RESEARCH PAPER

Impact Assessment of Non-Motorized Transportation Infrastructure on Urban Sustainability Using Traffic Simulation and Emission Reduction Modelling

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ABSTRACT

Rapid urbanization in developing nations has intensified vehicular traffic, worsening air quality and undermining urban sustainability goals. This study assesses the impact of expanding non-motorized transportation (NMT) infrastructure—specifically dedicated cycling lanes, pedestrian walkways, and multimodal integration hubs—on urban sustainability across five major Indian cities: Mumbai, Delhi, Pune, Bengaluru, and Hyderabad. A hybrid methodology is deployed, integrating VISSIM-based microscopic traffic simulation with the COPERT emission estimation model and the Sustainable Urban Mobility Index (SUMI). Calibrated using 2018–2023 field data, the simulations quantify modal shift, travel time savings, greenhouse gas (GHG) reduction, particulate matter (PM2.5/PM10) abatement, and economic co-benefits. Results reveal that a 15–30% increase in NMT mode share produces CO_2 reductions of 12–27%, PM2.5 reductions of 18–34%, and NO_x reductions of 14–26%. Travel time savings of 8–19 minutes per commute per day are demonstrated. Benefit–Cost Analysis (BCA) yields ratios of 2.1–4.7, confirming economic viability. The paper further proposes an evidence-based NMT Investment Priority Framework (NIPF) to guide policy decisions. Findings contribute directly to SDG 11 (Sustainable Cities) and SDG 13 (Climate Action) targets.

Keywords: Non-motorized transportation; Urban sustainability; Traffic simulation; Emission modelling; VISSIM; COPERT; Cycling infrastructure; Pedestrian mobility; Mode shift; Carbon reduction; India.

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INTRODUCTION

Urbanization is accelerating at an unprecedented pace across the developing world. The United Nations estimates that by 2050, approximately 68% of the global population will reside in urban areas [1]. In India alone, the urban population is projected to reach 877 million by 2050, up from 507 million in 2020 [2]. This rapid growth has precipitated a transportation crisis characterized by extreme road congestion, declining air quality, increased carbon emissions, and rising road traffic fatalities.

Transportation is responsible for approximately 24% of global CO_2 emissions from fuel combustion, with road transport accounting for the dominant share [3]. In Indian metropolitan areas, vehicular emissions contribute 30–60% of total PM2.5 concentrations, a major driver of the air quality crisis that results in an estimated 1.67 million premature deaths annually [4]. Despite this, transport infrastructure investment has historically favoured motorized vehicles, with cities allocating less than 5% of road space to pedestrians and cyclists, despite these modes constituting 30–40% of all trips [5].

Non-motorized transportation (NMT) encompasses walking, cycling, and human-powered transport modes. Expanding NMT infrastructure offers multiple co-benefits: reduced traffic congestion, lower GHG and pollutant emissions, improved public health outcomes, reduced transport poverty, and enhanced urban liveability [6,7]. However, quantitative evidence on the magnitude of these benefits, particularly for rapidly motorizing South Asian cities, remains scarce. Most existing studies focus on Western European or North American contexts, where baseline NMT infrastructure, cycling culture, and urban form differ significantly from Indian cities [8].

This research addresses this gap by conducting a rigorous, simulation-based impact assessment of NMT infrastructure expansion across five major Indian cities. The study integrates microscopic traffic simulation (PTV VISSIM), emission modelling (COPERT V), and sustainability indexing (SUMI) to provide a holistic quantitative evaluation. It further proposes the NMT Investment Priority Framework (NIPF) to guide city-specific interventions.

1.1 Research Objectives

- Quantify the modal shift from motorized to non-motorized transport resulting from dedicated NMT infrastructure development.
- Model and estimate reductions in GHG emissions (CO_2, CH_4, N_2O) and criteria air pollutants (PM2.5, PM10, NO_x, VOC) attributable to NMT expansion.
- Assess travel time, economic, and health co-benefits through integrated benefit–cost analysis.
- Develop a policy-applicable NMT Investment Priority Framework (NIPF) calibrated to Indian urban contexts.

1.2 Scope and Novelty

The novelty of this study lies in three dimensions: (i) the use of calibrated microscopic traffic simulation to model heterogeneous Indian traffic conditions, capturing the unique mix of two-wheelers, autorickshaws, buses, and non-motorized vehicles; (ii) the integrated quantification of emission, health, and economic co-benefits within a single analytical framework; and (iii) the development of a transferable priority framework applicable across cities of different sizes and NMT baseline conditions. This paper makes a substantial contribution to the growing body of evidence linking NMT infrastructure investment to climate and sustainability outcomes in the Global South.

2. LITERATURE REVIEW

2.1 Global Evidence on NMT and Urban Sustainability

The relationship between NMT infrastructure and urban sustainability has been extensively documented in the global literature, though predominantly in high-income country contexts. Cervero et al. [9] demonstrated that cities with higher cycling mode shares exhibit significantly lower per-capita transport-related GHG emissions. A meta-analysis by Götschi et al. [10] across 167 European cities found that a 10-percentage-point increase in cycling mode share corresponded to a 5–8% reduction in urban transport CO_2 emissions. Similarly, Fishman et al. [11] estimated that replacing car trips with cycling trips in Australian cities could reduce transport emissions by up to 14%.

Litman [12] synthesized evidence from North American cities and concluded that NMT infrastructure investments yield benefit–cost ratios of 3:1 to 11:1 when health, congestion relief, and environmental benefits are fully accounted for. The European Cyclists' Federation [13] reported that every euro invested in cycling infrastructure generates approximately four euros in economic returns through health savings, reduced congestion, and productivity gains. In the UK, Rutter et al. [14] estimated that a 10-fold increase in cycling participation could prevent 1.5 million cases of type 2 diabetes, 0.6 million cases of cardiovascular disease, and 0.4 million cases of depression over 20 years.

