509	2.10905
Pune - Mumbai	150	0.00003479	0.19407	0.42105	0.09227	0.70739
Chennai - Mumbai						**6.15494**
Mumbai - Surat	199	0.00004616	0.25973	0.55859	0.12275	0.94107
Surat - Ahmedabad	270	0.00006264	0.35685	0.75788	0.16721	1.28194
Ahmedabad - Jaipur	670	0.00015543	0.94769	1.88067	0.42425	3.25262
Jaipur - Delhi	280	0.00006495	0.37072	0.78595	0.17350	1.33017
Mumbai - Delhi						**6.80580**
Delhi - Lucknow	323	0.00007493	0.43087	0.90665	0.20063	1.53815
Lucknow - Varanasi	280	0.00006495	0.37072	0.78595	0.17350	1.33017
Varanasi - Patna	260	0.00006032	0.34303	0.72981	0.16093	1.23377
Patna - Kolkata	590	0.00013687	0.82358	1.65611	0.37195	2.85165
Delhi - Kolkata						**6.95375**
Kolkata - Bhubaneshwar	439	0.00010184	0.59742	1.23226	0.27445	2.10414
Bhubaneswar - Visakhapatnam	440	0.00010207	0.59889	1.23507	0.27509	2.10905
Visakhapatnam - Vijayawada	350	0.00008119	0.46908	0.98244	0.21773	1.66925
Vijayawada - Chennai	455	0.00010555	0.62089	1.27717	0.28471	2.18277
Kolkata - Chennai						**8.06520**

TABLE 21: COST BREAKDOWN OF CASE 4

Route	Case 1	Case 2	Case 3	Case 4
Chennai - Mumbai	8.019523935	8.043794913	6.517205823	6.15494
Mumbai - Delhi	8.821476328	8.848174404	7.215717218	6.80580
Delhi - Kolkata	7.854646631	9.060181402	7.401237621	6.95375
Kolkata - Chennai	10.46889791	10.50058189	8.677332619	8.06520
Breakeven without inflation	9.81 years	9.81 years	12.16 years	12.3 years
Breakeven with inflation	13 years	13 years	16 years	17 years

TABLE 22: SUMMARY OF ALL CASES

Demand	Case 1	Case 2	Case 3	Case 4
0.5	19.62998712	19.62119777	24.315945	24.61124715
0.6	16.3583226	16.35099814	20.2632875	20.50937263
0.7	14.02141937	14.01514127	17.36853214	17.57946225
0.8	12.26874195	12.26324861	15.19746563	15.38202947
0.9	10.9055484	10.90066543	13.50885833	13.67291509
1	9.814993559	9.810598886	12.13886477	12.30562358

TABLE 23: BREAK EVEN WITHOUT INFLATION

Demand	Case 1	Case 2	Case 3	Case 4
0.5	28	29	36	37
0.6	23	23	29	29
0.7	19	19	24	25
0.8	17	17	21	21
0.9	15	15	18	19
1	13	13	16	17

TABLE 24: BREAK EVEN WITH INFLATION

Inflation rate	Case 1	Case 2	Case 3	Case 4
1.16(base case)	13	13	16	17
3	15	15	20	20
5	18	18	27	28

TABLE 25: SENSITIVITY

6. Machine Learning Model Evaluation Report

6.1. Introduction

In order to assess the feasibility of Hyperloop as a transportation mode, a comprehensive machine learning (ML) approach was implemented. Instead of solely relying on static cost comparisons, the objective was to utilize data-driven modeling to capture the complex interplay of factors influencing transport mode selection. This approach enabled a deeper understanding of when Hyperloop might offer a viable advantage compared to existing modes such as rail, road, air, and water.
The process involved collecting real-world transportation data, engineering relevant features, applying preprocessing steps, and training multiple ML models capable of predicting the optimal mode of transportation based on key logistics variables. These variables included not only economic metrics like cost but also time sensitivity, environmental impact, and cargo characteristics. The trained models were then used to analyze scenarios and uncover insights about the types of products and conditions where Hyperloop would be a preferred mode.

6.2. Data Set Description

The dataset consisted of structured numerical feature vectors (X) representing logistics and transportation characteristics, alongside target labels (y) representing the actual mode of transport used. The transportation modes under consideration included rail, road, air, water, and Hyperloop (included as a theoretical mode for analysis).
Key features

- Cost per kg per km: Quantifying the transportation expense.
- Time Taken (hours): Capturing delivery duration.
- Carbon Footprint (g CO_2/kg/km): Measuring environmental impact.
- Urgency: Indicating delivery speed requirements (low, medium, high).
- Perishability: Indicating whether the product required special handling due to its perishable nature.

The dataset was carefully balanced across the different transport modes using stratified sampling during the train-test split (60% training, 40% testing). This ensured that each transport mode was proportionally represented, avoiding bias during model training.

6.3. Pre-processing Steps

Several preprocessing steps were executed to prepare the dataset for ML modeling:

6.3.1. *Label Encoding*

The target labels, originally categorical (e.g., Rail, Road, Air, Hyperloop), were numerically encoded to make them compatible with ML algorithms.

Transport Mode	Encoded Label
Rail	0
Road	1
Air	2
Hyperloop	3

Table 26: Label Encoding for Transport Modes

6.3.2. *Train-Test Split with Stratification*

A stratified 60:40 train-test split was applied to preserve class proportions across both training and testing sets, ensuring fair representation and model generalization.

6.3.3. *Feature Scaling*

Because features had varying units and scales (e.g., INR/kg/km for cost, hours for time, kg CO_2 for emissions), scaling was applied to prevent features with larger numeric ranges from dominating model learning. Two scaling techniques were used based on model requirements:

- StandardScaler (also known as Z-score normalization) : Applied to features for models sensitive to Gaussian distributions.
- MinMaxScaler(Normalization to [0,1] range) : Applied for models sensitive to absolute distance calculations.

Scaling was performed only on training data, and the same transformation was applied to the test set to prevent data leakage.

6.4. Model Development Approach

Multiple ML models were trained on the preprocessed dataset to learn the patterns governing optimal transportation mode selection. The ML pipeline involved:

- Training each model using the stratified, scaled training data.
- Evaluating models on the independent test set.
- Using cross-validation during training to avoid overfitting and assess model robustness.
- Incorporating ensemble learning to combine multiple classifiers for improved predictive stability.

6.5. Rule-Based Transport Mode Selection Logic

6.5.1. *Objective*

This rule-based system is designed to estimate the optimal transportation mode—Rail, Road, Air, or Hyperloop—for shipments between two cities. The decision is based on engineered metrics that quantify cost, time, and carbon emissions. These metrics are combined into a weighted scoring model that adapts dynamically depending on shipment-specific factors such as demand level and perishability. The goal is to select a transportation mode that best balances efficiency, expense, and environmental impact, tailored to the urgency and sensitivity of the shipment.

6.5.2. *Methodology*

Step 1: Estimation of Raw Metrics Given a shipment distance DDD in kilometers, the model first computes raw, empirical estimates for three critical parameters—cost, time, and carbon emissions—for each transport mode. These values are derived by applying fixed per-kilometer rates that reflect typical operational characteristics of each mode.

Transport Mode	Cost(INR/km)	Time(hours)	Carbon Emissions(g CO_2/km)
Rail	0.00136×D	D/60	0.00996×D
Road	0.0028×D	D/50	0.062×D
Air	0.025×D	D/850	0.6×D
Hyperloop	0.00415×D	D/765	0.006×D

TABLE 27: COMPARISON OF COST, TRANSIT TIME, AND CARBON EMISSIONS FOR DIFFERENT FREIGHT TRANSPORT MODES IN INDIA

Step 2: Normalization of Features Since the metrics are on different scales, normalization is applied using pre-fitted scalers (StandardScaler or MinMaxScaler) based on historical data, bringing all features to a comparable scale.

Step 3: Weighted Score Computation

$$\begin{aligned}\text{Score}_{\text{mode}} = w_{\text{cost}} \cdot \text{Cost}_{\text{mode}} + w_{\text{time}} \cdot \text{Time}_{\text{mode}} \\ + w_{\text{carbon}} \cdot \text{Carbon}_{\text{mode}}\end{aligned}$$

Base weights:

- Cost weight: 0.452
- Time weight: 0.281
- Carbon weight: 0.267

These weights are dynamically adjusted depending on perishability and demand urgency:

- High perishability or demand increases time weight.
- Perishability slightly increases carbon weight.
- Cost weight is recalculated to ensure the weights sum to 1.

Step 4: Mode Selection The transport mode with the lowest total weighted score is selected as the optimal transportation option for the given shipment.

Example Application

For a 1000 km shipment (e.g., Chennai to Bangalore) with high demand and no perishability, raw metrics are calculated, normalized, weights are adjusted, and a final score is computed for each mode. In this scenario, Rail or Hyperloop often emerge as optimal choices due to balanced cost, time, and emissions performance.

6.5.3. *Strengths of Rule-Based Model*

- **Interpretability:** Every decision step is transparent and explainable.
- **Customizability:** Weights and formulas can be adjusted to reflect changes in business priorities or policy regulations.
- **Domain Integration:** Shipment attributes like perishability and demand directly influence the model behavior.

