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Good Things Come to Those Who Wait: A Carbon Payback Analysis of the Pune Metro Project

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6 July 2026

Introduction

The Pune Metro Project (henceforth PMP) began in December 2016. Pune is the second-largest city by population and area in Maharashtra, and it is also the second-most congested city in India [1]. This congestion can be attributed primarily to an unchecked explosion of private vehicle usage combined with an overwhelmed, slow public transit system. The Pune Metro aims to aid this problem by transporting 6,00,000 people daily (future expected ridership), across long distances; cutting commute times and reducing congestion [2]. As of June 2026, 33km of metro is operational (Phase I), with nearly 33km more (Phase II) under construction and scheduled to open soon in parts [3].

The PMP is cause of major debate. It faces major criticisms for low ridership, last-mile connectivity issues, route misalignment with actual commute vectors, and problems caused by construction and delays. On the other hand, users praise the metro's punctuality and facilities, arguing that ridership will increase as construction nears completion on remaining lines. Primarily the Purple Line (Line 3), which is under construction and connects the city centre (Shivajinagar) to the city's busiest information technology park (Hinjewadi), and is therefore expected to ease many road traffic gridlocks.

As with most public transit projects and alongside congestion relief, the metro has been put forward as a project with many environmental benefits, especially carbon savings. Metro systems in India emit 19.2 gCO_2/km [4] as compared to the 115 gCO_2/km of cars [5]. With the criticisms faced by the PMP, it risks becoming a simple point of publicity and modernity-signalling, given the emissions created during construction and operation. With the support it receives from users, it may become a hero of Pune's public transit. This paper aims to end this debate from an environmental perspective: when will the PMP repay its carbon debt and actually contribute to carbon savings? Is this timeframe reasonable?

Process

This brief builds on the carbon-debt repayment equations constructed in ASL5 [6]. A central part of this model is the carbon savings equation:

$$S(t) = \frac{R(t) \cdot D \cdot (e_{\text{current}} - e_{\text{metro}}(t))}{10^6} \quad \text{(tonnes CO}_2\text{-eq/day)} \tag{1}$$

where $R(t)$ is daily ridership at time t, D is the average trip distance, e_{current} is the blended emission factor of displaced private vehicles, and $e_{\text{metro}}(t)$ is the operational emission factor of the metro at time t.

This paper considers the completed PMP: current metro distance (i.e. existing operational lines), added with future metro distance (lines under construction). Out of the PMP's ridership, a certain fraction shifted their commute from private vehicles (prevalently cars and two-wheelers in Pune) to the metro, while the remainder is considered induced demand and shift from other public transport (buses and auto-rickshaws). This fraction is assumed to be split as 55% two-wheelers and 45% cars (Pune has a majority of two-wheelers), with the quantity itself being known as modal shift (see Appendix A). We will test the sensitivity of this modal shift in the actual payback model, from modal shift of 30% to 70%.

This paper improves upon a major limitation of ASL5. We introduce the logistic growth curve in ridership (the S-curve mentioned in ASL5's limitations). This models ridership as a function of time, slowly growing from current ridership to expected future ridership and appropriately simulating how ridership reaches design capacity asymptotically. This brief will utilise two S-curves, where one forms the base and plateaus (i.e. showcasing the construction and operation of Phase I), and then a second incorporating the impact of Phase II's opening. See Appendix A for derivation. The Phase I S-curve begins with a ridership of approximately 50,000 people

[7] and plateaus at 2,00,000 [8] in four years (these real numbers determine the rate of the curve's growth). The Phase II curve begins here and pessimistically plateaus at 4,00,000 (not the 6,00,000 expected ridership). Due to unavailability of data, the Phase II curve accelerates at the same pace as the Phase I curve, which is a limitation.

$$R(t) = \begin{cases} R_0 + \dfrac{R_A - R_0}{1 + e^{-k_1(t-\tau_1)}} & t < t_1 \\ R(t_1) + \dfrac{R_B - R(t_1)}{1 + e^{-k_2(t-t_1-\tau_2)}} & t \geq t_1 \end{cases} \tag{2}$$

where $R_0 = 52{,}000$ is opening ridership, $R_A = 2{,}00{,}000$ is the Phase I plateau, $R_B = 4{,}00{,}000$ is the Phase II ceiling, $t_1 = 4$ years is the checkpoint year, and k_1, k_2, τ_1, τ_2 are the logistic growth rate and midpoint parameters (see Appendix A for derivation).

The PMP sources nearly 40% of its electricity from renewable solar (with negligible emissions) [9], which is incorporated into the e_{metro} factor (see Appendix A for explanation):

$$e_{\text{metro}}(t) = (1-s) \cdot e_{\text{base}} \cdot (1-r)^t + s \cdot e_{\text{solar}} \tag{3}$$

where $s = 0.40$ is the solar share, $e_{\text{base}} = 19.2$ gCO_2/pkm is the grid-adjusted metro emission baseline [4], $r = 0.04$ is the annual grid decarbonisation rate [6], and $e_{\text{solar}} \approx 0$ is treated as negligible.