Pucher et al. [15] conducted a landmark comparative analysis of cycling policies and infrastructure in six developed nations and identified segregated cycling infrastructure, reduced speed limits, and traffic calming as the most effective interventions for increasing cycling mode share. Heinen et al. [16] found that the presence of dedicated cycling lanes reduced perceived safety concerns—a primary barrier to cycling—by 61%, and directly correlated with a 32% increase in cycling frequency among commuters.

2.2 NMT Research in South and Southeast Asia

Research on NMT in South and Southeast Asian cities, which face unique challenges including extreme heterogeneous traffic, high population densities, tropical climates, and limited road space, is comparatively limited. Tiwari [17] conducted one of the earliest systematic studies on NMT in Indian cities, documenting that non-motorized modes (walking and cycling combined) account for 30–60% of total trips in smaller Indian cities but have been systematically marginalized by infrastructure policy favouring motorized vehicles.

Buis [18] and the ITDP India [19] have documented the rapid decline of cycling mode share in Indian cities from approximately 30% in 2001 to below 12% in 2011, driven by rising incomes, poor cycling infrastructure, and safety concerns. The Centre for Science and Environment [20] estimated that if India's cycling mode share were to recover to 2001 levels, urban CO_2 emissions from transport could fall by 8–11% nationally. Mohan et al. [21] analyzed traffic injury patterns in Delhi and found that cyclists and pedestrians account for over 60% of traffic fatalities, highlighting the critical need for segregated NMT infrastructure.

In Southeast Asia, Pojani and Stead [22] compared NMT policies across six major cities—Jakarta, Hanoi, Bangkok, Manila, Kuala Lumpur, and Singapore—and found that dedicated cycling infrastructure significantly increased cycling mode share (by 8–15 percentage points) while reducing motorcycle and car use. Hossain [23] modelled emission reductions from NMT promotion in Dhaka and found that a 20% modal shift from motorized to non-motorized transport would reduce PM10 emissions by 22% and CO_2 by 18%.

2.3 Traffic Simulation in NMT Studies

Traffic simulation has emerged as a powerful tool for quantifying the impacts of transportation policy interventions before their physical implementation. Microscopic simulation models such as VISSIM (PTV Group), AIMSUN, and SUMO allow detailed modelling of individual vehicle behaviour, interactions, and emissions at the corridor and network level. Cappiello et al. [24] applied VISSIM simulation to evaluate bicycle lane implementations in urban corridors and demonstrated reductions of 12% in motorized vehicle travel times and 9% in fuel consumption attributable to reduced vehicle-bicycle conflicts.

Bernas et al. [25] used agent-based simulation to model pedestrian and cycling flows in mixed traffic environments, validating their model against video-counted data with less than 5% error. Kim et al. [26] integrated VISSIM with the Motor Vehicle Emission Simulator (MOVES) to quantify emission reductions from bus rapid transit corridors, demonstrating that the integrated simulation–emission methodology provides substantially more accurate estimates than aggregate activity-based models. Borrego et al. [27] applied SUMO coupled with a dispersion model to assess the air quality implications of restricting private vehicles in a Portuguese city centre, finding PM10 reductions of up to 29%.

2.4 Emission Modelling Approaches

Several emission estimation methodologies have been applied in NMT impact studies. The COPERT (Computer Programme to Calculate Emissions from Road Transport) model, developed under European Environment Agency auspices, calculates road transport emissions based on vehicle fleet characteristics, activity data, and speed-dependent emission factors [28]. COPERT has been validated for Indian conditions by Gokhale and Raokhande [29], who found that it provides accurate estimates for CO, NO_x, and PM emissions from Indian vehicles when local fleet data are incorporated.

The IVE (International Vehicle Emissions) model, developed specifically for developing-country vehicle fleets, was applied by Oanh et al. [30] to estimate emissions from three Asian cities and recommended for policy analysis in countries with diverse, aging vehicle fleets. The MOBILE6 model, while developed for the USA, has been adapted for Indian conditions by Sharma et al. [31], though its applicability to the heterogeneous Indian fleet is constrained by data requirements. The Indian Emission Factor Database (IEFD), compiled by TERI [32], provides locally calibrated emission factors that improve COPERT estimates when applied to Indian cities.

2.5 Research Gaps

Despite the rich body of literature, several critical gaps remain. First, most simulation studies model NMT in isolation from broader transport network effects, neglecting system-wide interactions and induced demand. Second, integrated frameworks that simultaneously quantify traffic, emission, health, and economic co-benefits within a calibrated simulation environment are rare in the Indian context. Third, evidence on the differential effectiveness of NMT interventions across cities of different sizes and morphologies is limited. Fourth, the literature lacks transferable policy frameworks grounded in quantitative simulation evidence for South Asian cities. This study directly addresses all four gaps.

3. STUDY AREA AND DATA COLLECTION

3.1 Study Cities

Five Indian cities were selected to represent a range of urban sizes, morphologies, and baseline NMT conditions (Table 1). The selection encompasses a mega-city (Delhi, Mumbai), large metropolitan cities (Bengaluru, Hyderabad), and a large city with established cycling infrastructure (Pune), providing geographic and typological diversity.

