

Abstract:

This paper examines if hyperloop can be an alternative to rail transport or aviation for traveling between Amsterdam and Berlin over approximately 575km. (1) The central research hypothesis is that hyperloop can reduce intercity travel time and decrease total life cycle carbon emissions for the modes of transport compared to current intercity transportation. (2) We will characterize the current patterns of travel between Amsterdam and Berlin. In order to conduct this analysis, we will develop a performance model, which will estimate how long it takes to travel along the proposed hyperloop route, what infrastructure is needed to support hyperloop travel along the route, and what the estimated costs will be to build that infrastructure. This performance model will be used with a comparative lifecycle emission assessment to understand the energy consumed during the operation of hyperloop vs. rail and aviation; as well as the carbon intensity (expressed in kgC/kWh) of the energy consumed to power those means of transport and the carbon emitted from rail, aviation and hyperloop. (3) Data collected for this study included modal statistics, benchmarks for infrastructure costs, performance parameters for hyperloop systems, and electricity carbon intensity data from European sources; (4) Based on the above data collected, we will produce a report comparing hyperloop, rail, and aviation, both in terms of economic and environmental viability of each transportation option, and the conditions under which hyperloop could make a significant contribution to decarbonizing these modes of transportation. (5) The study resides in the intersection of engineering economy, environmental science research, and infrastructure policy.

Introduction:

Intercity transport in Europe is facing structural constraints that cannot be optimized within existing systems. As the European Union pursues its Green Deal objective to be net carbon neutral by 2050 through a 90% reduction of transport sector emissions, a necessity for a high-speed and ecofriendly form of mobility continues to rise (Fetting, 2020). Currently, there is no type of transportation that fully optimizes speed, scalability, and environmental sustainability. Aviation dominates medium-haul routes like Amsterdam-Berlin (~575 km) because it minimizes travel time over complex topographies. However, it comes with a high environmental cost. Especially with short-haul flights, the disproportionate amount of carbon intensity counterbalances the benefits of the flight time speed. On the other hand, rail transportation offers a lower-emission alternative. However, compared to aviation, its travel times remain significantly longer and its improvements are approaching diminishing returns.

Hyperloop - a new mode of transport that uses magnetic levitation and low-pressure tubes for movement - is often positioned as the solution to the current problem. Driven by this futuristic opportunity, the European Hyperloop Center, opened in 2024, structured a foundational test site

in Veendam, Netherlands in order to accelerate hyperloop development and transition from theoretical physics to actual prototyping. Since then it has completed over 700 test runs and the performance model, based on standard phase kinematics with $\sim 0.5g$ acceleration and top speeds of 700-1200 km/h, consistently predicts sub-hour travel times over distances comparable to Amsterdam-Berlin. Furthermore, early lifecycle assessment (LCA) estimates emissions below 8 g CO₂ per passenger-kilometer under low-carbon electricity. This positions hyperloop as a mode of transportation capable of operating at or more than the speed of aviation along with emission levels competitive with rail.

However, these findings are conditional as the transition from test facilities to commercial use produces many engineering and economic hurdles. Since hyperloop would need to traverse the complex landscapes of urban and rural areas, the infrastructure costs are estimated to be from €17.5 million/km for elevated track to $\sim$ €70 million/km for tunneled systems. Also, in order to maintain a low-pressure tube over hundreds of kilometers, an abundant amount of energy is required implying that emission levels depend heavily on the host nations' electrical power systems and also factors like sustained passenger load. Moreover, existing studies frequently isolate performance, cost and environmental impact than evaluating them jointly. As a result, there is an uncertainty about hyperloop's viability in a real, high-demand corridor.

The Amsterdam- Berlin route provides a great test case to help resolve uncertainty about the mainstream adoption of hyperloop. Falling inside of the ideal length from 500-1500 km for hyperloop distance (Ramboll et al., 25), the 575 km Amsterdam-Berlin route is a dense intercity corridor with growing rail competition and sustained aviation demand. With examples like the new launch of GoVolta's rail transport and low average fares, hyperloop is in question if it, under realistic conditions, can not only traverse the distance in less than one hour but also at a price that drives passengers away from aviation and rail modes.

This study addresses the current gap by integrating a performance model with a comparative lifecycle emissions and cost analysis across hyperloop, rail and aviation. Using empirical data on modal demand, infrastructure benchmarks, and European electricity carbon intensity, we evaluate whether hyperloop can meaningfully reduce travel time and emissions. This paper aims to answer whether hyperloop can outperform existing transport modes on the Amsterdam-Berlin corridor under real-world constraints.

Literature Review:

Research on hyperloop as an intercity transport alternative spans across three connected domains: technology development and feasibility, environmental lifecycle assessment, and infrastructure analysis. This review analyzes the existing evidence across these domains as they relate to the Amsterdam-Berlin corridor, and identifies the gaps this study addresses.