6.6. Model Predictions Report

6.6.1. *Model Performance Metrics*

Model Type	Accuracy	Precision	Recall	F1-Score
Ensemble Voting	1.00	1.00	1.00	1.00
MLFFNN (Neural Network)	1.00	0.97	1.00	0.98
XGBoost	1.00	0.97	1.00	0.98
KNN	0.95	0.97	0.96	0.97
SVM	0.94	0.72	0.70	0.71
Logistic Regression	0.94	0.48	0.46	0.47
Random Forest	1.00	0.97	1.00	0.99
LightGBM	1.00	0.97	1.00	0.98

TABLE 28: MODEL PERFORMANCE METRICS COMPARISON

6.6.2. *Predictions Distribution*

- Hyperloop : 67.4%
- Rail: 23%
- Road: 0.8%
- Air: 0.8%

6.6.3. *Key Insights*

- The majority of predictions favored Hyperloop, particularly for high urgency shipments, indicating that the models consistently identified Hyperloop as the most suitable option when quick delivery was critical.
- Highly accurate models (Ensemble, Neural Network, Gradient Boosting) generalized well across classes despite dataset imbalance.

- Simpler models like Logistic Regression and SVM struggled with class imbalance, particularly failing to predict minority classes such as Air and Road.

6.6.4. *Handling Class Imbalance*

Due to the inherent class imbalance in the dataset, macro-averaged F1-scores were used to better reflect model performance across all classes, ensuring that minority classes were not ignored despite high overall accuracy.

6.7. Summmary Insight

Both the rule-based and machine learning models identified that Hyperloop consistently emerged as the optimal mode for shipments with high urgency or perishability. The rule-based model provides transparent logic for such decisions, while the machine learning models offer high predictive accuracy when trained on sufficient data. This combination allows for both reliable predictions and understandable decision-making frameworks in real-world logistics planning.

7. Socio-Economic Aspects of Hyperloop Technology for Freight Logistics in India

The social implications of Hyperloop technology represent one of the foundational aspects of this study, as they align its technological and economic capabilities with the broader goal of national development for India and the overall societal well-being [6]. This report undertakes a comprehensive economic analysis of four key metropolitan regions — Delhi, Mumbai, Chennai, and Kolkata — along with their surrounding urban and semi-urban clusters, which together form the backbone of India's commercial and logistical network [7]. From the previous subsections, each of these logistic cases were analysed with 4 different cases. While the financial evaluation of the cases focuses on metrics such as operating margins, investment returns, and payback periods, our broader objective is to assess how Hyperloop can contribute meaningfully to the quality of life for diverse communities [8].
As with any impactful technological innovation, the ultimate measure of success lies in its ability to address human challenges and close systemic gaps. Hyperloop's proven ability to drastically reduce transit times[10] has far-reaching potential for public health, particularly in strengthening vaccine delivery, emergency medical logistics, and overall healthcare resilience . At the same time, it establishes chances to empower MSMEs, enhance rural producers' access to the supply chain, and promote more equitable economic growth[6]. In addition to supporting safer, cleaner communities, the system's low emissions and inherent energy efficiency help achieve climate goals [9]. Furthermore, its capacity to facilitate rapid mobilization during disasters positions it as a strategic asset in India's future-ready infrastructure landscape [9]. In the sections that follow, we examine these social dimensions in greater depth via data-driven insights, predictive modeling, and comparative analysis. The aim is to demonstrate how Hyperloop can become a catalyst for inclusive, resilient, and sustainable development across India [6].

The case study taken as reference introduces Hyperloop technology into India's freight logistics landscape, especially along the critical Delhi – Mumbai corridor, promises transformative socio-economic benefits [7][52]. Drawing from projections, government reports, and recent academic and industry analyses, this report details the quantitative and qualitative impacts of Hyperloop on time-sensitive logistics, cost efficiency, agricultural and MSME upliftment, carbon and energy efficiency, job creation, healthcare supply chain resilience, road decongestion, and disaster response [6][9][9]. Comparative insights with existing freight modes (road, rail, and air) are provided, with projections and data integrated from the latest national and sectoral studies [52][8].

7.1. Time Sensitivity:

In a country as vast, populous, and geographically diverse as India, time sensitivity is a critical determinant of freight transport efficiency — particularly in sectors where delivery speed is directly linked to economic value and societal impact. Timely freight movement is not merely a matter of convenience; it is fundamental to the functioning of essential industries such as healthcare, agriculture, pharmaceuticals, and disaster response, where even minor delays can result in severe consequences. For temperature-sensitive and perishable goods, including vaccines, insulin, blood plasma, diagnostic samples, and fresh produce delays during transit can lead to spoilage, loss of potency, reduced shelf life, and substantial financial losses. These inefficiencies propagate through supply chains, increasing costs, eroding reliability, and in critical sectors such as healthcare, potentially endangering lives.
India's key metropolitan freight corridors, in the case the most notable is the Delhi–Mumbai axis and serve as vital arteries for economic activity, yet remain constrained by congestion, infrastructural bottlenecks, and inconsistent delivery timelines. Along such important routes addressing time sensitivity is therefore not only a logistical concern, but a strategic economic and public health imperative. In this context, the proposed Hyperloop technology provides reliable high speed transport and presents a promising opportunity to redefine logistical standards by offering ultra-fast, reliable, and energy-efficient alternatives.
To illustrate the significance of time as a limiting factor, we begin this analysis with a comparison of average transit times across key modes of transport, chosen modes are road, rail, air, and our proposed Hyperloop—on the Delhi–Mumbai corridor, which handles a substantial volume of India's high-value freight. This comparison provides a baseline understanding of the limitations of existing systems and the transformative potential of next-generation infrastructure in addressing time-critical logistical needs.
The Mumbai–Delhi corridor was chosen as the focus case study for this comparative transport study due to its economic, logistical, and geographic significance. This corridor forms a critical segment of India's Golden Quadrilateral, connecting the nation's financial capital with its political hub. It spans diverse terrains, includes both high-density industrial clusters and agricultural zones, and witnesses heavy freight movement of both perishables and manufac-

tured goods. The complexity of this corridor—marked by high congestion, multiple logistics nodes, and multimodal infrastructure—makes it an ideal case study to evaluate the practical viability and comparative efficiency of emerging technologies like Hyperloop. Insights drawn from this corridor are likely to be representative of challenges and opportunities that exist across India's broader transport ecosystem.

The Mumbai–Delhi freight corridor represents a critical testbed for next-generation logistics solutions in India. The following conclusions highlight Hyperloop's transformative potential in speed, cost-efficiency, and strategic viability along this high-volume route.

Key Insight	Details
Hyperloop Enables Game-Changing Speed	Reduces transit time to under 2 hours vs. 3–4 days by road, 16–27 hours by rail, and 2 hours by air. Major improvement in perishables and responsiveness.
Air Freight's Cost Barrier	Air freight costs INR 80/kg–INR 150/kg; Hyperloop offers similar delivery times at a **fraction of the cost**, enabling mass express logistics for MSMEs.
Road's Declining Relevance	Road takes up to 96 hours and is prone to spoilage. Still useful for low-value, non-urgent cargo, but not competitive for time-critical goods.
Policy & Planning Implications	The Mumbai–Delhi corridor is ideal for pilot deployment of Hyperloop—offering scalability and strong economic rationale for first-phase investment.

TABLE 29: CORRIDOR SPECIFIC CONCLUSIONS

7.1.1. *Mode of transport Comparison*

The efficiency of freight movement along the Delhi–Mumbai corridor, considered India's busiest route, varies significantly by transport mode. While road and rail remain dominant due to affordability and coverage, their transit times range from several hours to days, making them suboptimal for time-sensitive cargo. Air freight offers rapid delivery but at high costs, limiting its accessibility. Hyperloop, as a next-generation transport mode, promises to deliver freight in under 2 hours which is comparable to air, but at a fraction of the cost. The following graph illustrates the stark differences in transit times, emphasizing Hyperloop's transformative potential for just-in-time logistics and cold chain delivery. Table 30 is an overview of the average transit time and typical freight vehicle used for road, rail, air, and proposed Hyperloop systems. It highlights Hyperloop's potential to match air transport in speed while offering a more scalable and potentially cost-effective logistics solution.

Mode of transport (Name of vehicle)	Time
Road (Multi-axle truck)	3–4 days (normal highways) 1.5–2 days (expressway)
Rail (Kisan Express)	16–27 hrs
Air (Indigo cargo)	Around 2 hrs
Hyperloop (hyperloop)	1.91 hrs (approx 2)

TABLE 30: COMPARISON OF FREIGHT TRANSIT TIMES AND REPRESENTATIVE VEHICLES ACROSS TRANSPORT MODES ON THE DELHI–MUMBAI CORRIDOR

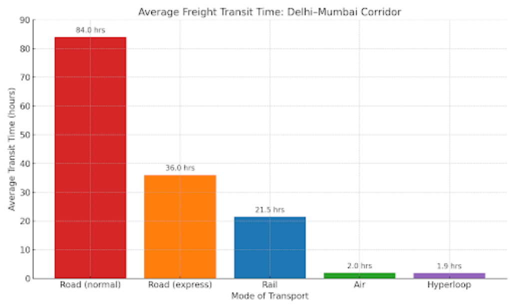

Fig. 12: Comparison of average freight transit times by mode on the Delhi–Mumbai corridor, highlighting Hyperloop's significant time advantage.

