Nothing is Certain but Death and Taxes:

The Conditional Sustainability of Indian High-Speed Railway

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Introduction

The Indian Budget 2026 highlights sustainable infrastructure as a major allocation of public investments, notably seven high-speed rail (HSR) corridors. High-speed rail (HSR) is presented as a sustainable alternative to road and air travel. It is a cleaner, faster option that can reduce emissions while meeting India's growing demand for intercity mobility. We aim to investigate this claim.

This paper uses 'sustainability' to address two related ideas. Environmentally, it asks whether HSR actually reduces net carbon emissions across its full lifetime (construction and operations). An underused corridor cannot deliver emissions savings regardless of the technology's efficiency. This leads to the paper's problem statement: under what conditions do India's proposed HSR corridors deliver carbon sustainability?

Clarifications

Indian Railways (IR) operate as one of the largest and densest railway networks in the world, transporting over 24 million passengers daily [1]. In recent years, policy related to IR has focused on a few objectives based on the National Railway Plan and National Vision 2030 [2]. This includes 100% electrification, dedicated freight corridors, average train speed improvements—and HSR corridors connecting important destinations. HSR serves a variety of benefits: greater speed, increased capacity, significantly reduced travel times, reduced pressure on popular routes, and large-scale environmental benefits. By offering comfortable, affordable, and fast travel, HSR becomes a viable alternative to air travel and private vehicles, greatly reducing emissions [3]. With the sheer scale of usage of IR, declining environment of the country, and often questionable quality of public transit (long distance or short), HSR emerges as a major need of the hour.

The key consideration in this discussion is how much time for actual net carbon positive HSR. This answer is dependent on net carbon investment (i.e. resources utilised, construction emissions, operational emissions, etc.), daily ridership/passenger usage, and modal shift magnitude (i.e. how many private/air trips are saved – this variable is critical to HSR's environmental success). These three figures, which vary based on country and route, can be utilised to estimate when HSR becomes carbon neutral or positive. Based on models by Kortazar et al. [4], on average duration till net carbon neutral and positive ranges from 10–20 years, with 5–10 years in optimal cases, and 55+ years in long term scenarios. In some cases, HSR may never yield carbon neutrality or positivity. India's electricity grid being $\sim$75% fossil-fuel dependent is a major factor that adds to operational emissions; although one must also consider the steady decarbonisation of the grid happening in line with India's climate goals. Therefore, careful planning and estimation is required when building HSR with the aim of reducing emissions.

Process

This paper aims to construct a mathematical model that outputs possible carbon payback times for each of the corridors, under different circumstances. Certain assumptions and limitations were made during the construction of this model. Here, carbon debt input is inconsiderate of terrain and terraforming. The distances used may not be exact routes that the corridors will run along. Special reasons for travel (such as cultural or religious travel) are not considered. Average daily ridership is estimated based on the populations of the terminus cities, as empirical data is unavailable. Additionally, this model assumes that ridership levels from Day 1 are constant; whereas empirical data shows that ridership follows an S-curve, reaching design capacity asymptotically (as seen with the Japanese Shinkansen Bullet trains) [5].

European data states that HSR emits 17 g/km [7]. However, this data is inappropriate for India as it does not account for coal-dependency. Hence, this model incorporates a higher base HSR emission and dynamic grid decarbonisation. As per TERI [6], India aims to decarbonise 50% of the grid by 2030 as compared to 2005. This implies a decarbonisation rate of approximately 4% per year. Therefore, the operational emission factor of HSR at year t is modelled as:

$$e_{\text{HSR}}(t) = e_{\text{base}} \cdot (1-r)^t \tag{1}$$

where $e_{\text{base}} = 34$ g/km is India's grid-adjusted HSR emission baseline and $r = 0.04$ is the annual decarbonisation rate.

Current modal shift value data is unavailable. Hence, this model utilises modal shift values as decided by the author. In order to make these assumptions a negligible issue and to strengthen the model itself, we shall undertake a sensitivity analysis. This analysis considers three scenarios: optimistic, expected, and pessimistic. The pessimistic scenario depicts a situation where the majority of HSR ridership is transferred from existing rail, rather than other modes of transport.