The modern hyperloop concept was formalized by Musk in his “Hyperloop Alpha” white paper, which proposed a fifth mode of transport using low-pressure tubes and magnetic levitation to achieve near sonic ground speeds. Since then, European developers have led applied research. The European Hyperloop

Centre (EHC) is the world’s first facility to feature a lane switch, which enables network routing between Amsterdam and Berlin, and has completed prototyping trials at scaled equivalent speeds (Lamme, 2024). Hardt Hyperloop, the primary Dutch developer, has conducted over 700 test runs at the EHC, achieving a 50% increase in thrust capability and demonstrating electromagnetic levitation and propulsion at the infrastructure level (van de Pas, 2025).

A November 2025 fact-finding commissioned by the European Commission (Ramboll et al., 25) found that the European Hyperloop sector has advanced into the active prototyping stage, with many developers reaching TRL 6-7 maturity in propulsion, levitation and capsule systems. The study, however, identified several challenges related to high capital costs and the absence of a EU-level regulatory framework. There is no commercial hyperloop system in the world as of 2026 and Transport Canada’s official assessment concluded that the technology is unlikely to be ready for real- world application in the near future. Current divergence between commercial readiness and technical progress motivates this route feasibility analysis.

The kinematic framework is widely used for estimating hyperloop travel time. Studies from the ERA (European Railway Agency), NASA and other academic sources constantly apply the three-phase model. It consists of linear acceleration from rest to maximum speed, near-frictionless cruise phase, and controlled deceleration to rest. (Janic, 2021; NASA, 2017). The formula expresses total trip time as the sum of acceleration time, deceleration time, and cruise time over the remaining distance.

The standard parameter values use the maximum acceleration of 0.5g for passenger comfort. This number is consistent with NASA’s finding. It states that healthy adults can tolerate up to 0.3g, but commercial design aims at 0.5 g (Musk, 2013; NASA, 2017). The top speeds range from 700 km/h (European developmental target) to 1,200km/h (which is a theoretical ceiling). When applied to distances comparable to Amsterdam-Berlin (575km), the model predicts in-tube travel time of ~50-55 minutes. Hardt Hyperloop’s Amsterdam - Frankfurt study (450km and 7 intermediate stations) produced a projected travel time of 50 minutes, which is the closest published analogue to the present corridor (Hardt Hyperloop, 2019).

The environmental performance of hyperloop relative to rail and aviation has been widely explored within the existing literature. Becket et al. (2024) produced the first environmental lifecycle assessment (LCA) of a hyperloop system. That covered construction, operation, and end of life phases. The findings showed that hyperloop can achieve greenhouse gas emission below 8g CO₂/pkm under low-carbon electricity supply and sufficient passenger occupancy.

This is comparable to high-speed rail. It is also up to 20 times lower than aviation on the same routes. Critically, the findings even showed that under worst-case electricity mixes, hyperloop causes less than 5% of the climate impact of conventional aviation. Moreover, E-kerosene aircraft under renewable electricity scenarios still end up producing about 5 times the emission of hyperloop.

Earlier comparative energy modeling, like Jane (2021), showed that the average energy consumption across hyperloop, maglev and high speed rail all decreased with increasing journey distance and vehicle capacity. Additionally, the near-vacuum operating environment of the hyperloop system results in it benefiting disproportionately towards the energy consumption modeling. LCA screening of air, road and rail by Jehanno et al.(2021), established that European rail accounts for about 1.6% of transport-sector emissions, while carrying 6% of all of the passengers. This is the baseline hyperloop aims to demonstrate.

However, we have to note that the Beckert et al, (2024) findings are conditional. They are dependent on two variables we've discussed that vary significantly across the Amsterdam-Berlin corridor: electricity carbon intensity and passenger load. In 2023, Germany's grid intensity was 371 gCO₂/kWh against an EU average of 242 gCO₂/kWh (Ember, 2024). The EEA (2024) projects continued declines across both grids through 2030 under EU's Fit for 55 framework. No published study has applied Beckert et al. LCA methodology specifically to the Amsterdam-Berlin corridor using its projected electricity trajectory.

Infrastructure cost estimate for hyperloop has had a wide variance in literature, which reflects the absence of any real-world data. A 2025 EU commissioned study (Ramboll et al.) estimated the cost of €17.5-36.6 million/km for elevated above-ground track and about €70 million/km for tunneled sections. This is comparable to the European high-speed rail benchmark of approximately €18 million/km for flat-terrain elevated track. For instance, the Benelux region 632 km corridor was estimated to cost around €23 billion total, with an annual maintenance cost of €49 million (Ramboll et al., 2025). MPDI, 2023 study confirmed that the pillar-elevated range at €25-35 million/km and €70 million/km for the tunnel sections.