Hyperloop's sub-2-hour transit time between Delhi and Mumbai is a tenfold improvement over rail and road, and matches air cargo in speed but at a fraction of the cost. For cold chain industries (agriculture, pharma), this speed is critical: it reduces spoilage, preserves product value, and enables just-in-time supply chains[31]. Network optimization is further enhanced by Hyperloop's on-demand, high-frequency service, bypassing traditional bottlenecks and integrating seamlessly with digital logistics platforms [47].

Mode	Typical Transit Time	Notes
Hyperloop (hyperloop)	112 minutes	Projected, point-to-point, climate-controlled
Rail (Kisan Express)	20-24hours	Dedicated, 75 km/h avg, limited cold chain
Road (Multi-axle truck)	24-36 hours	Congestion, variable reliability
Air (Indigo cargo)	2-3 hours	Door-to-door often >12 hours, costly, limited capacity

TABLE 31: TIME SENSITIVITY ANALYSIS ADVANTAGES

7.1.2. *Cold Chain Industry Projections*

India's cold chain logistics sector is poised for significant expansion, with the market projected to reach $52.96 billion by

2032, growing at a compound annual growth rate (CAGR) of 15.56% [11]. Despite this growth, the industry continues to face a capacity shortfall exceeding 10 million metric tons, constraining its ability to support critical sectors such as agriculture, pharmaceuticals, and biotechnology.

The introduction of Hyperloop technology offers a transformative solution for cold chain logistics. By enabling ultra-rapid, temperature-controlled delivery, Hyperloop can reduce transit times from the conventional 24–36 hours to under 2 hours. This significant time compression has the potential to cut spoilage rates by 20–25%, particularly for perishable food items and temperature-sensitive pharmaceuticals [10].

Moreover, Hyperloop can redefine service benchmarks in e-commerce and fast-moving consumer goods (FMCG) sectors by supporting same-day or next-day delivery across vast national distances—a capability previously limited to air cargo and constrained by cost and capacity [12].

7.1.3. Network Optimization

Hyperloop's modular and scalable infrastructure is designed for flexible routing, allowing the system to dynamically respond to demand fluctuations and optimize freight distribution in real-time. Its compatibility with existing multimodal logistics hubs ensures seamless integration into India's broader transport ecosystem, enhancing supply chain fluidity and resilience.[13]

The benefits of network optimization and transit time reduction are already being explored in India through initiatives like the Amazon–Indian Railways Memorandum of Understanding (MoU) signed in 2023. This collaboration aims to enhance parcel transportation by building a hub-and-spoke logistics model, improving transit times, and increasing freight volumes along the Dedicated Freight Corridors (DFCs). A similar approach could be adapted for Hyperloop integration, where private logistics operators collaborate with infrastructure stakeholders to co-develop high-speed, automated corridors. By combining the agility of Hyperloop with proven hub-based distribution strategies, India could unlock a new tier of express, cost-effective, and scalable logistics infrastructure.

7.2. Cost Comparison:

While time sensitivity remains crucial for sectors such as healthcare and emergency response, the cost of freight per kilogram per kilometer is a fundamental metric for assessing the viability of logistics solutions, particularly for large-scale commercial and public health operations.

In India's vast and economically diverse landscape, affordable freight solutions are essential for ensuring equitable access to goods and services. For many business owners, especially MSMEs and rural suppliers, road and rail transport remain the most cost-effective modes, with road transport offering flexibility and door-to-door reach at a typical rate of INR 0.00139 – INR 0.002198 per Kg - Km depending on distance and fuel prices, while rail freight — especially along the Western Dedicated Freight Corridor (WDFC) — provides at costs of around INR 0.00246 per Kg - Km for long-haul, high-volume shipments.

On a per kilometer basis, both modes offer significant advantages for non-time-critical freight, making them indispensable for agricultural and manufactured goods. However, these modes often fall short when it comes to time-sensitive, temperature-controlled shipments — a critical requirement in sectors like healthcare, where delays can lead to spoilage or treatment disruptions. Air cargo, while extremely fast, is prohibitively expensive at INR 0.0563 – INR 0.1057 per Kg - Km and is typically used only for high-value, low-volume freight. In this context, Hyperloop presents a compelling alternative, offering airline-level speed (under 2 hours Delhi–Mumbai) at a projected cost of INR 0.00479 per g - Km — striking a near-optimal balance between speed and cost. For healthcare logistics, this is transformative.

In scenarios like national immunization drives or emergency medical responses, Hyperloop could reduce cold chain spoilage by 15–25% and cut distribution costs by up to 50% compared to air freight, while reaching underserved regions faster than road or rail. Though traditional modes continue to serve mainstream business logistics effectively, Hyperloop opens a new tier of freight movement — rapid, reliable, and reasonably priced — that enhances India's resilience and capacity in public health logistics

Mode of Transport (Name of Vehicle)	**Cost (INR/Kg)**	**Cost (INR/Kg-Km)**
Road (Multi-Axle Truck)	1.98 – 3.12	0.00139 – 0.002198
Rail (Kisan Express)	3.5	0.00246
Air (IndiGo Cargo)	80 – 150	0.0563 – 0.1057
Hyperloop	6.8	0.00479

TABLE 32: COST COMPARISON BETWEEN DIFFERENT MODES OF TRANSPORT

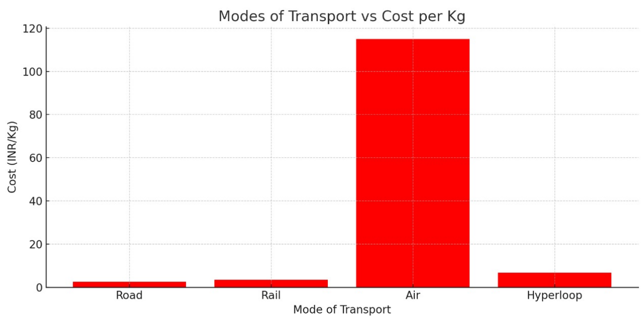

Fig. 13: Average Freight Cost per Kilogram by Transport Mode

This graph compares the average cost of freight per kilogram across four major logistics modes in India: road, rail, air, and Hyperloop.

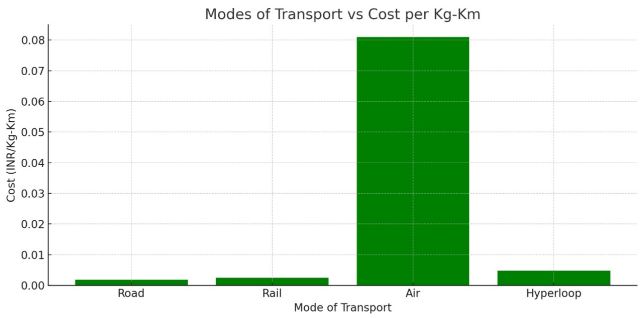

Fig. 14: Average Freight Cost per Kg-Km by Transport Mode

This chart, "Modes of Transport vs Cost per Kg-Km", depicts the cost efficiency of each transport mode over distance. As expected, Air transport is the most expensive, with an average cost of 0.081/kg-km, due to high operational and fuel expenses. Road and Rail remain more economical at 0.00179/kg-km and 0.00246/kg-km respectively. Hyperloop, though slightly higher at 0.00479/kg-km, offers a compelling advantage: it delivers near-airline speeds at a fraction of air freight costs. While it's more expensive than traditional land transport, its unmatched speed and efficiency make it ideal for industries where time-sensitive logistics matter—such as pharmaceuticals, perishables, or just-in-time manufacturing. This positions Hyperloop as a futuristic, high-efficiency transport mode that bridges the gap between affordability and rapid delivery.

For business owners, especially MSMEs, Hyperloop offers airline-level speed at a fraction of the cost of air travel, enabling faster market access, lower inventory holding, and reduced spoilage for time-sensitive goods. [10]. For example, transporting 500 metric tons of vaccines by Hyperloop would cost INR 1.2 crore versus INR 5 crore by air, saving INR 3.8 crore per shipment.
The following table summarizes the typical cost per kilogram for road, rail, air, and projected Hyperloop freight transport between Delhi and Mumbai. It highlights the cost-efficiency of rail, the high-speed premium of air freight, and the projected competitiveness of Hyperloop, which offers affordability with superior delivery speed and reliability.