By compiling all these features, we get a complete model that outputs the minimum time for carbon payback, which incorporates the modal shift, solar energy savings, and ridership logistic growth (see Appendix B for all inputs). The payback year T^* is defined as:

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

where C is the total construction carbon debt of the full 66km network. Put simply, this model checks at which year the cumulative carbon savings first exceed the construction carbon debt.

Certain limitations must be kept in mind with this model. The 55–45 split of cars and two-wheelers in modal shift is an estimate by the author to avoid overcomplicating. Cases as different splits, electric vehicles, auto-rickshaws, etc. are beyond the scope of this paper. The impact caused by modal shift from other public transport is considered as cannibalisation and absorbed into the remainder fraction (as per sensitivity analysis scenario). The average metro journey is taken to be 7km [10], but this may change. The ridership curves assume logistic growth, but the PMP actually saw significant fluctuations as lines opened. The time gap between Phases and the opening of Phase II (which will take place in parts with certain stations opening first, then certain extensions, and so forth) may again cause fluctuations in ridership and is not considered in the model for the sake of simplicity. Lastly, other causes of carbon emissions, such as last-mile connectivity issues, are not considered in the model as they are out of scope.

Results

By running this model through a Python script (see Appendix C), we get the following result:

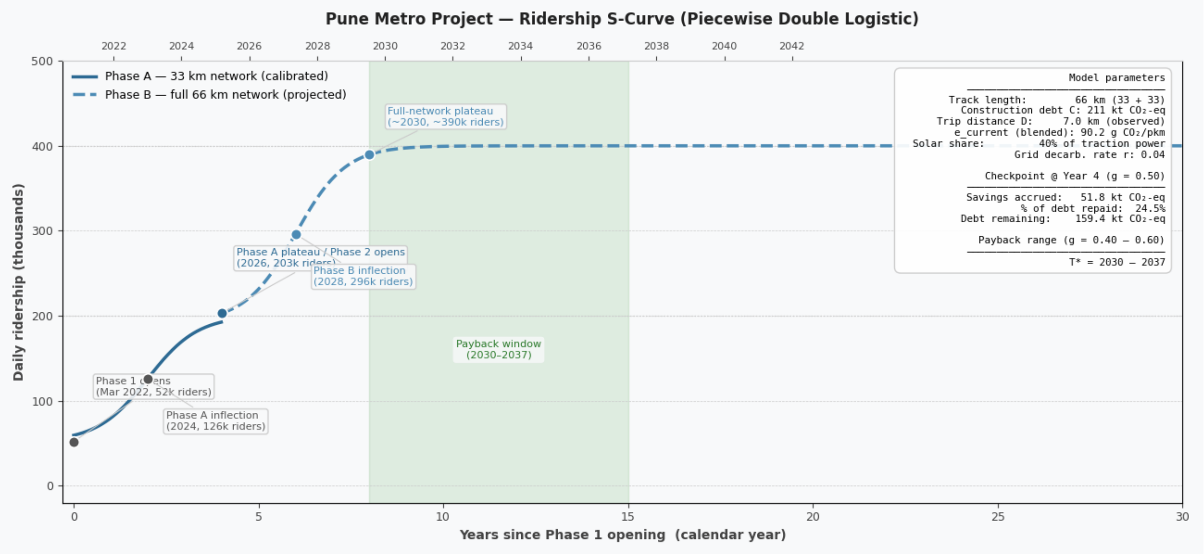

Figure 1: Piecewise double-logistic ridership curve for the Pune Metro Project. Phase A (solid) is calibrated from real data (52k to 2,00,000 over 4 years). Phase B (dashed) projects the full 66km network to a conservative ceiling of 4,00,000 daily riders. The shaded region marks the payback window across the modal shift sensitivity range ($g = 0.30$–0.70). Parameters and checkpoint statistics (at $g = 0.50$) are shown in the embedded summary box.

Insights

Based on the modal shift sensitivity scenario, the PMP will pay off its carbon debt in 8–15 years. At the opening of Phase II in year 4, approximately 25% of the carbon debt is paid. This implies that the remaining 75% is paid off in the next 4–11 years. While single-step increments in modal shift decrease the payback by only one year, it is important to note the 7 year gap purely due to the upper and lower bounds of modal shift (30% and 70%). This agrees with a result of ASL5, pointing towards the importance of modal shift in the carbon payback of public transportation; sheer ridership, while important, does not leave such a large impact on the numbers. To attest, when the maximum ridership was increased from 4,00,000 to 6,00,000, payback times decreased only by a year or two.