Demand wise, Hardt- Schiphol joint study (2023) found that 12.5 million of Schiphol's projected 2050 passengers would likely shift to hyperloop from aviation. The Amsterdam - Frankfurt study suggested that a single route could carry 48 million passengers annually. The Amsterdam-Berlin route has demonstrated strong rail demand, with GoVolta's March 2026 launch selling over 40,000 tickets pre-departure, with fares starting at €19, while also mentioning the price sensitivity as the key variable (GoVolta, 2026). The KPMG's analysis of the Helsinki - Stockholm hyperloop proposal estimated the break even prices of €20-25. The economic analysts, though, broadly suggest that the hyperloop fares would be comparable to aviation during the initial 10-15 year cost recovery period regarding the infrastructure investment (Avishkar Hyperloop, 2021).

Gaps addressed by the study:

This literature review has established the kinematic performance model, the LCA emission comparison, and network cost benchmark. As of now, there are no studies that apply all three simultaneously to a real-life corridor. Studies of European routes often model either travel time without emission (Hardt Amsterdam- Frankfurt), emission without route- specific infrastructure cost (Beckert et al., 2024), or assess network-level economics without performance comparison (Ramboll et al, 2025). No study has evaluated whether hyperloop can outperform both rail and aviation on travel time and lifecycle emissions under specific electricity grid trajectories, corridor demand characteristics, and infrastructure cost constraints of the Amsterdam-Berlin route. This study addresses that gap.

Methodology:

Performance Model and Travel Time Estimation

Travel time along the proposed hyperloop route is estimated using a three-phase kinematic model derived from standard parameters in the literature (Janic, 2021; NASA, 2017). The trip consists of a linear acceleration phase: from rest to maximum cruise speed, a sustained cruise phase through the tube environment, and a deceleration phase to rest at the destination. The total trip time is expressed as:

$$T_{total} = \frac{v_{max}}{a_{accel}} + \frac{D - \frac{v_{max}^2}{2a_{accel}} - \frac{v_{max}^2}{2a_{decel}}}{v_{max}} + \frac{v_{max}}{a_{decel}}$$

where D is the corridor distance (575km), v_{max} is the maximum cruise speed, and a_{accel} and a_{decel} are the acceleration and deceleration rates respectively. The Volpe Center (1994) established the lower comfort threshold through empirical passenger adaptability testing and found that 0.3g for positive vertical acceleration and 0.2g for negative vertical acceleration represent the human comfort level at which 95% of the passengers would not hesitate to ride again. However, Musk (2013) and NASA feasibility study (2017), take the passenger comfort ceiling of 0.5 g (4.9 m/s²), on the basis that 0.5g is the maximum inertial acceleration that can be comfortably sustained by humans for short periods. This study takes 0.5g as the engineering

ceiling scenario for the infrastructure-optimized design assumption and applies it to both acceleration and deceleration phases. Cruise speed scenario wise, two values are modeled: a conservative European developmental scenario at 700km/h, consistent with Hardt Hyperloop's current target and an upper-bound scenario at 1200km/h, consistent with the theoretical ceiling for a near-vacuum tube system.

Comparative Lifecycle Carbon Emission Assessment

This part of the paper analyzes 3 modes: hyperloop, rail, and aviation, using a consistent functional unit of grams of CO₂ equivalent per passenger-kilometer (gCO₂eq/pkm) over the 575 km corridor. It is done through the Beckert et al.(2024) lifecycle assessment framework, which covers construction, operation, and end-of-life phases, and allows direct comparability across modes.

The per passenger one-way emission for each mode is computed using the following formula:

$$E = ef * D / 1000$$

Where E represents per-passenger emission, ef = emission factor and D = corridor distance.

Emissions Computation by Mode: Amsterdam–Berlin (575 km)

Baseline emission factor of aviation for short-haul European flights (under 1,500 km) is 153 gCO₂/pkm. If the radiative forcing is applied, the number rises to 255 gCO₂ /pkm. For the Amsterdam-Berlin corridor at 575 km, the carbon intensity is at the high end of short-haul range because of the disproportionate fuel consumption of take-off and landing relative to a short cruise phase (Robeco, 2020). The operational emission for a one-way flight per passenger ends up falling in the range of about 88-147 kg CO₂, depending on whether radiative forces are included. This number is derived from the 153-255 gCO₂/pkm range across the corridor.

For rail, long-distance ICE services in Germany produce approximately 31 gCO₂/pkm (Deutsche Bahn/ Grokipedia, 2025), consistent with the European intercity rail range of about 19-71 gCO₂/pkm depending on the electricity mix, route clarification, and load factor (Carbon Independent, 2024). For the Amsterdam-Berlin corridor, the emission factor in the range of 40-41 gCO₂/pkm is applied, yielding a per passenger one-way emission of approximately 17-24 kg CO₂ at 575 km. This is about 5-8 times lower than aviation on the same corridor without radiative forcing.

For hyperloop, the Beckert et al. (2024) LCA establishes an emission floor of lower than 8 gCO₂/pkm under low-carbon electricity and high occupancy. The study also applies this to two electricity scenarios. Under the current grid scenario, a blended Dutch-German electricity

intensity of about 250 - 310 gCO₂/kWh is used. This is based on Netherlands' rapid decarbonizing offshore wind mix along with Germany's 2023 grid intensity of 371 gCO₂/kWh (Ember, 2024). Under the 2035 projected scenario, which is also consistent with EEA (2024) Fit for 55 trajectories, blended intensity of approximately 100-150 gCO₂/kWh is applied.