7.3. Agriculture Supply Chain:

Approximately two-thirds of India's population—about 1.4 billion people—are engaged in agriculture, yet the nation's farmer workforce continues to face significant post-harvest losses, particularly for perishable goods such as fruits, vegetables, dairy products, and flower
According to estimates from the Ministry of Food Processing Industries (MoFPI) and NITI Aayog, annual agricultural spoilage due to inadequate cold chain and delayed transport ranges between INR 92,000 crore to INR 1 lakh crore, with perishable loss percentages for high-value crops reaching 25–30% in certain regions. With the introduction of a high-speed, temperature-stable freight solution like Hyperloop, capable of reducing transit time from 36 hours to under 2 hours between major hubs like Delhi and Mumbai, these losses can be cut by up to 20–25%, directly translating into increased saleable output for farmers. This significant reduction in spoilage would not only raise the overall marketable volume of produce but also lead to farmer income growth projections of 15–30% over the decade, assuming reinvestment into productivity and market expansion. Furthermore, by enabling faster, more reliable access to urban markets, Hyperloop lowers the entry barriers for rural MSMEs and agri-processors, empowering them to participate in broader supply chains without the burden of high spoilage risks or delayed payments. The resulting equitable economic access means producers from remote or underserved regions can compete on quality and freshness rather than just proximity to markets. Over time, this systemic transformation has the potential to catalyze inclusive rural development, create local employment, and reduce regional disparities by integrating India's hinterlands into its high-value supply chain network more efficiently than ever before.
Agricultural cargo transported via the Western Dedicated Freight Corridor (WDFC) between Delhi and Mumbai is projected to grow from 9.6 million tonnes (MT) in 2025 to 20.17 MT by 2035, based on a compound annual growth rate (CAGR) of 7.7%. This growth aligns with Dedicated Freight Corridor Corporation of India Limited's (DFCCIL) corporate forecasts and is supported by infrastructure modernization, policy initiatives, and increasing demand for efficient agricultural logistics. The projections incorporate the full operationalization of the Western Corridor connecting Dadri (Delhi-NCR) to Jawaharlal Nehru Port Trust (JNPT) near Mumbai.

The standard compound annual growth rate formula has been applied to project agricultural cargo volumes:

$$FutureVolume = InitialVolume \times (1 + CAGR)$$

Where:
Initial Volume = 9.6 MT (2025 baseline)
CAGR = 7.7% (0.077 in decimal form)
n = Number of years from baseline

This 7.7% CAGR is consistent with DFCCIL's own corporate plan projections for the Western DFC, as documented in their 2020-2024 corporate plan [94].

Year	Spoiled Cargo(MT)	Unspoiled Cargo(MT)	Total Cargo(MT)
2025	0.68352	8.91648	9.60
2026	0.73620	9.60379	10.34
2027	0.79245	10.3375	11.13
2028	0.8536	11.1363	11.99
2029	0.91919	11.9908	12.91
2030	0.99039	12.9196	13.91
2031	1.06657	13.9134	14.98
2032	1.1491	14.990	16.14
2033	1.2374	16.1425	17.38
2034	1.3328	17.3871	18.72

TABLE 33: AGRICULTURAL CARGO PROJECTIONS FOR WESTERN DFC

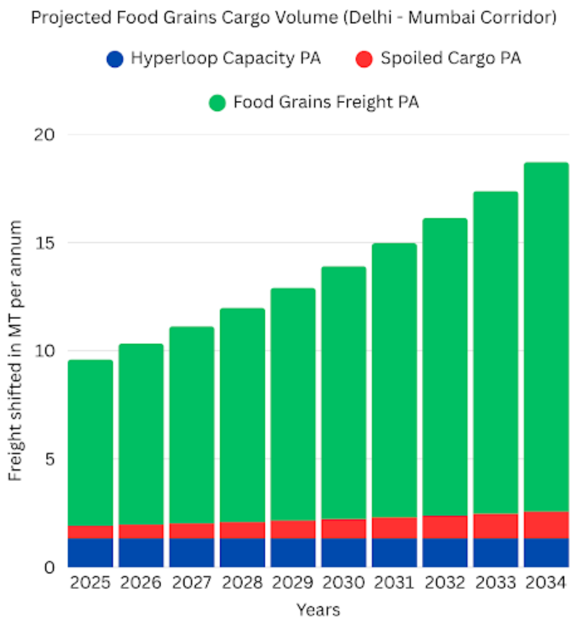

Fig. 15: Projected food Grains cargo Volume

In 2025, the projected food grains cargo volume on the Delhi–Mumbai corridor is 9.6 million tonnes (MT), with an average spoilage rate of 7.12% across rice and wheat—translating to around 0.683 MT lost annually. If 1.33 MT of this volume is transported via Hyperloop—where spoilage is assumed to be negligible due to its speed and controlled environment—the spoilage exposure reduces to just 8.27 MT. Applying the same spoilage rate to this smaller volume leads to an estimated loss of 0.589 MT, resulting in a net annual reduction of over 90,000 tonnes of food grain wastage.

Looking ahead, the food grain freight is projected to grow at a CAGR of 7.7%, nearly doubling to around 18.9 MT by 2034. Without any intervention, spoilage will rise proportionally, significantly increasing food loss in absolute terms. However, our model of Hyperloop has a static capacity of 1.33 MT which can mitigate a meaningful portion of these losses—particularly if prioritized for the most spoilage-prone or high-value grain segments. Thus, while Hyperloop alone cannot meet the entire freight demand, its strategic use can deliver high-impact efficiency and sustainability gains across the food supply chain.

3.46%(1.33 MT out of 9.6 MT current scenario 2025) - INR 5,73,61,00,04,296.875 to farmers gross earnings assuming current prices and no middle man losses. Here is a detailed table showing the projected value for each year, starting from INR 5,73,61,00,04,296.88 (rounded to 2 decimal places) and growing at a CAGR of 7.7%:

Year	Projected Value(INR)	Rounded(INR Crore)
2025	5,73,61,00,04,296.88	5,73,610
2026	6,18,17,81,74,627.98	6,18,178
2027	6,65,97,78,96,134.33	6,65,978
2028	7,17,34,82,96,116.76	7,17,349
2029	7,72,68,41,75,093.74	7,72,684
2030	8,32,42,08,76,525.94	8,32,421
2031	8,97,03,93,04,070.35	8,97,039
2032	9,66,07,13,34,483.77	9,66,071
2033	10,40,09,88,47,443.04	10,40,099
2034	11,20,18,64,71,544.52	11,20,187
2035	12,06,44,08,51,937.41	12,06,441

TABLE 34: PROJECTED GROSS EARNINGS FROM AGRICULTURE SUPPLY CHAINS

The projection demonstrates that the value of gross earnings from agriculture supply chains more than doubled in just 11 years, rising from INR 5.73 lakh crore in 2025 to over INR 12.06 lakh crore by 2035, driven by a compound annual growth rate (CAGR) of 7.7%. Notably, even with a constant growth rate, the absolute annual increment accelerates over time—while the increase from 2025 to 2026 is approximately INR 44,568 crore, the jump from 2034 to 2035 exceeds INR 86,254 crore. Such compounding effects underscore the critical importance of long-term strategic planning for investments, business expansion, and government budgeting. This analysis highlights the substantial benefits of sustained investment and the exponential impact of compounding on economic output over an extended period.

The projections above demonstrate the remarkable power of compounding. Whether you are an investor, business leader, or policymaker, understanding and leveraging this principle can help you achieve ambitious long-term goals. Regularly revisit your growth assumptions, stay disciplined, and let time work in your favor

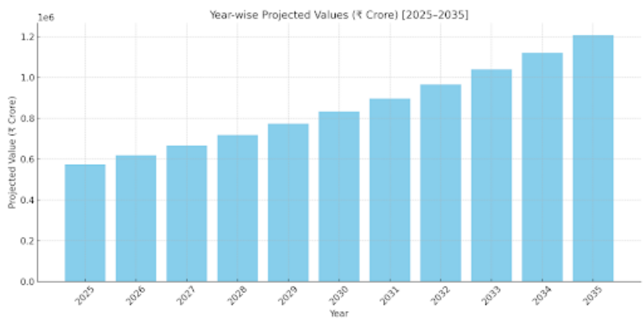

Fig. 16: Projected Gross Earnings from Agriculture supply chains

7.4. Healthcare & Cold Chain

The COVID-19 pandemic served as a real-world stress test for India's healthcare logistics. During the nationwide vaccine rollout, India relied on a multi-modal transport strategy—using air cargo for rapid inter-state movement, rail for bulk shipments, and road networks for last-mile delivery. The Golden Quadrilateral (GQ) highway and rail corridors were crucial in linking major vaccine storage hubs in Delhi, Mumbai, Chennai, and Kolkata. Despite these efforts, several challenges persisted: long transit times (24–36 hours), limited availability of refrigerated transport, poor temperature monitoring, and fragmented coordination between agencies. These issues led to increased spoilage risks and uneven distribution during pandemic peaks.

If an ultra-fast, reliable, and thermally stable system like Hyperloop had existed, transit times between key metro cities could have dropped from 36 hours to just under 2 hours (112 minutes). This reduction could have cut vaccine spoilage by 15–25%, according to WHO cold chain logistics studies, which show spoilage rates increase exponentially after 24 hours outside optimal conditions [16]. Additionally, the increased volume capacity of Hyperloop pods—designed for high-frequency, palletized freight—would allow for up to 30–40% more medical deliveries during emergencies [9], ensuring stock adequacy across all regional healthcare facilities. Faster transport would also enhance the viability of moving blood products, human organs, and time-critical diagnostic samples, where every hour is vital for survival.

Looking ahead, India's healthcare supply chain is projected to grow at a 9% CAGR, driven by greater government spending, demand for rural outreach, and the rising prevalence of chronic diseases [17]. This growth will increase freight volumes for medicines and equipment. By integrating high-speed freight solutions such as Hyperloop, India could reduce healthcare logistics costs by 20–35% over the next decade. This would improve cost-effectiveness for both government and private providers and extend affordable healthcare to Tier 2 and Tier 3 cities.