Another important result: when the model was implemented with higher e_{car} and e_{2w} values found in [11] ($e_{\text{car}} = 280$, $e_{\text{2w}} = 100$), the payback times shifted drastically to 5–10 years. The higher emissions of [11] led to PMP usage saving more carbon emissions with every percent of modal shift. This highlights the fact that quality and age of private transport (i.e. whether they emit less or more), is also a large factor determining the carbon payback time of public transport. This model split modal shift into two-wheelers and cars as a 55-45% split – an assumed value. Actual registered vehicle data in Pune shows approximately shows approximately 75% two-wheelers and 15% cars [12], with the remainder being miscellaneous vehicles. Running the model more in line with these numbers (i.e. a 70-30% split) shifts the payback by at most two years, implying that the model is not sensitive to this parameter.

Conclusion

The above analysis serves its aim: we determine that under reasonable circumstances, the PMP should reach carbon neutrality and begin contributing to carbon positivity in 8–15 years, i.e. in the 2030–2037 window. The model provides an average payback time of approximately a decade. This range for carbon payback time of an urban metro system like the PMP is quite reasonable. Hence from an environmental perspective, the debate of PMP's stated sustainability can be put to rest. It is important to note the major takeaways of this model: the proven significance of modal shift fraction, the diminished importance of sheer ridership, and lastly, the impact of the environmental quality of private transport.

While the lower modal shift value of 30% yields an acceptable 15-year payback time, it does little to actually ease the congestion problem. 30% may indicate that potential future private-vehicle users shifted to the metro, but this still leaves Pune as a heavily congested city. To answer this crisis, promotion and investment in public transport, and discouragement or restrictions on private vehicles will be required from a policy perspective.

References

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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 author's. AI was used as a computational aid, not for generating any written content.

Blended displaced-mode emission factor

The PMP primarily displaces car and two-wheeler (2W) trips. Based on the author's estimate of the Pune modal split, 55% of displaced trips are from two-wheelers and 45% from cars. The blended displaced-mode emission factor is therefore:

$$e_{\text{current}} = w_{2\text{W}} \cdot e_{2\text{W}} + w_{\text{car}} \cdot e_{\text{car}} \tag{5}$$

where $w_{2\text{W}} = 0.55$, $w_{\text{car}} = 0.45$, $e_{2\text{W}} = 70$ gCO$_2$/pkm (half of e_{car}, per author's instruction), and $e_{\text{car}} = 115$ gCO$_2$/pkm [5]. This yields:

$$e_{\text{current}} = 0.55 \times 70 + 0.45 \times 115 = 38.5 + 51.75 = 90.25 \approx 90.2 \text{ gCO}_2\text{/pkm} \tag{6}$$

Solar-corrected operational emission factor

The PMP sources 40% of its traction power from solar, which carries negligible emissions [9]. The remaining 60% is drawn from the grid. Incorporating grid decarbonisation at rate $r = 0.04$ per year:

$$e_{\text{metro}}(t) = (1 - s) \cdot e_{\text{base}} \cdot (1 - r)^t \tag{7}$$

where $s = 0.40$ and $e_{\text{base}} = 19.2$ gCO$_2$/pkm [4].

Daily carbon savings

Only the genuine modal shift fraction g of riders represents real displaced private-vehicle trips and generates savings. The remaining fraction $(1-g)$ is induced demand or shifted from other public transport, modelled as a pure emissions cost (the metro's own operational footprint, with no offsetting avoided trip). The daily net carbon savings are therefore:

$$S(t) = \frac{R(t) \cdot D \cdot [g \cdot (e_{\text{current}} - e_{\text{metro}}(t)) - (1-g) \cdot e_{\text{metro}}(t)]}{10^6} \tag{8}$$

Piecewise double logistic ridership curve

Ridership is modelled as a piecewise double logistic, calibrated from real PMP data. The standard logistic function is:

$$L(t; \text{start}, \text{target}, k, \tau) = \text{start} + \frac{\text{target} - \text{start}}{1 + e^{-k(t-\tau)}} \tag{9}$$

Phase A is calibrated from observed data: ridership grew from 52,000 at opening ($t = 0$, March 2022) to approximately 2,00,000 by $t = 4$ years (2026). Setting the 5%–95% crossing points at $t = 0$ and $t = 4$ respectively gives $\tau_1 = 2.0$ and $k_1 = \ln(19)/\tau_1 \approx 1.472$.

Phase B stitches continuously from the Phase A plateau at checkpoint $t_1 = 4$, and grows toward a conservative ceiling of $R_B = 4{,}00{,}000$. The same growth parameters are reused ($k_2 = k_1$, $\tau_2 = \tau_1$) as no additional calibration data is available. The full piecewise curve is given by Equation (2) in the main text.