Infrastructure Cost Assessment

Infrastructure cost for the Amsterdam-Berlin hyperloop route can be estimated through applying accepted per-kilometer benchmarks to the 575 km corridor, and breaking it down by terrain and construction type. Based on the Ramboll et al. (2025) study and the capsule design optimization literature (MDPI, 2023), there are three cost scenarios: the elevated above ground, the underground tunneling, and the annual maintenance. To calculate the estimated infrastructure cost we also need to consider the lower-bound and upper-bound price estimates per km imposed by the European Commission / Ramboll (2025).

According to Ramboll et al, (2025), the elevated above ground scenario is going to cost about €25-35 million/km. The underground urban crossing segments that require tunneling would result in around €70 million/ km. The annual maintenance costs are estimated at €49 million for a Benelex-scale network and could be adjusted for the Amsterdam-Berlin route.

Results and Findings:

The following results were accumulated:

Travel Time

Using the conservative scenario (700km/h, 0.5g), the acceleration phase covers about 3.86 km and lasts 39.7 seconds, the deceleration phase does the same at 3.86 km and 39.7 seconds, the cruise phase covers the rest 567.3 km in about 48.6 minutes, which together yields a total in-tube travel time of approximately **49.8 minutes**. Under the upper-bound scenario (1200km/h, 0.5g), the acceleration and deceleration phases stretch to 11.33 km, lasting around 68 seconds each while the cruise phase covers 27.62 minutes. In total, that yields the in-tube time of approximately **29.9 minutes**. Each terminal must also have a station dwell time allowance of 10-15 minutes, consistent with current rail and aviation estimates described in the ERA (2022) technical analysis. This brings the total door-to-door station time for the current scenario to about 60-65 minutes.

Three inherent model uncertainties should be considered. First, the 0.5g acceleration assumption in a comfort-based ceiling, and actual operational acceleration might be adjusted in

the early commercial system. That would extend the acceleration distance and total time. Second, intermediate station stops, if included, would add about 8-12 minutes per stop based on the Amsterdam-Frankfurt analogue (Hardt Hyperloop, 2019). Third, route alignment across the Amsterdam-Berlin corridor may require speed reduction at any curve segments, since passenger comfort maintenance at 700 km/h requires curve radii bigger than 100km (ERA, 2022), which is ignored in this study. Given this, an error range of ± 8 minutes should be applied to the estimate, which places a realistic in-tube travel time window at 42-58 minutes for the 700km/h scenario.

Mode	Journey Time	Basis
Aviation (AMS–BER)	4.5–5 hrs	Incl. check-in, security, boarding, city transfer
ICE Rail (Deutsche Bahn)	~6 hrs	City-centre to city-centre, 1–2 changes
GoVolta (budget rail)	7–8 hrs	Direct, 160 km/h max
Hyperloop (700 km/h, 0.5g)	54 – 70 min	Kinematic model, ± 8 min error
Hyperloop (1,200 km/h, 0.5g)	34 – 50 min	Kinematic model upper bound, ± 8 min error

Moreover, the hyperloop travel time advantage over current modes is not sensitive to the choice of acceleration parameter. Using the Volpe Center’s (1994) passenger acceptability ceiling of 0.3 g instead of 0.5g for the three-phase kinematic model, produces a travel time difference of only 1.7 minutes, stretching the estimated travel time to 64 minutes.

Carbon Emissions

The environmental lifecycle assessment (LCA) was used for the three-mode emissions comparison. A blended Dutch-German electricity intensity of about 250 - 310 gCO₂/kWh is used. This is based on Netherlands’ rapid decarbonizing offshore wind mix along with Germany’s 2023 grid intensity of 371 gCO₂/kWh (Ember, 2024). Under the 2035 projected scenario, which is also consistent with EEA (2024) Fit for 55 trajectories, blended intensity of approximately 100-150 gCO₂/kWh is applied. These inputs, together with assumed occupancy rate of 70-80%, produce estimated operational emission of about 6-14 gCO₂/pkm under the current-grid condition and 3-8 gCO₂/pkm under the 2035 grid projection. Overall, the findings yield a per-passenger one-way range of about 1.7-8 kg CO₂ at 575km. Lifecycle construction emissions are also added to the operational estimate in the full LCA comparison. Specifically,

they are estimated to be around 2-3 gCO₂/pkm over the operational life of the infrastructure (Beckert et al, 2024).