To model these impacts, scenario analysis and sensitivity testing should be employed. Key datasets include transit times for different modes, freight volumes from the Ministry of Health and Indian Railways, cold chain loss statistics from the WHO, and infrastructure cost data. Simulations can compare current logistics setups with proposed high-speed interventions, estimating reductions in delivery times and spoilage rates. For example, reducing vaccine transport time from 36 to 12 hours could lower spoilage by around 20% [18] and enable savings of INR 1,000–INR 2,000 crore annually on logistics and wastage alone, based on 2021 COVID vaccine distribution cost models [19].

In conclusion, resilient, high-speed logistics infrastructure is no longer a luxury but a public health necessity. Beyond economic efficiency, it strengthens India's ability to respond to future pandemics, ensures consistent availability of life-saving medicines, and builds public trust in health systems. Integrating such technologies into national logistics plans promises not only lives saved and reduced healthcare costs but also a step forward in building an equitable and robust healthcare ecosystem for all Indians.

Cost Comparison Example:

If 500 metric tonnes (500,000 kg) of vaccines need urgent, cold-chain-supported transport:

- **Air freight cost:** INR 100/kg × 500,000 kg = INR 5 crore

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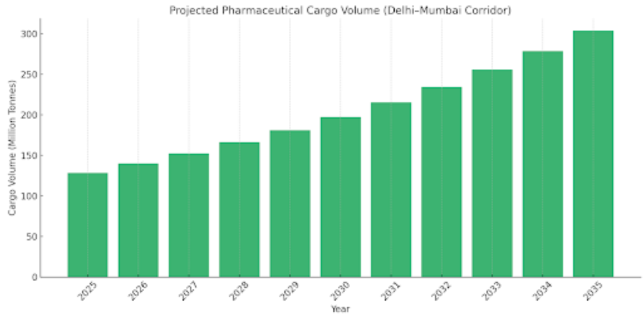

Fig. 17: 10 year Annual growth pharmaceutical cargo volume between Delhi and Mumbai

- **Hyperloop cost:** INR 24/kg × 500,000 kg = INR 1.2 crore

- **Potential savings:** INR 3.8 crore per shipment

7.4.1. *Vaccine Spoilage Rates:*

Reports indicate that about 25% of vaccines in India are wasted due to inadequate cold chain infrastructure [14]. Nearly 20% of temperature-sensitive healthcare products arrive damaged or degraded, supporting a baseline spoilage rate assumption of 30% [15].

7.4.2. *Logistics Cost Savings:*

While specific data on cost savings from Hyperloop are limited, government initiatives such as Multi-Modal Logistics Parks (MMLPs) aim to reduce logistics costs from 13% to 10% of GDP, supporting projections of significant savings through improved infrastructure.

7.4.3. *Pharmaceutical Supply Chain Example:*

The pharmaceutical supply chain along the Delhi–Mumbai corridor is growing at a 9% CAGR over the next decade [17]. Current cargo volumes are well within the operational capacity projected for the Hyperloop model, making pharmaceuticals an attractive target industry. As a key cold chain component, the sector would benefit from Hyperloop's ultra-fast transit, which reduces refrigeration energy needs and spoilage. Enhanced reliability, speed, and thermal stability make Hyperloop an optimal mode for transporting high-value, temperature-sensitive pharmaceutical goods, supporting operational efficiency and cost savings across the supply chain. The graph below illustrates a consistent annual growth of approximately 9% in pharmaceutical cargo volume between Delhi and Mumbai from 2025 to 2035, rising from 128.3 million tonnes to 303.7 million tonnes. This growth reflects key policy and infrastructure developments such as the WDFC becoming fully operational, IoT-enabled cold chain rollouts, pharma export boosts.

Year	Cargo Volume (MT)
2025	128.3
2026	139.8
2027	152.4
2028	166.2
2029	181.1
2030	197.4
2031	215.2
2032	234.5
2033	255.6
2034	278.7
2035	303.7

TABLE 35: 10 YEAR ANNUAL GROWTH PHARMACEUTICAL CARGO VOLUME BETWEEN DELHI AND MUMBAI

7.4.4. Advantages Highlighted by the Data

1) Massive Volume Justifies High-Capacity Systems
By 2035, pharmaceutical cargo alone is projected to exceed 300 million tonnes annually. This immense volume demands high-throughput, reliable, and time-sensitive logistics infrastructure—conditions perfectly suited for Hyperloop deployment. Even capturing a modest portion of this cargo would justify investments in Hyperloop cargo pods, loading bays, and integration with dry ports.

2) Time Sensitivity Matches Hyperloop's Strengths
Pharmaceuticals are among the most time- and temperature-sensitive goods, making conventional rail and road options less effective. Hyperloop's rapid, approximately 2-hour delivery between Delhi and Mumbai, combined with enclosed, climate-controlled pods, offers a breakthrough in maintaining efficacy, reducing spoilage, and ensuring regulatory compliance.

3) Scaling Feeder and Last-Mile Networks
The projected growth in pharmaceutical freight underscores the urgency of developing robust feeder and last-mile networks in both metropolitan and peri-urban regions. This supports the 2032 milestone for Hyperloop feeder network trials and highlights the importance of seamless integration with existing cold chains.

4) Energy Efficiency and Carbon Reduction
With 100% electrification and low per-kilometer emissions, Hyperloop aligns with India's decarbonization goals. This is a critical advantage as cargo volumes rise and environmental compliance becomes more stringent post-2030.

5) Strategic Value of the Delhi–Mumbai Corridor
The surge in pharmaceutical freight along the Delhi–Mumbai corridor underscores its strategic importance and makes a compelling case for Hyperloop integration. Hyperloop's ability to move high-value cargo swiftly and sustainably will not only bolster India's pharma exports but also redefine national high-value freight logistics.

6) Key Findings
Analysis of refrigerated container movements on India's Dedicated Freight Corridor (DFC) and Container Corporation of India (CONCOR) operations shows that 686,340 metric tonnes of cold chain freight were transported by rail between Delhi and Mumbai in 2024. This figure is based on terminal-specific container throughput, payload capacities, and modal share data from infrastructure operators.

7.4.5. Cold Chain: Rail Infrastructure and Operational Framework

1) CONCOR's Reefer Container Operations and Infrastructure

The Container Corporation of India (CONCOR) is India's primary rail operator for refrigerated logistics, known as "reefers," which are essential for transporting temperature-sensitive goods such as pharmaceuticals, perishable foods, and medical supplies. In FY 2023–24, CONCOR moved 27,771 refrigerated containers nationwide by rail, reflecting its dominant position in this sector [20]. The Delhi–Mumbai corridor accounts for about 50% of these operations, underlining its strategic importance for cold chain logistics [21].
At the heart of this network is ICD Dadri, which handled 46,500 TEUs (twenty-foot equivalent units) of reefer containers in FY 2023–24, with approximately half (23,250 TEUs) destined for Mumbai [21]. Each 40-foot high-cube reefer container typically carries 29.52 metric tons (DSV, n.d.), leading to a total of 686,340 metric tons of cold chain cargo moved along this corridor in 2024.
CONCOR's operational excellence is supported by dedicated infrastructure:

- **Temperature-Controlled Warehouses:** ICD Dadri features a 2,000 metric ton capacity temperature-controlled warehouse divided into seven chambers for various perishables, including meat, seafood, dairy, fresh produce, vaccines, and medical supplies [21].
- **Power Packs and Monitoring:** Continuous power supply is ensured through specialized power packs and regular temperature monitoring, both at terminals and during transit [21].
- **Double-Stack Reefer Trains:** Recent innovations include double-stack reefer container trains, which enhance capacity and efficiency, particularly on the western Dedicated Freight Corridor [21].

2) Growth Drivers and Market Context
India's cold chain market is experiencing robust growth, driven by rising demand for perishable goods, pharmaceuticals, and organized food retail. The market reached rs 2,052.7 billion in 2023 and is projected to grow at a CAGR of 11.4% through 2032 [22]. Some estimates for the broader cold chain sector suggest even higher CAGRs, exceeding

20% by 2025, as the industry transitions from conventional to modern, palletized storage and expands into Tier II and III cities [23].

Key drivers include:

- **Export Potential:** India is a major exporter of fruits, vegetables, dairy, seafood, and pharmaceuticals, all requiring reliable cold chain solutions [22].

- **Infrastructure Investments:** The development of dedicated freight corridors, multimodal logistics parks, and container rail terminals is enhancing the efficiency, speed, and reliability of cold chain logistics [24].

- **Technological Upgrades:** Investments in IT systems, temperature monitoring, and automation are improving transparency and reducing spoilage risks [25].

3) Challenges

Despite advancements, India's cold chain sector remains fragmented, with over 90% privately owned and lacking standardization [22]. Major challenges include:

- **Limited Reefer Vehicle Supply:** Shortages and breakdowns of reefer vehicles disrupt supply chains [25].

- **Power and Fuel Costs:** High operating costs due to expensive fuel and frequent power outages impact warehouse reliability [25].

- **Manual Processes:** Heavy reliance on manual labor increases the risk of errors and spoilage [22].