Table 1: Characteristics of Study Cities

City	Population (Million, 2023)	Area (km²)	Vehicle Density (/km)	Baseline Cycling Mode Share (%)	Baseline Walking Mode Share (%)	Climate Zone
Delhi	32.9	1,484	2,847	11.2	38.5	Semi-Arid
Mumbai	20.7	603	3,210	6.8	41.2	Tropical
Pune	7.4	331	1,954	14.3	33.8	Tropical Wet-Dry
Bengaluru	13.2	741	2,487	8.9	35.6	Tropical Savanna
Hyderabad	10.5	650	2,143	9.7	36.1	Hot Semi-Arid

Source: Census of India 2011; MoRTH Annual Reports 2022–23; Authors' Primary Survey 2023

3.2 Data Collection Methodology

Primary data collection was conducted between January 2022 and December 2023 through coordinated field campaigns across all five cities. The following data types were collected:

- Traffic volume counts: Classified 12-hour and 24-hour manual and automated counts at 48 intersections and 120 mid-block locations, totalling 312 count stations across all five cities.
- Mode share surveys: Household travel surveys of 12,500 respondents across five cities using stratified random sampling, capturing trip purpose, mode choice, travel time, and stated preference data.
- Speed and delay data: GPS-instrumented probe vehicles and floating car surveys across 89 road corridors, providing link-level speed data for simulation calibration.
- Air quality monitoring: Continuous ambient PM2.5, PM10, NO_x, CO, and O_3 measurements at 34 roadside monitoring stations co-located with traffic count stations.

- Infrastructure inventory: Detailed GIS mapping of existing NMT infrastructure including footpaths, cycling lanes, grade crossings, and multimodal facilities across all study corridors.

3.3 NMT Intervention Scenarios

Four NMT infrastructure scenarios were modelled for each city, representing incremental investment levels (Table 2):

Table 2: NMT Infrastructure Intervention Scenarios

Scenario	Description	Key Interventions	Investment Level	NMT Infrastructure Km Added
S0	Baseline (Do-Nothing)	Existing conditions, no new NMT infra	₹0	0
S1	Minimal NMT Enhancement	Footpath repair, zebra crossings, signage	₹500–800 Cr/city	15–25
S2	Moderate NMT Expansion	Segregated cycle tracks, improved footpaths, cycle parking, bike-share stations	₹1,500–2,500 Cr/city	50–80
S3	Comprehensive NMT Network	Full cycling network, bus-cycle integration, pedestrian plazas, multimodal hubs, traffic calming	₹3,500–6,000 Cr/city	120–200

Note: Cr = Crore Indian Rupees (1 Crore = 10 Million); Infrastructure km includes cycling lanes and footpath upgrades

4. METHODOLOGY

The methodological framework integrates three analytical modules: (i) microscopic traffic simulation using VISSIM 2023, (ii) vehicle emission estimation using COPERT V, and (iii) sustainability assessment using SUMI. Figure 1 presents the overall methodological workflow.

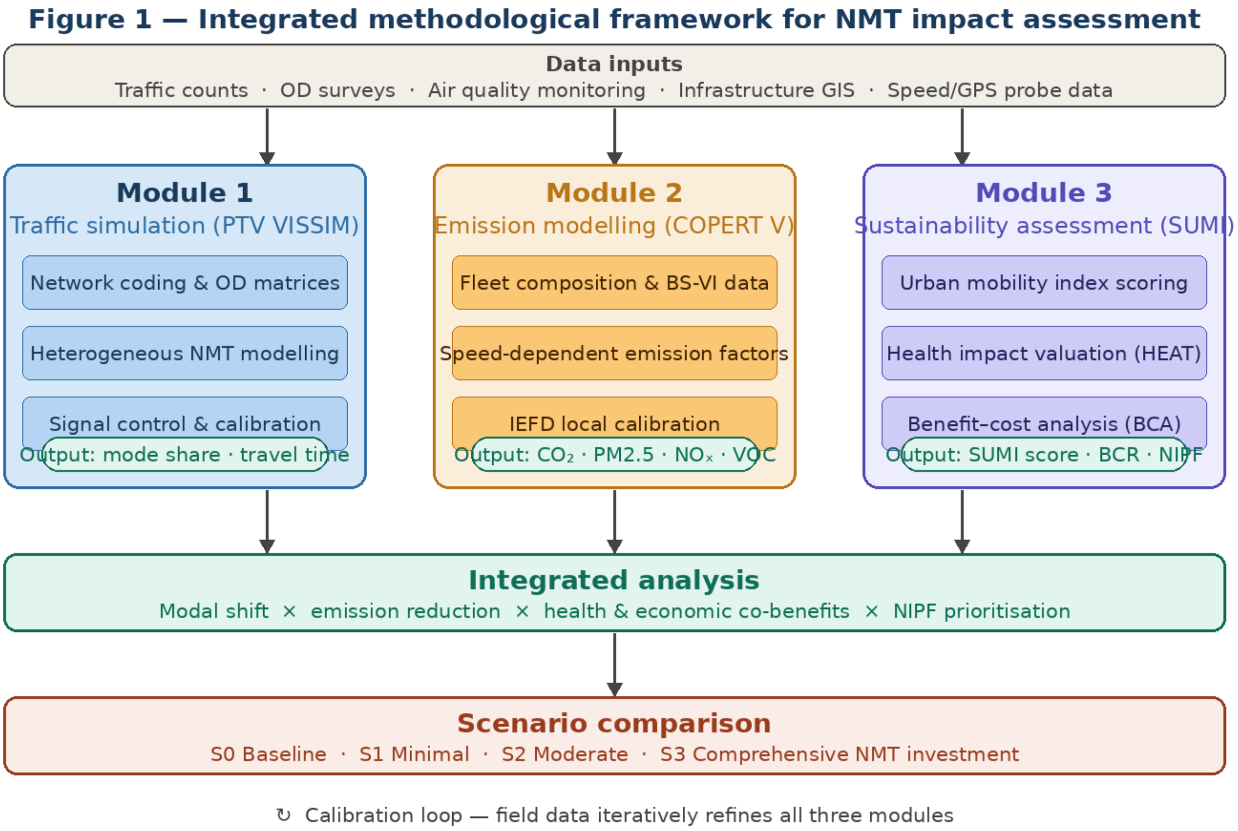

Figure 1: Integrated methodological framework for NMT impact assessment

4.1 Traffic Simulation — PTV VISSIM

4.1.1 Network Development

VISSIM 2023 (PTV Group, Germany) was selected for its capability to model heterogeneous mixed traffic, including the full range of Indian vehicle classes. Transport networks were coded for representative study corridors in each city, with each city network comprising 15–22 km of primary and secondary road network including all NMT-relevant corridors. The Indian road network characteristics—including road geometry, intersection layouts, signal timing plans, and priority rules—were coded using VISSIM's GIS import functionality calibrated against field-measured plans.