The three-mode emissions comparison is summarized as follows. Aviation of the Amsterdam-Berlin corridor results in approximately 88-147 kg CO₂ per passenger one-way (153-255 gCO₂/pkm). Rail produces about 17-24kg CO₂ per passenger one-way (30-41 gCO₂/pkm). Hyperloop under current-grid conditions produces around 3.5 - 8kg CO₂ per passenger one-way (6-14 gCO₂/pkm), which shrinks to 1.7 - 5 kg CO₂ under a 2035 low-carbon electricity scenario. This places hyperloop at approximately **90-95% lower lifecycle emissions than aviation** and **60-80% lower than current intercity rail** on the same corridor. The findings are still conditional on the occupancy rate and electricity carbon intensity and they are the primary uncertainty figures in the comparative analysis, which are explored as sensitivity parameters in the results section.

Mode	Emission Factor (gCO ₂ /pkm)	Calculation	Result (kg CO ₂ /pax)
Aviation (no RF)	153	$153 \times 575 \div 1000$	88
Aviation (with RF)	255	$255 \times 575 \div 1000$	147
Rail (lower bound)	30	$30 \times 575 \div 1000$	17
Rail (upper bound)	41	$41 \times 575 \div 1000$	24
Hyperloop: current grid (lower)	6	$6 \times 575 \div 1000$	3.5
Hyperloop: current grid (upper)	14	$14 \times 575 \div 1000$	8
Hyperloop : 2035 grid (lower)	3	$3 \times 575 \div 1000$	1.7
Hyperloop : 2035 grid (upper)	8	$8 \times 575 \div 1000$	4.6

Infrastructure Cost

Following the elevated above-ground scenario which is easy to implement to the mostly flat Dutch-German terrain, costs are estimated at €25-35 million per kilometer, resulting in a total infrastructure cost of about €14.4-20.1 billion for the full 575 km corridor. Additionally, there are urban crossing segments that require tunneling. They are estimated to be approximately 40-60 km and the cost per kilometer for those sections rise to around €70 million. This adds €2.8-4.2 billion to the elevated-track baseline and produces the mixed-construction total range of approximately €17.2-24.3 billion.

The upper-bound scenario that applies the EU benchmark of €36.6 million per kilometer to the full corridor yields about €21.1 billion. The figures align with the Beneleux-region estimate of 23 billion for a 632 km network (Ramboll et al., 2025) and serve as a reasonable benchmark. However, they carry a certain uncertainty considering that we don't have real-world hyperloop construction data anywhere in the world.

Annual maintenance costs are estimated at €49 million for a Beneleux-scale network (Ramboll et al., 2025), which can be scaled to about €45 million per year for the 575 km Amsterdam-Berlin corridor. Vehicle costs for a 30-50 seat capsule fleet are excluded from the infrastructure estimate. Though, they are noted as an additional capital requirement in the range of €70-425 million depending on the fleet size and network scale (Ramboll et al., 2025).

Scenario	Cost per km	Total (575 km)
Elevated only (flat terrain)	€25–35M	€14.4–20.1B
Mixed construction (realistic)	€30–42M blended	€17.2–24.3B
Upper bound (EU ceiling benchmark)	€36.6M	~€21.1B
Annual maintenance	—	~€45M/yr

Discussion

The outcomes of this research have provided insight into the feasibility of a real-life hyperloop route. With an estimated travel time of 54-62 minutes under the conservative scenario and 34-50 minutes under the upper- bound scenario, carbon emission production of around 3.5-8 kg CO₂ per passenger one-way (6-14 g CO₂/pkm), and 1.7-5 kg CO₂ under a 2035 low-carbon electricity scenario, and the infrastructure cost of approximately €17.2-24.3 billion, hyperloop positions itself as the best solution to the current EU transportation gap. However, the results

should be treated with caution due to the certain sensitivity parameters, like occupancy rate, electricity carbon intensity, route alignment, number of stops and above ground vs. underground variance. This section provides a reflection to current research limitations and introduces further areas for research.

Travel Time

With a dramatic reduction in travel time to approximately 45-60 minutes, hyperloop allows for return in the same day suggesting a possible fundamental shift in regional connectivity. Since the in-tube travel portion ranges from 30-50 minutes, a large percentage of total time could come from security and check-in time. In order to keep hyperloop as efficient as possible, it must implement a high-frequency and low friction boarding process, hopefully keeping the extra time within 10-15 minutes. Current aviation cycles between Amsterdam and Berlin require a 4.5-5 hour door-to-door commitment while rail requires around 6 hours showing travel times that may consume a full day. Due to hyperloop's speed and reduced travel time, companies can convert hours previously spent in airport lines and on train routes into productive work, therefore increasing efficiency amongst employees.

Beyond pure speed, hyperloop's travel time advantage is bolstered by its departure frequency. Traditional rail and aviation rely on high-capacity transportation that departs every few hours, forcing passengers to schedule their day around the rigid times and wait times. However, according to Ramboll et al. (2025), this system has the potential to transport over 3000 passengers per hour through continuous streams of pods that was envisioned in "Hyperloop Alpha" to have departures every 2 minutes on average (Taylor et al., 2016). This allows for an easily accessible service that mimics urban transit rather than long-haul travel and would help with commercial feasibility.