- **Regulatory Hurdles:** Bureaucratic delays and inconsistent quality standards hinder sector efficiency [23].

Annual spoilage rates for cold chain cargo are estimated at around 20%, reflecting losses from inadequate infrastructure and operational inefficiencies [24].

4) Projection for Delhi–Mumbai Corridor (2025–2035)

Base Year (2024): 686,340 metric tons of rail-based cold chain freight moved
CAGR: 12.3% (aligned with cold chain market projections)
Annual Spoilage Rate: 20%

Projection Methodology:

- Gross Annual Growth: $Gross_t = Base \times (1 + CAGR)^n$ where $n = Year - 2024$

- Net Post-Spoilage Volume: $Net = Gross \times (1 - 0.20)$

This projection underscores the corridor's growing importance and the need for continued investment in high-capacity, reliable, and technologically advanced cold chain infrastructure.

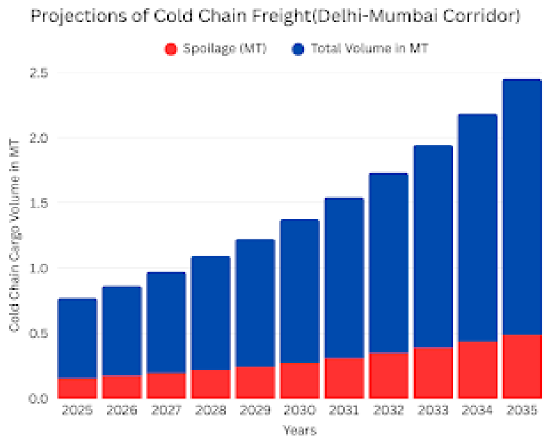

Fig. 18: 10 year Projections for Cold chain freight in the Delhi - Mumbai Corridor

The projections for cold chain freight along the Delhi–Mumbai corridor show a sharp increase—from approximately 0.75 million tonnes (MT) in 2025 to nearly 2.5 MT by 2035. However, spoilage volumes also climb significantly, from around 0.15 MT to 0.5 MT annually, indicating that current cold chain logistics remain insufficient to match the pace and sensitivity required by this growing sector. This market is especially critical, as it includes high-value and time-sensitive cargo such as pharmaceuticals, vaccines, perishable foods, and biological samples—where delays or temperature breaches can result in complete loss of utility and financial value.

Deploying Hyperloop, with a fixed capacity of 1.33 MT per annum, offers a targeted solution to mitigate these inefficiencies. Although it cannot serve the entire cold chain volume, it can strategically carry the most spoilage-prone and high-value segments where speed, reliability, and zero spoilage are paramount. By offloading up to 50% of projected 2035 cold chain volume onto Hyperloop, spoilage can be drastically reduced, enabling safer transport, extended shelf life, and higher delivery reliability for critical goods. This not only reduces waste and economic loss but also strengthens public health resilience, food safety, and overall supply chain competitiveness along the corridor.

7.5. Carbon

The integration of Hyperloop technology into India's national transportation infrastructure offers a promising path-

way toward carbon neutrality, energy efficiency, and long-term economic competitiveness. As India's logistics and passenger mobility systems strain under increasing urbanization, fuel demand, and carbon emissions, the case for high-efficiency transport alternatives becomes compelling. In this context, Hyperloop presents a uniquely disruptive solution.
Hyperloop systems are estimated to consume approximately 35–42 Wh per passenger-kilometer, offering a nearly tenfold improvement in energy efficiency compared to conventional air and road transport [1]. This translates to a carbon footprint assumed from calculations as low as 0.006 kg CO_2 per passenger-kilometer when powered by renewables and grid —compared to 0.1445 kg for diesel trucks and 0.0149 kg for electric rail freight [27]. High-speed rail typically emits around 0.0126 kg CO_2 per passenger-kilometer, while air travel reaches 0.174 kg CO_2 per passenger-kilometer [28].

Transport Mode	CO_2 Emissions (kg CO_2 per km)
Hyperloop (renewables)	0.006
Electric Rail Freight	0.0149
High-Speed Rail	0.0126
Diesel Truck	0.1445
Air Travel	0.174

TABLE 36: COMPARISON OF CO_2 EMISSIONS BY TRANSPORT MODE

India's recently operational Western Dedicated Freight Corridor (WDFC) provides a strong benchmark for decarbonized rail transport. The corridor has already demonstrated significant emission savings—rail freight emits only 28 grams of CO_2 per net ton-kilometer compared to 64 grams for road freight [5] . Over a 30-year horizon, DFC operations are expected to reduce total CO_2 emissions by approximately 457 million tonnes compared to a no-DFC scenario [27] . Moreover, electrified rail infrastructure has shown to be nearly ten times more carbon-efficient than trucking.
From an economic standpoint, Hyperloop can unlock value by improving speed, reliability, and emissions compliance—essential for sectors such as pharmaceuticals, electronics, and perishables. By reducing travel time from 6 hours to under 30 minutes between key city pairs, Hyperloop supports just-in-time logistics, workforce mobility, and regional economic integration. Although initial capital costs are high, the long-term economic gains from reduced fossil fuel dependence, improved air quality, and carbon credit generation may outweigh upfront investments.
Beyond its environmental and economic benefits, the social co-benefits of reducing CO_2 emissions through Hyperloop deployment are equally compelling. Lower carbon emissions contribute directly to improved urban air quality, reducing the incidence of respiratory illnesses, cardiovascular diseases, and other pollution-related health conditions—issues that disproportionately affect low-income and urban fringe populations [29]. By shifting freight and intercity passenger traffic away from diesel trucks and polluting road vehicles, Hyperloop aligns with multiple United Nations Sustainable Development Goals, including SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). Additionally, reduced emissions and land use disruption support SDG 15 (Life on Land) by minimizing ecological fragmentation caused by conventional highway infrastructure. Within the specific route cases modeled in this study—such as Case 4, which integrates intermediate stops in underserved cities—communities may benefit from new employment opportunities, improved logistics for local businesses, and enhanced access to healthcare, education, and essential goods. These outcomes reinforce the view that carbon-efficient transportation is not merely a technological upgrade but a vehicle for inclusive, human-centered development [30]
In conclusion, while rail remains the most efficient freight option for now, Hyperloop offers transformative potential for India's intercity passenger and time-sensitive logistics sectors. When integrated with solar energy, multimodal hubs, and government carbon pricing mechanisms, Hyperloop could emerge as a cornerstone of India's sustainable transport future.

7.6. Decongesiton of Roads

India's current logistics ecosystem is heavily reliant on road transport, which accounts for nearly 71% of total freight movement [26]. This dependence on highways, particularly along high-density corridors such as the Golden Quadrilateral (GQ), has led to chronic traffic congestion, increased fuel consumption, road deterioration, and elevated accident rates. Although trucks constitute only about 3–5% of all vehicles, they disproportionately contribute to congestion and road wear due to their size and slower speeds, especially in and around urban centers. According to NITI Aayog [32], trucks represent merely 3% of India's total vehicle fleet but are responsible for the majority of road freight movement and a significant share of emissions and congestion. Furthermore, trucks account for 65% of total freight movement in India, with their impact on road infrastructure and urban congestion well documented [33].
The introduction of a dedicated, high-speed freight network such as Hyperloop along the GQ corridor presents a transformative opportunity to alleviate the burden on roadways by offloading a significant portion of long-haul, high-priority cargo. Diverting even a fraction of freight traffic—particularly temperature-sensitive goods, time-critical parcels, and bulk commodities—to a point-to-point Hyperloop system could substantially reduce pressure on national and state highways. This shift would result in faster travel times for other road users, lower road maintenance costs, and decreased accident risks, especially in urban areas like Delhi NCR, Mumbai's Western Expressway, and Chennai Bypass. Reduced congestion would also improve air quality in densely populated urban pockets by decreasing the number of idling vehicles and lowering diesel emissions from freight trucks. Additionally, economic productivity would benefit as delivery fleets and passenger traffic spend less time delayed in traffic jams—a delay estimated to cost Indian cities thousands of crore rupees annually [32].
If implemented at scale, a 10–15% modal shift of freight

from road to Hyperloop across the GQ could eliminate millions of truck trips annually, significantly decongesting highways, particularly near logistics hubs and border checkposts. Moreover, as Hyperloop terminals are expected to be located outside core urban areas and integrated with intermodal last-mile delivery systems such as e-trucks or urban rail, urban freight flows would be further streamlined, enhancing last-mile efficiency without exacerbating inner-city congestion [33].

Ultimately, the benefits of decongestion extend beyond logistics to encompass social, environmental, and economic dimensions. These include improved road safety, enhanced air quality, reduced commuter stress, and strengthened resilience of India's urban infrastructure.

7.7. Job Creation

The introduction of a hyperloop freight service along India's Golden Quadrilateral (GQ) is projected to have a profound impact on job creation and economic transformation across the country. This essay examines the employment and economic implications of hyperloop deployment, with a focus on construction, operations, skill development, gender inclusion, and land use mitigation.