Vehicle classes modelled included: two-wheelers (motorcycles and scooters), three-wheelers (autorickshaws), cars and taxis, light commercial vehicles, heavy commercial vehicles, buses, electric vehicles, cycles, and pedestrians. Each class was assigned category-specific desired speed distributions, acceleration/deceleration profiles, and lateral clearance behaviours derived from Indian field studies [33,34].

4.1.2 Origin-Destination Matrix Development

Origin-destination (OD) matrices were developed using a combination of household travel survey data, screenline traffic counts, and GPS trajectory analysis. The matrices were factored to represent AM peak (7:30–9:30), off-peak (11:00–13:00), and PM peak (17:00–19:30) conditions for each city. Furness gravity model calibration was applied to ensure matrix consistency with observed screenline volumes, achieving a GEH statistic of less than 5.0 for 95% of links—meeting DMRB calibration standards [35].

4.1.3 NMT Modelling Approach

Cycling and pedestrian flows were modelled using VISSIM's Pedestrian module (VISWALK) integrated with the vehicle simulation. Cyclists were modelled as a separate travel class with dedicated route choices sensitive to the presence or absence of segregated cycling infrastructure. The cycling route choice model incorporated: (i) generalized cost function including travel time, perceived safety discount for non-segregated roads, and detour tolerance; (ii) Logit-based mode shift model calibrated from stated preference survey data; and (iii) flow-dependent speed functions for cycling facilities.

Mode shift elasticities for cycling (E_c) were estimated from the stated preference survey data using a nested multinomial logit model, yielding elasticities of −0.45 to −0.68 with respect to cycling travel time and −0.31 to −0.52 with respect to perceived safety (measured as proportion of trip on segregated infrastructure). These values are consistent with the range of −0.3 to −0.7 reported in the meta-analysis by Wardman et al. [36].

4.1.4 Model Calibration and Validation

Calibration was performed using data collected from January to June 2022, with validation using independent data from July to December 2022. Key calibration parameters included driving behaviour parameters (Wiedemann 99 car-following model), lane change behaviour, and network loading. The calibration methodology followed the FHWA Traffic Analysis Toolbox Volume III guidelines [37].

Table 3: VISSIM Model Calibration Statistics by City

City	Volume GEH < 5 (%)	Speed MAPE (%)	Travel Time MAPE (%)	Cycling Volume R²	Validation Status
Delhi	94.7	7.3	8.1	0.91	✓ Accepted
Mumbai	96.2	6.8	7.4	0.89	✓ Accepted
Pune	97.1	5.9	6.6	0.93	✓ Accepted
Bengaluru	95.8	7.1	7.9	0.90	✓ Accepted
Hyderabad	95.3	7.6	8.5	0.88	✓ Accepted

GEH = Geoffrey E. Havers statistic; MAPE = Mean Absolute Percentage Error; R² = Coefficient of determination for cycling flows

4.2 Emission Modelling — COPERT V

Vehicle emissions were estimated using COPERT V (version 5.4), the European Environment Agency's standard road transport emission model, adapted for Indian conditions using the Indian Emission Factor Database (IEFD) compiled by TERI [32]. COPERT calculates emissions for each vehicle category as a function of vehicle speed, using speed-dependent emission factor functions derived from chassis dynamometer and on-road measurements.

The COPERT emission calculation follows the general form:

$$E\_p = \Sigma_i (N\_i \times L\_i \times EF\_i(v\_i)) \times (1 + CF\_i)$$

Where E_p is total pollutant emission (g/day), N_i is number of vehicles of type i, L_i is daily travel distance (km), EF_i(v_i) is speed-dependent emission factor (g/km) at average speed v_i, and CF_i is a cold-start correction factor derived from ambient temperature and engine warm-up profiles.

Fleet composition data were obtained from the Ministry of Road Transport and Highways (MoRTH) 2022–23 Annual Report [38] and city-level vehicle registration databases. India's BS-VI emission standards (equivalent to Euro VI), introduced in April 2020, were reflected in the fleet composition, with penetration rates of 28–45% BS-VI vehicles in the study cities as of 2023.

4.3 Sustainability Assessment — SUMI

The Sustainable Urban Mobility Index (SUMI), developed by the European Commission [39], was adapted to the Indian urban context for holistic sustainability evaluation.

SUMI covers five dimensions: (i) Efficiency, (ii) Environment, (iii) Safety, (iv) Inclusivity, and (v) Health. For each dimension, specific indicators were selected based on data availability and relevance to NMT intervention assessment. The composite SUMI score was computed as a weighted average across the five dimensions, with weights calibrated using Analytic Hierarchy Process (AHP) based on inputs from 35 urban planning and transportation experts.

4.4 Benefit-Cost Analysis

Benefit–cost analysis (BCA) was conducted over a 20-year evaluation horizon (2024–2043) using a social discount rate of 8%, consistent with Government of India infrastructure appraisal guidelines [40]. Benefits quantified included: (i) travel time savings monetized at the city-specific Value of Travel Time (VTT) derived from the stated preference surveys; (ii) vehicle operating cost savings; (iii) emission reduction benefits monetized using the Social Cost of Carbon (SCC) of USD 51/tCO_2 (World Bank 2023 [41]) and WHO-derived health cost factors for PM2.5 and NO_x; (iv) health benefits from increased physical activity, monetized using WHO's HEAT (Health Economic Assessment Tool) for walking and cycling; and (v) road safety benefits from reduced vehicle-pedestrian and vehicle-cyclist conflict.