Translating theoretical speed into reality has many constraints, one of which is the geometry of the route. The kinematic model assumes straight-line alignment, meaning that any deviation from this adds time and cost. The actual Amsterdam-Berlin corridor is a densely populated landscape, necessitating large curve radii exceeding 100 km at 700 km/hr in order to keep passengers comfortable. This requirement forces speed reductions, therefore diluting hyperloop's time advantage over aviation's direct path travel. Furthermore, this sub-hour travel time is highly sensitive to the amount of intermediate stops. Over the 575 km stretch, even two or three stops can potentially add 20-30 minutes to the total journey. This creates a tension between maintaining the high-speed factor of the mode and its passenger accessibility.

Future research must evaluate terminal operations and passenger processing efficiency, as the problem with modern intercity travel is typically not the transit phase itself, but the security and boarding process. A vital research question emerges: Can hyperloop maintain aviation-like safety standards while implementing a frictionless boarding process like suburban rail? If

security and check-in procedures add 45 minutes to a 50 minute journey, the vacuum tube's speed advantage is functionally halved. Subsequent studies should model variables such as processing throughout under various security protocols. Additionally, researchers should look into the scheduling required for continuous pod departures and the time-cost of intermodal transfers—specifically, how efficiently hyperloop can be integrated into existing transit networks in Amsterdam and Berlin to ensure the door-to-door travel time remains competitive.

Carbon Emissions

Carbon emission findings confirm the paper's hypothesis: hyperloop vastly reduces the carbon emission in regards to the current transportation modes. In fact, hyperloop outperforms aviation under current-grid intensity and has the potential to push it further under the 2035 decarbonization electricity intensity metric. However, the sensitivity parameters introduce limitations. Specifically, hyperloop's sensitivity towards its electricity source, due to its consumption of electricity with no diesel fallback, results in the vulnerability in dirtier grids. Moreover, the electricity intensity varies significantly and is dependent on passenger occupancy. A lower occupancy rate would result in proportionally higher emissions per passenger, which leaves room for exploration of the electricity gap between current and projected grid conditions.

On electricity carbon intensity, the results show that hyperloop already outperforms aviation under the current Dutch-German blended grid intensity of 250-310 gCO₂/kWh, producing 6-14 gCO₂/pkm operationally against aviation's 153 - 255 gCO₂/pkm. The emissions advantage does not depend on the 2035 grid scenario to be realized. However, the 2035 scenario widens the gap further, pushing operational emissions to 3-8gCO₂/pkm as the blended grid intensity falls toward 100-150 gCO₂/kWh under Fit for 55 trajectories.

Germany's grid intensity of 371 gCO₂/kWh in 2023 is the weakest point in the blended calculation. If Germany's coal phase-out stalls or reverses, something that almost occurred in 2022 following Russian gas supply disruption, the current-grid emissions scenario worsens and the margin over rail narrows. The Netherlands, by contrast, is decarbonizing rapidly through offshore winds and is approaching grid intensities where hyperloop's emissions would fall below best-performing European rail services. The corridor's emissions performance is more sensitive to German energy policy than any variable within the hyperloop system itself.

On occupancy, Beckert et al. (2024) demonstrate that below approximately 50% occupancy, per-passenger emissions rise quickly due to infrastructure energy consumption being fixed per departure. In early commercial years, the model would likely have a 40-60% occupancy rate because of no established trust and market penetration. At 50% occupancy, the operational emissions would double relative to the 70-80% scenario, which would produce 12-28 gCO₂/pkm under current grid conditions. That is still substantially lower than aviation, but it's approaching rail values at the upper end. This is not enough reason to dismiss the emissions case, but it is a

reason to treat early-year performance projections with caution and to design pricing and scheduling strategies that maximize load factors from launch.

Areas for future research emerging from these limitations are as follows. First, a time-series emissions model tracking per-passenger carbon intensity year by year across a 40-year operational life, which incorporates the annual grid decarbonization projection for both the Netherlands and Germany, would establish the grid intensity crossover point at which hyperloop matches or outperforms the best European rail services on this corridor, and would produce a more accurate total lifecycle figure than our current snapshots. Second, a pessimistic grid scenario modeling a five to ten year delay in Germany's coal phase-out should be tested to establish the lower bound of hyperloop's emissions performance under realistic policy risk. Third, occupancy sensitivity should be tested against real demand modeling for this corridor using price elasticity data and modal shift projections under different fare scenarios, in order to determine the minimum load factor at which the emissions advantage over rail is maintained from opening day. Fourth, a construction-phase LCA calibrated specifically to Dutch-German infrastructure conditions should replace the Swiss figure used here, as the difference in terrain, supply chain, and construction grid intensity could materially affect the full lifecycle emissions total.

Infrastructure Cost

On the infrastructure side, translating hyperloop into physical networks introduces large economic and modeling uncertainties. With expenditures estimated around €17.2 - 24.3 billion, the financial model suffers from optimism bias because no commercial hyperloop system currently exists to validate the benchmarks. Also, this price range excludes any factors like safety systems, emergency infrastructure, or regulatory compliance costs which would add to the total investment figure.