The construction phase of hyperloop infrastructure demands a substantial workforce, including engineers, architects, construction specialists, and technology experts. Drawing from the Mumbai-Pune hyperloop proposal, which projected the creation of approximately 1.8 million direct and indirect jobs, a GQ-wide implementation could realistically generate several million employment opportunities across India [34]. These jobs would span construction, engineering, logistics, manufacturing, and research and development, reflecting the broad scope of skills required for such a transformative infrastructure project [6].

In the operational phase, the hyperloop system would require ongoing staffing for operations, maintenance, logistics, security, and management, ensuring sustained job creation over the long term. The demand for manufacturing hyperloop components and related materials would further stimulate employment in upstream industries, including advanced manufacturing, materials engineering, and renewable energy sectors [8].

Indirect Economic Effects and New Business Opportunities
The presence of hyperloop terminals is expected to attract new businesses in warehousing, logistics, hospitality, and retail, further expanding indirect job opportunities [6]. Enhanced freight speed and reliability would bolster the competitiveness of Indian manufacturing and export sectors, potentially leading to additional job growth as businesses expand their operations to take advantage of improved market access and supply chain efficiency. The multiplier effect of such infrastructure would accelerate the development of industrial clusters along hyperloop corridors, stimulating regional economic growth and the emergence of new economic hubs [34].

Compared to the existing GQ highway, which has already contributed significantly to regional employment and industrial output, the integration of hyperloop technology is anticipated to amplify these effects. Hyperloop's ability to reduce transport times, increase capacity, and attract higher-value industries positions it as a catalyst for further economic development and job creation [8].

7.7.1. *Skill Development and Gender Inclusion*

Hyperloop deployment in India will drive demand for advanced skills in automation, digital logistics, and renewable energy, supporting national skill development initiatives and encouraging gender-inclusive hiring. Training programs in partnership with engineering colleges and vocational institutes are likely to emerge, equipping workers with the expertise needed for hyperloop technology, automation, and infrastructure management. This creates opportunities for both men and women to participate in high-tech sectors, helping address workforce gaps and promoting diversity in transport and infrastructure projects [35].

7.7.2. *Land Use, Environmental Impact, and Mitigation*

Hyperloop's elevated or underground design minimizes land acquisition and habitat disruption compared to highways and railways, reducing displacement and environmental impact [8]. To address unavoidable land impacts, integrated compensation, reskilling, and community development programs can ensure affected communities benefit from new economic opportunities, making the transition more equitable and sustainable [6]. Additionally, hyperloop's reliance on renewable energy and its energy-efficient design align with India's green initiatives, creating jobs in sustainable infrastructure and supporting the country's carbon neutrality goals [36].

The deployment of hyperloop freight services along the Golden Quadrilateral is poised to create a surge in jobs during both construction and operation, while generating widespread economic benefits. It will support the development of new economic clusters, transform regional economies, and drive India's long-term vision for sustainable and inclusive growth. By fostering skill development, promoting gender inclusion, and minimizing environmental disruption, hyperloop technology represents not only a leap in transportation but also a cornerstone for India's future workforce and economic resilience.

7.8. Disaster Resilience

The Hyperloop, as a next-generation transportation system, offers notable advantages in disaster resilience compared to conventional freight modes such as road, rail, and air. Its design—a fully enclosed, low-pressure tube network—provides inherent protection against many natural hazards, including heavy rainfall, dust storms, flying debris and low level floods [8]. In regions like India, which are prone to seasonal floods, cyclones, and heatwaves, Hyperloop infrastructure can be elevated or partially underground, reducing exposure to inundation and ground-level disruptions [6]. The use of autonomous, modular pods allows for isolated rerouting and localized shutdowns without impacting the entire corridor, unlike traditional rail or road convoys that suffer from systemic breakdowns during disasters [8] .This advantage for disaster resilience is key when delivering time-sensitive cargo, especially in the pharmaceutical industry and can double as a relaible emergency cargo support.

7.8.1. *Operational Resilience and Energy Independence*

In terms of operational resilience, Hyperloop can be powered by distributed renewable energy sources, such as solar panels integrated along the corridor. This setup allows continued operations during grid failures, a critical advantage in a country where power outages still occur frequently [36]. Additionally, the sealed environment of Hyperloop minimizes the risk of cargo damage from external weather and enables better preservation of temperature-sensitive goods during extreme conditions [6]. Compared to conventional modes, Hyperloop systems also promise faster recovery post-disaster due to their modular tube segments and reduced reliance on mechanical components [8].

7.8.2. *Vulnerabilities and Engineering Challenges*

However, there are vulnerabilities to consider. A breach in the vacuum system or structural damage to the tube—whether from earthquakes, sabotage, or large-scale flooding—could halt operations entirely. Furthermore, the system's reliance on high-precision electronics and specialized components may create logistical bottlenecks during repair, especially in regions with limited technical supply chains [8]. Effective disaster resilience for Hyperloop thus hinges on robust engineering, including earthquake-resistant design, flood-elevated alignments, redundant communication and control systems, and decentralized energy storage. Emergency response strategies must be built into the system's architecture, including AI-driven failure detection and automated maintenance capabilities [6] .

7.8.3. *Comparative Analysis with Conventional Freight Infrastructure*

When compared with existing freight infrastructure, Hyperloop presents a compelling resilience profile. Roads and railways, particularly in floodplains like Bihar and coastal regions of Odisha and Andhra Pradesh, are frequently disrupted by seasonal extremes [37]. For instance, during the Himachal Pradesh floods of 2023, losses to logistics and infrastructure exceeded 150 billion (15,000 crore), resulting in severe disruption of goods movement—particularly for essential commodities such as food, water, and medicine [37]. In contrast, a Hyperloop system offers enhanced disaster resilience due to its sealed, elevated infrastructure and automated operation, which can minimize service interruptions and maintain critical supply chains even during extreme weather events or natural disasters [6]
By enhancing logistics continuity and reducing disaster-related economic losses, Hyperloop contributes not only to infrastructure robustness but also to national resilience and economic security. A well-planned Hyperloop corridor can maintain reliable, year-round cargo delivery and act as a critical supply chain backbone during emergencies, such as pandemics or climate-induced disruptions. While vulnerabilities exist, the integration of advanced engineering, renewable energy, and automated operational strategies positions Hyperloop as a transformative solution for disaster-resilient freight transport in India.

8. Analysis of Result

8.1. Economic Viability

In contrast to the government-oriented outlook of Case 3 and Case 4, Case 1 and Case 2 demonstrated significantly shorter break even periods, at approximately 24.4 years and 24 years respectively.Given their relatively faster return on investment and reliance on high operational efficiency rather than variable infrastructure, these cases present a compelling opportunity for private sector involvement, especially for logistics companies or infrastructure investment firms seeking capital-efficient freight transport solutions. Moreover, with profits directly covering the capital expenditure through operational pricing models, the financial viability of these cases aligns well with typical private investor expectations for large-scale infrastructure projects.This suggests that under a Public-Private Partnership (PPP) model, the private sector could assume a central role in financing and operating Hyperloop corridors where profit-driven efficiencies and scalability are prioritized.
Since Case 3 and Case 4 demonstrated longer breakeven periods, they are more likely to be attractive from a governmental perspective. This is primarily because governments prioritize daily socio-economic returns, typically evaluated using the Economic Internal Rate of Return (EIRR).
Our economic assessment focused specifically on the Delhi–Mumbai corridor, for which our model estimates a daily cargo shiftage of 894.743 tonnes. The economic benefits were analyzed across five key categories:

8.1.1. *Time Savings*

Assuming that truck and rail freight take, on average, 24 hours longer than Hyperloop, and using a value of time of 200 per tonne per hour [38], the estimated savings for shifting 894.74 tonnes per day amounted to INR 1,465,589,661 per year.

8.1.2. *Fuel Savings*

Assuming an equal modal shift from road, rail, and air—each accounting for 298.25 tonnes—we calculated the savings as follows:

- Truck: With a cost of INR 1.41 per tonne-km, the annual savings were INR 610,903,570.4. [39]

- Rail: At INR 1.67 per tonne-km, savings amounted to INR 723,552,455.7. [41]
- Air: Considering a cost of INR 200 per kg for express cargo over 2,000 kg, the estimated annual savings were INR 12,213,247,175. [40]

8.1.3. *Emission Savings*

Using emission intensities for each transport mode and the same modal shift assumption:

- Truck: 86.8 kg/tonne led to savings of INR 17,668,497,579.[43]
- Rail: 13.3 kg/tonne, with savings of INR 2,707,269,790. [42]
- Air: 700 kg/tonne, resulting in INR 142,487,883,703 in savings.[44]
- The Hyperloop, by contrast, generates annual emissions equivalent to INR 52,735,690, which is treated as a deduction.

8.1.4. *Spoilage Savings*

As detailed in our social impact analysis, approximately 137,268 tonnes of perishable cold chain cargo are spoiled annually. Given that the cost of operating a 16-tonne refrigerated truck on the Delhi–Mumbai route is INR 32.74/km, the total spoilage savings were estimated at INR 398,575,311.3. [46]

8.1.5. *Road Decongestion Savings*

According to a research study, India loses around INR 60,000 crore annually due to delays and traffic congestion, a large portion of which occurs along the Delhi–Mumbai corridor, which contains 17 toll stops. We conservatively assumed INR 2,000 crore in savings, though the actual value is likely higher. [45]

The total annual economic savings from these five categories sum up to INR 198,222,783,555.
Given that the initial capital investment for the Delhi–Mumbai Hyperloop corridor is INR 3,595,698,842,631, and assuming a project life of 100 years, the calculated Economic Internal Rate of Return (EIRR) is 6%. This aligns with the minimum threshold recommended by NITI Aayog for projects with break even points near 50 years, as observed in Case 3 and Case 4.