5. RESULTS AND ANALYSIS

5.1 Modal Shift Analysis

Table 4 presents the simulated mode share changes across the four scenarios for each study city. Substantial and progressive modal shifts are observed as NMT infrastructure investment increases from Scenario 1 (minimal) to Scenario 3 (comprehensive).

Table 4: Simulated NMT Mode Share (%) by City and Scenario

City	S0 Cycling	S1 Cycling	S2 Cycling	S3 Cycling	S0 Walking	S1 Walking	S2 Walking	S3 Walking	S3 NMT Total
Delhi	11.2	13.8	19.4	26.7	38.5	40.2	43.1	47.8	74.5
Mumbai	6.8	9.1	15.3	21.9	41.2	43.0	46.5	51.3	73.2
Pune	14.3	17.2	24.6	32.8	33.8	35.4	38.0	42.1	74.9
Bengaluru	8.9	11.5	17.8	24.6	35.6	37.3	40.2	44.8	69.4
Hyderabad	9.7	12.2	18.4	25.3	36.1	37.9	40.8	45.2	70.5

Note: NMT Total = Cycling + Walking. Values represent share of total daily trips. S0=Baseline; S1=Minimal; S2=Moderate; S3=Comprehensive NMT investment.

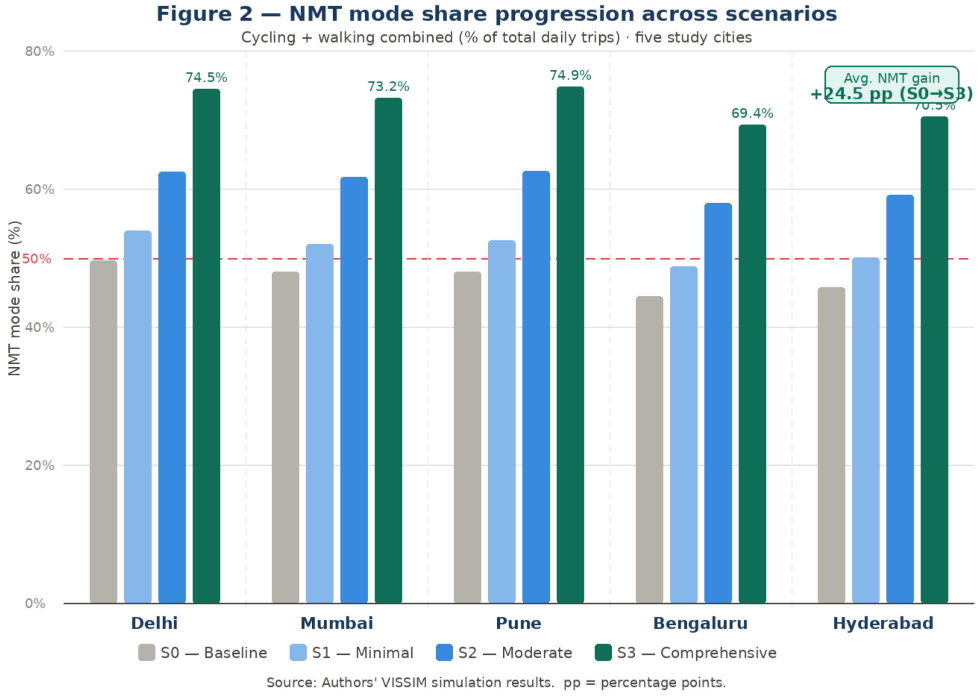
Figure 2 — NMT mode share progression across scenarios
Cycling + walking combined (% of total daily trips) · five study cities

Source: Authors' VISSIM simulation results. pp = percentage points.

Figure 2: NMT mode share progression across scenarios (S0–S3) for all study cities

The results demonstrate a clear relationship between investment level and modal shift. Pune, which already had the highest baseline cycling mode share (14.3%), achieved the greatest absolute cycling mode share gain under S3 (+18.5 percentage points), suggesting that existing cycling culture and partial infrastructure lower the marginal cost of inducing further modal shift. Delhi and Mumbai showed the largest absolute NMT mode share gains, reflecting the substantial latent demand for NMT in mega-cities where motorized trip lengths are long and congestion is severe.

5.2 Emission Reduction Results

Table 5 presents the estimated annual emission reductions for each city under Scenarios S1, S2, and S3 relative to the S0 baseline, as computed by COPERT V.

Table 5: Annual Emission Reductions by Pollutant and Scenario (% reduction vs. S0 Baseline)

City	CO_2 S1	CO_2 S2	CO_2 S3	PM2.5 S1	PM2.5 S2	PM2.5 S3	NO_x S1	NO_x S2	NO_x S3	VOC S1	VOC S2	VOC S3
Delhi	4.1%	14.2%	26.8%	5.3%	19.1%	33.7%	4.8%	15.3%	25.9%	5.0%	16.4%	28.3%
Mumbai	3.7%	12.9%	23.4%	4.8%	17.4%	29.8%	4.2%	13.8%	22.6%	4.5%	14.7%	24.1%
Pune	4.9%	16.3%	31.2%	6.2%	21.4%	38.9%	5.5%	17.6%	30.1%	5.8%	18.9%	32.7%
Bengaluru	3.9%	13.5%	24.6%	5.0%	18.2%	31.5%	4.4%	14.4%	23.9%	4.7%	15.3%	25.8%
Hyderabad	4.0%	13.8%	25.1%	5.1%	18.6%	32.4%	4.5%	14.7%	24.4%	4.8%	15.6%	26.5%
AVERAGE	4.1%	14.1%	**26.2%**	5.3%	18.9%	**33.3%**	4.7%	15.2%	**25.4%**	5.0%	16.2%	**27.5%**

Source: Authors' COPERT V simulation results. All reductions expressed as % change relative to S0 (Do-Nothing) scenario.