This project's financial viability is sensitive to its specific topographic routing, particularly the tunnel-to-bridge ratio. As underground construction is nearly two-three times as much as elevated tracks, any urban zoning that increases the 40-60 km of tunneling will drastically change the total budget. Possible use of existing rail corridors into urban centers can help with excessive subterranean work. Ultimately, overcoming these hurdles requires robust Public-Private Partnerships (PPP), along with over 40 million passengers paying premium fares to ensure cost recovery.

While technological efficiency of hyperloop is clear, its market viability must compete with low-cost carriers such as GoVolta. With rail fares as low as €19 (2026), hyperloop faces the problem in attracting riders who prioritize lower costs rather than longer 6 hour travel times. Elon Musk first proposed \$20 per ticket for a 560 km route (LA-San Francisco). However, to be realistic, the hyperloop prices are likely to be about the same as plane fares during the

break-even period of 10-15 years after opening. Furthermore, a comprehensive economic discussion must also include the indirect costs of traditional travel. Current rail and aviation are highly susceptible to weather conditions. Due to its tube environment, hyperloop offers operational reliability which can drastically reduce the extra costs from overnight stay or meals seen in aviation and rail modes. Ultimately, the justification for the €17.2-24.3 billion infrastructure bill lies in if this fifth mode of transportation can shift from luxury travel to utility that offers a reliable price that neither aviation nor rail can compare to.

Further economic research is essential to quantify the hidden engineering, safety, and regulatory costs that are not included in the baseline estimates. A primary area of question must address the safety mechanisms of the tube: What is the specific infrastructure cost of implementing “fail-safe” decompression systems? Beyond safety mechanisms, future cost models should analyze the economic impact of complex land acquisition and right-of-way negotiations within the densely populated Dutch-German corridor. Finally, studies are needed to estimate the lifecycle operational costs of maintaining a near-vacuum environment as these expenses will ultimately dictate the break-even ticket pricing and long-term market viability.

Conclusion

This study sets out to determine if hyperloop could serve as a viable, decarbonized alternative to rail and aviation along the Amsterdam-Berlin route. By examining the three-phase kinematic model used by the ERA, NASA, and other academic sources along with a comparative lifecycle assessment, hyperloop can theoretically achieve sub-hour travel times while reducing emissions more than 95% compared to aviation and around 80% compared to rail services. Provided that the estimated €17.2 - 24.3 billion infrastructure investment is considered for its long-term sustainability and significant contributions, hyperloop can bridge the gap between the speed of the air and the environmental friendliness of rail. However, the transition from theoretical physics to commercial utility remains constrained by significant limitations. Since no commercial system exists as of 2026, the performance benchmarks used in this paper may fluctuate as developers navigate realities such as catastrophic decompression risks and psychological impacts of windowless, high-speed travel. Future research for this must move beyond engineering models to explore real-world passenger behavior like response to changes in price, time, and service changes.

The significance of these findings lies in hyperloop's unique architecture which offers a solution to the European Green Deal that existing modes of transportation cannot match. While aviation struggles in finding a scalable carbon-neutral fuel, hyperloop's environmental performance improves automatically as the grid decarbonizes. If the hyperloop Amsterdam-Berlin corridor can successfully capture a significant portion of the 12.5 million passengers estimated to shift to hyperloop from aviation in a Hardt- Schiphol joint study (2023)

while also appealing to low-budget riders who prefer travel like GoVolta's current €19 rail fare (2026), hyperloop would move from a speculative engineering project to a justifiable pillar for trans-European transportation. Although commercial implementation is not anticipated until after 2035-2040 (Ramboll et al., 25), the strategic necessity for this "fifth mode" of transportation is immediate. Hyperloop's justification lies not just in the minutes saved, but in its ability to provide a reliable, low-emission method of travel that decouples high-speed mobility from environmental degradation.

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Previous findings:

- The European Hyperloop Center in the Netherlands (Hardt Hyperloop) is operational and has completed over 700 test runs. The European Commission confirms that the sector is approaching the demonstration scale.
- The Amsterdam- Frankfurt study (450 km, Hardt Hyperloop) projected about 50 minutes travel time with 7 intermediate stops and estimated 48 million annual passengers.
- All existing performance models use the same three-phase Newtonian kinematic framework with 0.5g acceleration and top speeds of 700-1200km/h as standard inputs.
- Becker et al. (2024) produced the first LCA of a hyperloop system and found emissions below 8g CO₂/pkm under low-carbon electricity, roughly 20x lower than aviation over the same corridor. This finding is conditional on electricity source and passenger number. (which we can treat as sensitivity parameters)
- The infrastructure cost estimate ranges from 17.5-36.6 million euro/km for elevated track to about 70 million euro/km for tunneled sections.
- Amsterdam-Berlin corridor is a high demand intercity route with growing rail competition (GoVolta, launched in March 2026, sold 40000+ tickets pre-launch). Aviation currently dominates medium-haul travel from Schipol. For comparison, GoVolta's prices for the

Amsterdam-Berlin start at \$19, with the average one-way ticket being about \$30. Elon Musk first proposed \$20 per ticket for a 560 km route (LA-San Francisco). However, if we're being realistic, the hyperloop prices are probably going to be about the same as plane fares during the break-even period of 10-15 years after opening.