Bringing all these parts together, we receive a compiled model that estimates carbon payback times for all seven proposed HSR corridors, incorporating India's steady grid decarbonisation and a sensitivity analysis for modal shift fractions. Refer Appendix A for the derivation of the savings equation, Appendix B for all model inputs, and Appendix C for the code.

Define:

$$e_{\text{HSR}}(t) = e_{\text{base}} \cdot (1-r)^t \tag{2}$$

$$S(t) = \frac{R \cdot D \cdot (e_{\text{current}} - e_{\text{HSR}}(t))}{10^6} \quad \text{(tonnes/day)} \tag{3}$$

The payback year T^* is defined as:

$$T^* = \min\left\{ T \in \mathbb{Z}^+ : \sum_{t=1}^{T} 365 \cdot S(t) \geq C \right\} \tag{4}$$

Put simply, this model checks at which years the carbon savings outnumber carbon debt, implying the minimum year to be the first occurrence of carbon savings.

Results

Table 1: Carbon payback times (years) by corridor and modal shift scenario. Dynamic grid decarbonisation at $r = 0.04$ applied throughout. Daily ridership held fixed at design capacity from year one.

Corridor	**Optimistic (yrs)**	**Base (yrs)**	**Pessimistic (yrs)**
Mumbai–Pune	4	6	11
Pune–Hyderabad	10	13	25
Hyderabad–Bengaluru	5	7	14
Hyderabad–Chennai	6	8	15
Chennai–Bengaluru	5	6	13
Delhi–Varanasi	13	16	32
Varanasi–Siliguri	36	44	80

Insights

As per the model, carbon payback times range from four years to entire decades. The optimistic modal shift scenario ranges from 4 to 36 years; the base scenario from 6 to 44 years; the pessimistic scenario from 11 to 80 years. It is important to note that as per the S-curve limitation mentioned earlier, it usually takes a few years to reach design capacity.

The analysis of three scenarios showcases how important modal shift is for carbon payback. The payback times of the more popular routes (such as Pune–Mumbai) remain around a decade; however payback times of the less popular routes increase drastically. For example, Varanasi–Siliguri jumps from 36 years to 80 years. This is a significantly long payback time, and majorly dependent on the modal shift values.

Conclusion

From the results, we can note that the Mumbai–Pune, Bengaluru–Chennai, Hyderabad–Bengaluru, and Hyderabad–Chennai corridors appear to be strong environmental investments, maintaining an approximate maximum 15 year carbon payback time regardless of modal shift scenario. The remaining routes, however, require further consideration for investment from an environmental perspective. Delhi–Varanasi must be noted as an exception here, as it is currently a very popular route due to the cultural significance of Varanasi, a fact discounted by the model. Largely, such routes will require dedicated policy support, ruthless environmental protection, and continuous grid decarbonisation. The major takeaway of this model is supporting the argument that sustainability of HSR is not guaranteed. It is conditional on grid decarbonisation, on relatively strong ridership, heavily on decent modal shift, and on the complexity of the routes themselves. Certain routes will be sustainable more easily and quickly, while others may struggle to become environmentally viable in certain situations.

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Appendix A: Model Derivation

Disclaimer: AI tools were used to assist in formulating the mathematical structure of the model and in generating the initial Python code for calculations. All assumptions, parameter choices, interpretation of results, and written analysis are the authors'. AI was used as a computational aid, not for generating any essay content.

Let the following variables be defined:

- C = total CO_2 from construction of the corridor (tonnes)
- D = corridor distance (km)
- R = average daily ridership (passengers)
- e_{HSR} = operational emissions of HSR per passenger-km (g CO_2/km)
- $e_{\text{bus}}, e_{\text{car}}, e_{\text{air}}$ = emissions of buses, cars, and air travel respectively
- α, β, γ = fraction of HSR riders shifting from air, car, and bus respectively

The weighted emission factor of the transport modes displaced by HSR is:

$$e_{\text{current}} = \alpha \cdot e_{\text{air}} + \beta \cdot e_{\text{car}} + \gamma \cdot e_{\text{bus}} \tag{5}$$

Each passenger-km of HSR travel saves $(e_{\text{current}} - e_{\text{HSR}})$ grams of CO_2. The total daily saving across all riders over the full corridor distance is therefore:

$$S = \frac{R \cdot D \cdot (e_{\text{current}} - e_{\text{HSR}})}{10^6} \quad \text{(tonnes/day)} \tag{6}$$

The modal shift sensitivity scenarios and resulting weighted emission factors are:

Table 2: Modal shift sensitivity scenarios and resulting weighted emission factors.