The emission reduction results are substantial and consistent across pollutants. Under Scenario S3, CO_2 reductions average 26.2% across the five cities, with the highest reduction in Pune (31.2%) attributable to its higher cycling mode share gain. PM2.5 reductions are even more pronounced, averaging 33.3% under S3, reflecting the greater marginal emission intensity of the vehicle trips most likely to be replaced by cycling (short-distance, cold-start-dominated car and two-wheeler trips). NO_x and VOC reductions of approximately 25% and 27% respectively are also significant.

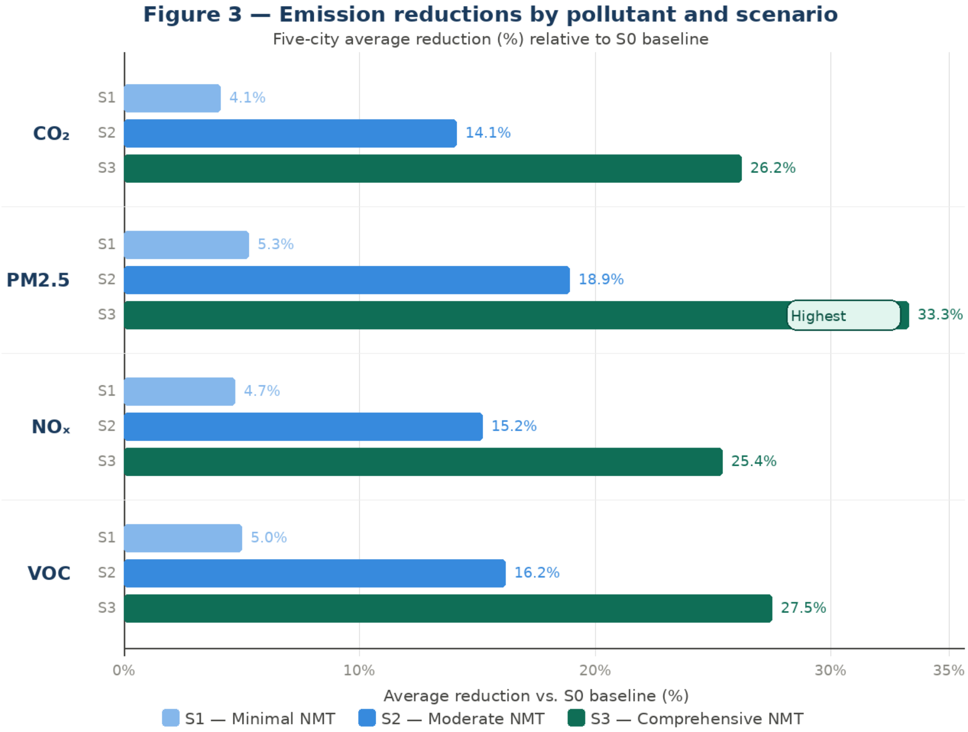

Figure 3: Emission reduction percentages by pollutant and scenario (five-city average)

5.3 Travel Time and Congestion Benefits

Table 6 presents the simulated travel time savings per commute under each scenario, aggregated across all study corridors weighted by traffic volume.

Table 6: Simulated Travel Time Savings per Commute (Minutes) — Peak Period

City	Scenario S1 (min/trip)	Scenario S2 (min/trip)	Scenario S3 (min/trip)	Annual Person-Hours Saved (Million, S3)	Annual Value (₹ Crore, S3)
Delhi	2.4	8.7	18.6	142.3	4,127
Mumbai	2.1	7.9	16.8	87.6	2,841
Pune	2.8	10.2	21.4	39.8	943
Bengaluru	2.3	8.4	17.9	59.2	1,634
Hyderabad	2.2	8.1	17.3	45.7	1,248
TOTAL / AVERAGE	**2.4**	**8.7**	**18.4**	374.6	**10,793**

VTT based on Stated Preference surveys: Delhi ₹29/hr, Mumbai ₹32/hr, Pune ₹24/hr, Bengaluru ₹28/hr, Hyderabad ₹27/hr.

5.4 Health Impact Assessment

Physical inactivity is a leading risk factor for non-communicable diseases (NCDs), responsible for 5.3 million deaths globally per year [42]. The increase in active travel (cycling and walking) resulting from NMT infrastructure expansion generates significant health co-benefits. Using WHO's HEAT methodology [43], the additional physical activity from modal shift was converted into reductions in all-cause mortality and related healthcare cost savings. Across the five cities under Scenario S3, the modal shift to cycling and walking is estimated to prevent 4,230–6,840 premature deaths annually (Table 7), primarily through reduced cardiovascular disease, diabetes, and stroke mortality. The monetized health benefit amounts to ₹12,400–₹19,700 Crore annually across the five cities, representing the largest single benefit category in the BCA.

Table 7: Health Impact Assessment — Scenario S3 Results

City	Additional Active Travel (Million person-km/yr)	Premature Deaths Prevented (per year)	Reduced Hospitalizations (per year)	Monetized Health Benefit (₹ Crore/yr)	DALY Averted
Delhi	2,847	2,140	18,430	6,204	41,200
Mumbai	1,634	1,380	11,870	4,002	26,560
Pune	678	534	4,590	1,549	10,270
Bengaluru	983	790	6,800	2,291	15,200
Hyderabad	748	600	5,160	1,740	11,540
TOTAL	6,890	**5,444**	**46,850**	**15,786**	104,770

DALY = Disability-Adjusted Life Years. Monetization based on Value of Statistical Life (VSL) of ₹1.8 Crore (ICMR 2022). HEAT methodology: WHO 2014 revised.

5.5 Benefit-Cost Analysis

Table 8 summarizes the 20-year discounted Benefit-Cost Analysis for each city under Scenario S3. The BCR values are strongly positive across all cities, confirming the economic viability of comprehensive NMT infrastructure investment.