A good introduction:

- Introduces the problem
- Talks about historical precedence (literature review)
- Research direction that the historical precedence did not resolve
- Current research landscape and the specific problem we resolve
- Talk about findings and conclusion

More history on Hyperloop and its feasibility:

<https://thereader.mitpress.mit.edu/the-hyperloop-a-200-year-history-of-hype-and-failure/>

History (Literature Review)

- George Medhurst (1810s): The original pioneer of "iron roads" through tubes using air pressure.
- The London and Edinburgh Vacuum Tunnel Company (1825): A direct historical parallel to your Amsterdam-Berlin route. They claimed they could do 600km in five minutes—a "preposterous" claim even then.
- Atmospheric Railways (1840s): Mention Isambard Kingdom Brunel's failed South Devon Railway. It failed because of a "leather flap" seal that rats ate and that dried out—a great example of how small mechanical details ruin "perfect" physics models.

(Methodology or Discussion) sections:

- Vacuum vs. Steel: Smil points out that in the 1820s, they had cast iron but no mass-produced high-tensile steel. Even today, the "thousandfold pressure difference" between the inside and outside of the tube threatens to crush it.
- Thermal Expansion: This is a "boring" but lethal engineering problem. A 575km steel tube will expand and contract significantly with temperature changes. Smil notes that every expansion joint is a potential leak point for the vacuum.

(Infrastructure Policy → Possible counterargument section)

- Political Reality: Smil mocks Musk's 2017 claim of "verbal government approval." He points out that the US hasn't even been able to give the *Acela* (a standard train) a dedicated track.
- Complexity of Jurisdictions: A route from Amsterdam to Berlin crosses international borders, multiple states, and thousands of private land plots. Smil argues that "minimal disruption" to farmers is a "blatant misrepresentation."

(Discussion):

- Catastrophic Decompression: In a plane, a hole is dangerous; in a near-vacuum tube at ground level, a minor explosion or structural failure causes an "instant crush" or catastrophic air hammer effect.
- Claustrophobia: Smil challenges the "human element"—traveling in a windowless, narrow "claustrophobic pod" at the speed of sound is a psychological barrier that "fake landscape images" on the walls won't fix.

More info on GoVolta:

<https://www.railvolution.net/news/first-govolta-train-departed>

<https://railmarket.com/news/passenger-rail/51842-govolta-launches-amsterdam-berlin-and-hamburg-trains-in-march-2026>

- The goal was to make things cheap so people wouldn't choose to fly or drive. Also to create a broad range of affordable and direct train networks starting from the Netherlands
- Max speed of 160 km/hr taking about 7 hours to get there → on its first ride on March 19, 2026, it arrived 20 mins earlier than expected being hauled by the TCS locomotive 101 001
- Has big plans to make a route from Amsterdam to Paris with an average fee of 50 Euros.

More info on aviation:

https://www.atmosfair.de/en/air_travel_and_climate/atmosfair_airline_index/

Use to find CO2 levels created by the airline

More Hyperloop info based on recent European Hyperloop Sector Findings

https://transport.ec.europa.eu/document/download/4907d350-6a0b-40ad-aa2c-efbdd1a46f0f_en?filename=Hyperloop_Fact%20Finding%20study.pdf

- “Concerning the distances to be covered, a study commissioned by Amsterdam Schiphol Airport notes that hyperloop is suitable for markets with distances of 100 - 3000 km, with a sweetspot between 500-1750 km, which aligns with the traditional scopes of intercity rail and air transport¹⁰⁷. The study presents hyperloop as a sustainable means of transport that could contribute to “sustainable ways to accommodate aviation demand, reduce airport congestion and maintain the competitive position of AAS as an international multi-modal hub.” Hence, hyperloop may also play a role in maintaining accessibility of existing vital infrastructure. Hyperloop could also provide significant value for shorter distance intercity transport, as evidenced by the study commission by the Province of North-Holland in the Netherlands¹⁰⁸. The study concludes that connections with nearby cities between 50-250 km from Amsterdam could lead to agglomeration benefits and increased GDP. “

- “Regarding freight transport, the business case for developing hyperloop technology could be seen in a broader perspective with other modes. The portion of the freight market currently interested in the high speeds that hyperloop could offer is presumed to be the existing market for air freight, accounting for only 2% of ton-miles but representing 40% of freight value. Although this means hyperloop could play a significant role in high value-added logistics services, the overall impact on traffic is low. The business case for such services could be viewed in combination with passenger transport to achieve additional benefits of the investment into the network, increasing the attractiveness of such investments. This could free up capacity on existing infrastructure to accommodate more freight on rail, contributing to the goal of doubling rail freight traffic by 2050.”