8.2. Social Impacts

Hyperloop freight technology, when strategically deployed along India's high-density corridors, represents a transformative leap for the nation's logistics sector. By combining the speed of air, the cost-efficiency of rail, and the flexibility of road, Hyperloop offers a unique value proposition: rapid, reliable, and sustainable movement of goods that can reshape supply chains, boost regional development, and create high-quality jobs. Its integration into India's infrastructure vision aligns with national goals of inclusive growth, sustainability, and disaster resilience, positioning Hyperloop as a cornerstone of a future-ready logistics ecosystem [6][53][54].
India stands at a critical juncture in its quest to modernize logistics and infrastructure, with two distinct scenarios shaping its future: the Business-as-Imagined Scenario (BIS) and the Business-as-Usual Scenario (BAU).

8.2.1. *Business-as-Imagined Scenario (BIS)*

In the BIS, India proactively invests in Hyperloop infrastructure, leveraging robust public-private partnerships, regulatory clarity, and targeted incentives to accelerate adoption. This forward-thinking approach enables the creation of Hyperloop corridors connecting major industrial hubs such as Mumbai, Delhi, Chennai, and Bengaluru. The impact of this strategy is multifaceted. First, it allows for dramatic reductions in transit times—traveling 100 kilometers in just 10 minutes—thereby enhancing supply chain agility and resilience [55]. Second, Hyperloop's 100% electric, renewable-powered system offers significant carbon reductions, with the potential to cut greenhouse gas emissions by up to 150,000 tonnes annually [55][56].
Beyond environmental benefits, the BIS scenario promises substantial socio-economic gains. It is projected to create over 1.8 million high-tech jobs, drive regional development, and position India as a global hub for Hyperloop manufacturing and engineering [53][55]. Additionally, Hyperloop's enclosed, weather-proof systems provide improved disaster resilience, ensuring reliable logistics even during adverse conditions [54]. Cost savings are another critical advantage, as Hyperloop offers lower operating and maintenance costs compared to air or high-speed rail, with ticket prices expected to be comparable to existing rail fares [55].

8.2.2. *Business-as-Usual Scenario (BAU).*

Conversely, the BAU scenario sees India continuing to rely on conventional logistics modes—road, rail, and air—without significant technological upgrades. This path is marked by persistent congestion and delays, as overburdened road and rail networks limit supply chain efficiency and drive up costs[6][57]. Traditional freight modes, still dependent on fossil fuels, contribute to higher carbon emissions and undermine national climate goals [54]. Regional development remains limited, with growth concentrated around existing urban centers and industrial corridors, perpetuating disparities [6]. Job creation is constrained to incremental improvements within established sectors, lacking the transformative surge in high-tech employment seen in the BIS scenario [53]. Finally, the BAU scenario leaves supply chains vulnerable to disruptions from weather, accidents, and infrastructure bottlenecks, further reducing overall resilience [54].
In summary, the BIS scenario, driven by Hyperloop adoption, offers India a strategic pathway to sustainable, inclu-

sive, and resilient economic growth, while the BAU scenario risks perpetuating inefficiencies and missed opportunities for transformative development.

Scenario	BIS	BAU
Logistics Efficiency	Very High	Moderate
Carbon Reduction	Significant	Low
Job Creation	High	Limited
Regional Development	Broad-based	Uneven
Supply Chain Resilience	Robust	Vulnerable

TABLE 37: COMPARATIVE OUTLOOK FOR BIS AND BAU OUTLOOKS

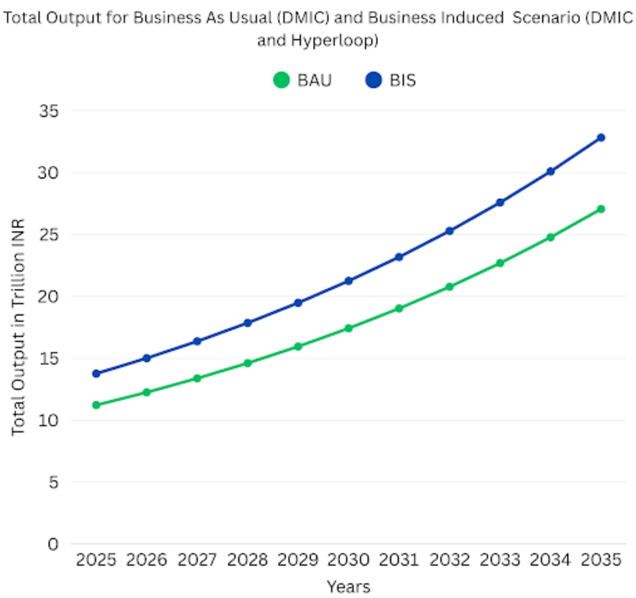

Fig. 19: Total projected total output for the Delhi-Mumbai Industrial Corridor (DMIC) and Hyperloop corridor under two scenarios: Business As Usual (BAU) and Business Induced Scenario (BIS)

Year	BAU (Output)(MT)	Hyperloop (MT)	BIS (output)(MT)
2025	11.220	2.542	13.762
2026	12.252	2.758	15.01
2027	13.379	2.993	16.372
2028	14.610	3.249	17.859
2029	15.955	3.526	19.481
2030	17.423	3.827	21.25
2031	19.026	4.154	23.18
2032	20.776	4.509	25.285
2033	22.687	4.895	27.58
2034	24.775	5.314	30.089
2035	27.055	5.769	32.824

TABLE 38: TOTAL PROJECTED TOTAL OUTPUT FOR THE DELHI-MUMBAI INDUSTRIAL CORRIDOR (DMIC) AND HYPERLOOP CORRIDOR UNDER TWO SCENARIOS: BUSINESS AS USUAL (BAU) AND BUSINESS INDUCED SCENARIO (BIS)

The graph illustrates the projected total output for the Delhi-Mumbai Industrial Corridor (DMIC) and Hyperloop corridor under two scenarios: Business As Usual (BAU) and Business Induced Scenario (BIS). Both scenarios show steady growth in total output from 2025 to 2035, but the BIS scenario (DMIC + Hyperloop) consistently outperforms BAU. By 2035, the total output in the BIS scenario surpasses INR 32 trillion, while the BAU scenario remains below INR 27 trillion. This represents a percentage increase of approximately 20% by 2035 when comparing BIS to BAU.
The compounding effect of higher annual growth rates in the BIS scenario results in a widening gap over time, underscoring the transformative impact of infrastructure and technology investments like DMIC and Hyperloop on regional economic output.
Importantly, these projections are underpinned by robust growth assumptions: the BAU scenario uses a 9.2% CAGR as projected in the DMIC Perspective Plan, while the BIS scenario uses an 8.5% CAGR in line with recent logistics sector forecasts2. This analysis highlights how strategic interventions can accelerate economic growth, yielding significant incremental gains in total output over the long term.
The adoption of Hyperloop freight technology under the BIS scenario offers India a strategic pathway to leapfrog traditional logistics constraints, ensuring sustainable, inclusive, and resilient economic growth. In contrast, the BAU scenario risks perpetuating inefficiencies and missing out on the full spectrum of benefits that next-generation transport systems can deliver. By embracing Hyperloop, India can secure its position as a global leader in green logistics and future-ready infrastructure [58][59].
As reported in [3], the logistics sector currently contributes approximately 14% to India's Gross Domestic Product

(GDP). Under the Business-Induced Scenario (BIS), the integration of Hyperloop technology—enabling the shift of an additional 2.542 billion tonnes of freight—has the potential to elevate the sector's contribution to as much as 17.18% of GDP.

9. Conclusion

From our perspective, Hyperloop represents not just a technological innovation, but a strategic opportunity to revolutionize freight transport in India. Through this study, we analyzed existing logistics inefficiencies and benchmarked them against our proposed Hyperloop-based freight system. The goal throughout was to identify a transportation mode that best balances efficiency, expense, and environmental impact, tailored to the urgency and sensitivity of freight shipments. To that end, we developed a machine learning model that evaluated mode suitability across a wide test dataset. Strikingly, 74.9% of the instances were predicted with Hyperloop as the optimal mode, followed by 24.29% for rail, 0.66% for road, and only 0.40% for air—reinforcing our confidence in Hyperloop's relevance for future-ready logistics.

The results affirmed our belief that Hyperloop can significantly reduce transit times, operational emissions, and long-term logistics costs—particularly for high-priority and sensitive cargo. We found that with the right capital structure and policy support, even substantial infrastructure investments can be offset by long-term socio-economic benefits such as enhanced regional connectivity, highway decongestion, and increased competitiveness for MSMEs. Hyperloop aligns seamlessly with India's push toward green, multimodal logistics and presents itself as a transformative force for equitable and sustainable economic growth. Our analysis reaffirms our conviction that investment in Hyperloop today is an investment in India's logistical resilience tomorrow.

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