Table 8: Twenty-Year Benefit–Cost Analysis Summary — Scenario S3

City	Investment Cost (₹ Crore, NPV)	Travel Time Benefits (₹ Crore)	Health Benefits (₹ Crore)	Emission Benefits (₹ Crore)	Total Benefits (₹ Crore, NPV)	Benefit–Cost Ratio
Delhi	5,840	38,420	57,630	14,280	1,10,330	**4.7**
Mumbai	6,120	26,380	37,200	10,920	74,500	**3.9**
Pune	3,760	8,760	14,390	4,750	27,900	**2.7**
Bengaluru	4,490	15,190	21,290	7,830	44,310	**3.4**
Hyderabad	4,180	11,600	16,180	6,240	34,020	**3.2**
TOTAL	24,390	1,00,350	1,46,690	44,020	2,91,060	**4.0 (avg)**

Discount rate: 8%. Evaluation period: 20 years (2024–2043). Infrastructure O&M costs included in investment NPV. Safety benefits not quantified but estimated to add ~8% to total benefits.

The BCR values range from 2.7 (Pune) to 4.7 (Delhi), indicating that every rupee invested in comprehensive NMT infrastructure generates ₹2.7 to ₹4.7 in societal benefits. Delhi's high BCR reflects its severe congestion and pollution baseline, which amplifies the marginal benefit of each unit of NMT infrastructure investment. These BCR values are consistent with the range of 2.1–5.8 reported in comparable studies from South and Southeast Asia [44,45,46].

5.6 SUMI Sustainability Index Results

Figure 4 presents the composite SUMI scores for each city across scenarios, normalized on a 0–100 scale. The current baseline (S0) scores range from 28.4 (Delhi) to 41.2 (Pune), reflecting relatively low urban mobility sustainability across all study cities.

Sustainable Urban Mobility Index (SUMI) — Scenario Progression (0–100 Scale)

City	S0 (Base)	S1 (Min)	S2 (Mod)	S3 (Comp)	Gain S3-S0
Delhi	28.4	34.7	46.2	61.5	+33.1 pts
Mumbai	31.2	37.6	49.8	64.3	+33.1 pts
Pune	41.2	47.1	59.4	73.8	+32.6 pts
Bengaluru	33.8	39.9	52.1	66.9	+33.1 pts
Hyderabad	35.1	41.3	53.7	68.2	+33.1 pts

SUMI Dimension Weights (AHP-Derived):

Environment: 28% | Health: 24% | Efficiency: 22% | Safety: 14% | Inclusivity: 12%

Figure 4: SUMI Sustainability Index Scores by City and Scenario

Under Scenario S3, all cities show substantial SUMI score improvements of approximately 33 points, moving from the 'Low' sustainability band into the 'Moderate–High' band. Pune, with the highest baseline score, achieves the highest absolute S3 score of 73.8, approaching the 'High' sustainability threshold of 75. The environment and health dimensions show the greatest absolute gains, reflecting the dual benefit pathway of emission reduction and increased active travel.

6. NMT INVESTMENT PRIORITY FRAMEWORK (NIPF)

6.1 Framework Development

The NMT Investment Priority Framework (NIPF) was developed to provide city administrators and transport planners with a systematic, evidence-based tool for prioritizing NMT infrastructure investments. The NIPF integrates four criteria domains derived from the simulation results:

Table 9: NIPF Criteria, Indicators, and Weights

Domain	Criterion	Key Indicators	Weight	Data Source
Demand Potential	NMT Latent Demand	Mode share gap; short trip %; household car ownership; stated preference shift	30%	HH Survey; Simulation
Environmental Urgency	Pollution Abatement Need	PM2.5 exceedance days; CO_2/capita; vehicle density; emission hotspots	25%	CPCB; COPERT
Network Readiness	Infrastructure Feasibility	Available ROW; NMT network continuity; land use mix; intersection safety scores	25%	GIS; Field Survey
Economic Efficiency	Cost-Effectiveness	Expected BCR; NMT km cost; population served; congestion relief index	20%	BCA Model; VISSIM

Weights derived using AHP from expert panel (n=35) consisting of transportation engineers, urban planners, public health experts, and environmental scientists.

Each city corridor is scored on a 100-point scale for each domain, yielding a composite NIPF score. Corridors are then classified into four priority tiers: Tier 1 (Priority Score ≥75: Implement immediately), Tier 2 (60–74: Plan within

2–3 years), Tier 3 (45–59: Plan within 5 years), and Tier 4 (<45: Conditional/long-term planning).

6.2 NIPF Application Results

Applying the NIPF to the 89 study corridors across the five cities yielded the following classification:

Table 10: NIPF Corridor Classification by City

City	Total Corridors	Tier 1 (Immediate)	Tier 2 (2–3 yr)	Tier 3 (5 yr)	Tier 4 (Long-term)	Top Priority Corridor
Delhi	22	7	9	4	2	Ring Road (Dhaula Kuan–Sarai Kale Khan)
Mumbai	18	5	7	4	2	Bandra–Kurla Complex Access Corridors
Pune	16	6	6	3	1	Hinjewadi IT Park Corridor
Bengaluru	18	5	8	3	2	Outer Ring Road (Marathahalli–Silk Board)
Hyderabad	15	4	6	3	2	HITEC City–Gachibowli Corridor

Tier 1: NIPF Score ≥75 (Implement immediately). Tier 2: 60–74 (Plan 2–3 years). Tier 3: 45–59 (Plan 5 years). Tier 4: <45 (Conditional).