Construction carbon debt

As per [4], construction carbon intensity for an elevated metro system is taken as 3,200 tCO_2-eq per track-km. For the full 66km network:

$$C = 3{,}200 \times 66 = 2{,}11{,}200 \ tCO_2\text{-eq} \tag{10}$$

Appendix B: Model Inputs

The genuine modal shift fraction g is the primary sensitivity axis, swept from 0.30 to 0.70 in steps of 0.05. All other parameters are held fixed. The blended displaced-mode emission factor $e_{\text{current}} = 90.2$ gCO$_2$/pkm is a constant derived from the car/2W split (see Appendix A).

Table 1: Fixed model parameters.

Parameter	**Value**	**Source**
Metro emission baseline e_{base}	19.2 gCO$_2$/pkm	Aryan et al. (2025) [4]
Car emission factor e_{car}	115 gCO$_2$/pkm	Jehanno et al. (2011) [5]
Two-wheeler factor e_{2W}	70 gCO$_2$/pkm	Author's estimate (half e_{car})
Two-wheeler weight w_{2W}	0.55	Author's estimate
Car weight w_{car}	0.45	Author's estimate
Blended e_{current}	90.2 gCO$_2$/pkm	Derived (Appendix A)
Solar share s	0.40	PuneMirror Bureau (2023) [9]
Grid decarbonisation rate r	0.04 yr^{-1}	ASL5 [6]
Average trip distance D	7.0 km	parisar.org (2017) [10]
Phase I opening ridership R_0	52,000	Express News Service (2023) [7]
Phase I plateau R_A	2,00,000	Dastane (2026) [8]
Phase II ceiling R_B	4,00,000	Author's conservative estimate
Checkpoint year t_1	4 years	Calibrated from Phase I data
Logistic rate $k_1 = k_2$	1.472	Solved from 52k→200k/4yr
Logistic midpoint $\tau_1 = \tau_2$	2.0 years	Solved from 52k→200k/4yr
Track length	66 km	PMRP (2025) [3]
Construction intensity	3,200 tCO$_2$/track-km	Aryan et al. (2025) [4]
Construction debt C	2,11,200 tCO$_2$-eq	Derived

Appendix C: Code

The following is a summary of the Python script used to compute the carbon payback model.

```
# --- Constants and parameters ---
e_base   = 19.2          # metro emission baseline, g CO2-eq/pkm (Aryan et al. 2025)
r_grid   = 0.04          # annual grid decarbonisation rate
s        = 0.40          # solar share of traction power
e_solar  = 0.0           # solar emissions, treated as negligible
e_car    = 115.0         # g CO2-eq/pkm (Jehanno et al. 2011)
e_2w     = 70.0          # g CO2-eq/pkm (half of e_car)
w_2w     = 0.55          # two-wheeler weight in modal split
w_car    = 0.45          # car weight in modal split
D        = 7.0           # average trip distance, km
C        = 3200 * 66     # construction debt: 211,200 t CO2-eq (Aryan et al. 2025)

# Genuine modal shift sensitivity range
genuine_shift_range = [0.30, 0.35, 0.40, 0.45, 0.50,
                        0.55, 0.60, 0.65, 0.70]

# --- Blended displaced-mode emission factor (constant) ---
e_current = w_2w * e_2w + w_car * e_car    # = 90.2 g CO2-eq/pkm

# --- Logistic growth function ---
def logistic(t, start, target, k, tau):
    return start + (target - start) / (1 + exp(-k * (t - tau)))

# Calibrated from real data: 52k -> 200k over 4 years
tau1 = 2.0
k1   = ln(19) / tau1    # = 1.472

# --- Piecewise double logistic ridership curve ---
def ridership(t):
```

```
    R_at_t1 = logistic(t1, R0=52000, RA=200000, k=k1, tau=tau1)
    if t < t1:
        return logistic(t, start=52000, target=200000, k=k1, tau=tau1)
    else:
        return logistic(t - t1, start=R_at_t1,
                        target=400000, k=k1, tau=tau1)

# --- Solar-corrected metro emission factor ---
def e_metro(t):
    return (1 - s) * e_base * (1 - r_grid)**t

# --- Daily carbon savings ---
def daily_savings(t, g):
    R_t  = ridership(t)
    em   = e_metro(t)
    delta = g * (e_current - em) - (1 - g) * em
    return (R_t * D * delta) / 1e6    # tonnes CO2-eq/day

# --- Payback loop ---
for g in genuine_shift_range:
    cumulative = 0
    for t in range(1, max_years + 1):
        cumulative += 365 * daily_savings(t, g)
        if cumulative >= C:
            T_star = t
            break
    # Report T_star and checkpoint stats at t=4
```