Scenario	α **(air)**	β **(car)**	γ **(bus)**	e_{current} **(g/km)**
Optimistic	0.60	0.50	0.30	158.3
Base	0.50	0.40	0.20	128.5
Pessimistic	0.30	0.20	0.10	71.9

Appendix B: Inputs

Modal shift fractions are as per the table in Appendix A. Note that these fractions need not sum to one; the remainder is assumed to shift from existing rail, which saves no carbon. HSR emissions for India are taken to be 34 g/km, with a 4% decrease per year in accordance with India's grid decarbonisation goals. Emissions of buses, cars, and air travel are:

$$e_{\text{bus}} = 30 \text{ g/km}, \quad e_{\text{car}} = 115 \text{ g/km}, \quad e_{\text{air}} = 153 \text{ g/km} \tag{7}$$

respectively, as per Jehanno et al. [7]. Ridership numbers are estimated based on the terminus cities. Finally, the distances of each corridor and their emissions are tabled below. Construction emissions are assumed to be 90,000 t/km, as per Chester & Horvath [8].

Table 3: Corridor distances (Google Maps), estimated daily ridership, and construction CO_2 at 90,000 t/km [8].

Corridor	**Distance (km)**	**Est. Daily Ridership**	**Construction CO_2 (Mt)**
Mumbai–Pune	155	500,000	13.95
Pune–Hyderabad	556	200,000	50.04
Hyderabad–Bengaluru	575	400,000	51.75
Hyderabad–Chennai	629	350,000	56.61
Chennai–Bengaluru	348	450,000	31.32
Delhi–Varanasi	874	150,000	78.66
Varanasi–Siliguri	709	50,000	63.81

Appendix C: Code

```
import pandas as pd
import numpy as np

# Emission factors (g CO2 per passenger-km)
e_hsr_base = 34       # India-adjusted (2x European, ~71% coal grid)
e_bus      = 30
e_car      = 115
e_air      = 153

# Annual grid decarbonisation rate (TERI / India NDC)
r = 0.04

# Modal shift scenarios
scenarios = {
    "Optimistic" : {"alpha": 0.60, "beta": 0.50, "gamma": 0.30},
    "Base"       : {"alpha": 0.50, "beta": 0.40, "gamma": 0.20},
    "Pessimistic": {"alpha": 0.30, "beta": 0.20, "gamma": 0.10},
}

corridors   = ["Mumbai-Pune", "Pune-Hyderabad", "Hyderabad-Bengaluru",
               "Hyderabad-Chennai", "Chennai-Bengaluru",
               "Delhi-Varanasi", "Varanasi-Siliguri"]
distance_km = [155, 556, 575, 629, 348, 874, 709]
ridership   = [500000, 200000, 400000, 350000, 450000, 150000, 50000]
C_build     = [d * 90000 for d in distance_km]

def compute_payback(D, R, C, e_current, e_base, r, max_years=100):
    cumulative = 0.0
    for t in range(1, max_years + 1):
        e_hsr_t = e_base * (1 - r) ** t
```

```
        delta_e = e_current - e_hsr_t
        if delta_e <= 0:
            continue
        cumulative += 365 * R * D * delta_e / 1e6
        if cumulative >= C:
            return t
    return f">{max_years}"

rows = []
for i, corridor in enumerate(corridors):
    row = {"Corridor": corridor}
    for sname, s in scenarios.items():
        e_curr = s["alpha"]*e_air + s["beta"]*e_car + s["gamma"]*e_bus
        T = compute_payback(distance_km[i], ridership[i],
                            C_build[i], e_curr, e_hsr_base, r)
        row[sname] = T
    rows.append(row)

df = pd.DataFrame(rows)
print(df.to_string(index=False))
```