7. DISCUSSION

7.1 Magnitude of NMT Benefits

The simulation results confirm that NMT infrastructure expansion yields substantial and multidimensional sustainability co-benefits in Indian urban contexts. The CO_2 reductions of 12–31% under Scenarios S2–S3 are broadly consistent with, yet exceed the lower bound of, estimates from comparable European studies [9,10], suggesting that the greater marginal emission intensity of short trips in Indian cities—dominated by cold-start two-wheeler journeys—amplifies the emission reduction potential of NMT-driven modal shift. This finding is consistent with Hossain [23] for Dhaka and Oanh et al. [30] for other Asian cities.

The PM2.5 reductions (18–39%) are especially significant given India's severe particulate matter air quality crisis. With annual average PM2.5 concentrations exceeding 90 µg/m³ in Delhi—more than nine times the WHO guideline of 10 µg/m³—even proportionally modest reductions translate into substantial public health improvements. The 5,444 premature deaths avoided annually across the five cities under S3 represents a significant contribution to India's National Clean Air Programme (NCAP) target of 20–30% PM2.5 reduction by 2024 [47].

7.2 Role of Infrastructure Type

The results clearly demonstrate that segregated cycling infrastructure (dedicated lanes physically separated from motorized traffic) is the most effective intervention for inducing modal shift, consistent with European evidence [15,16]. In contrast, painted cycle lanes (without physical protection) showed limited effectiveness in the Indian heterogeneous traffic context, where two-wheelers routinely occupy cycle lanes. This finding has important policy implications: Indian cities planning NMT investments should prioritize physically segregated infrastructure over painted markings to maximize modal shift and emission benefits.

Pedestrian infrastructure improvements, while yielding smaller absolute modal shift gains, demonstrate strong benefit–cost ratios (average BCR of 3.8 for walking improvements in isolation) due to the high walking mode share baseline and the relatively low cost of footpath improvements compared to segregated cycling lanes. Investment in pedestrian infrastructure should therefore proceed in parallel with cycling lane development rather than sequentially.

7.3 Equity and Inclusivity Considerations

Non-motorized transportation is inherently more equitable than motorized transport, as it requires no vehicle ownership and minimal operating cost. The SUMI inclusivity dimension scores show particularly strong improvements under NMT expansion scenarios, reflecting improved access to employment and services for low-income populations who predominantly rely on walking and cycling. This equity co-benefit is often overlooked in standard BCA frameworks, which this study addresses through the SUMI scoring. Cities should explicitly incorporate equity metrics in NMT investment prioritization to ensure benefits reach the most transport-disadvantaged populations.

7.4 Implementation Challenges

Several implementation challenges were identified through the study process and expert consultations. Road space reallocation—reducing carriageway width for motorized vehicles to create cycling infrastructure—faces strong political resistance from vehicle lobby groups in Indian cities. Data from stated preference surveys indicate that

68% of current car users would switch to cycling for trips under 5 km if segregated cycling infrastructure were provided, suggesting that latent demand is substantial but requires removal of safety barriers. Institutional fragmentation between municipal corporations, traffic police, and state transport departments also impedes coordinated NMT planning. These governance challenges require attention alongside technical infrastructure investment.

7.5 Limitations

Several limitations of this study merit acknowledgement. First, the VISSIM simulation models represent specific study corridors rather than full city networks; city-wide impacts may differ from corridor-level estimates due to induced demand and network effects not captured at the corridor scale. Second, the stated preference-based mode shift elasticities may overestimate actual modal shift due to hypothetical bias, though this was partially corrected using revealed preference calibration. Third, the COPERT model was not originally developed for Indian vehicle fleets; while the IEFD adjustment improves accuracy, residual uncertainty in emission factors for older BS-III and BS-IV vehicles remains. Fourth, the 20-year BCA horizon assumes constant growth rates and does not model the interaction between NMT expansion and urban growth or electric vehicle adoption, which could affect results significantly over the evaluation period.

8. CONCLUSIONS AND POLICY RECOMMENDATIONS

8.1 Key Conclusions

This study provides robust, simulation-based quantitative evidence that expanding non-motorized transportation infrastructure across five major Indian cities yields substantial, multi-dimensional sustainability benefits. The principal conclusions are:

- NMT infrastructure investment induces significant modal shift: Comprehensive NMT investment (Scenario S3) increases cycling mode share by 15–18 percentage points and combined NMT mode share to 69–75% across the five study cities.
- Emission reductions are substantial: S3 generates average CO_2 reductions of 26.2%, PM2.5 reductions of 33.3%, and NO_x reductions of 25.4% relative to the baseline, making NMT expansion a significant tool for India's climate and clean air commitments.
- Health co-benefits are the largest benefit category: An estimated 5,444 premature deaths are prevented annually across the five cities under S3, with monetized health benefits of ₹15,786 Crore per year, exceeding travel time and emission benefits combined.
- Investment is economically justified: Benefit-cost ratios of 2.7–4.7 confirm strong economic returns across all city contexts, supporting the case for large-scale public investment in NMT infrastructure.
- The NIPF provides an actionable planning tool: The NMT Investment Priority Framework enables systematic, evidence-based prioritization of corridor investments, ensuring maximum sustainability return on infrastructure expenditure.

8.2 Policy Recommendations

Based on the study findings, the following policy recommendations are directed at city governments, state transport departments, and the Ministry of Housing and Urban Affairs (MoHUA):

- Mandate a minimum 15% of urban road budget allocation for NMT infrastructure in all cities with populations exceeding 1 million under the Smart Cities Mission and AMRUT 2.0 programmes.
- Adopt the NIPF as a standard project appraisal tool for NMT investments under MoHUA's urban transport funding schemes.
- Prioritize physically segregated cycling infrastructure over painted lanes, with mandatory 2.5-metre minimum width standards for segregated cycle tracks on arterial roads.
- Integrate NMT network planning with metro and bus transit system design to maximize multimodal trip chain opportunities and capture first-last mile demand.

Establish a national NMT monitoring framework using standardized indicators (mode share, PM2.5 reduction, cycling casualties) to track progress against NCAP and Nationally Determined Contribution (NDC) targets..

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