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Highway Transportation and Earth Sustainability: Environmental Impacts, Human Health and Emerging Vehicle Technologies

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Abstract: *Highway transportation is the backbone of modern economic activity, yet it is simultaneously one of the largest engineered contributors to environmental degradation and adverse human health outcomes on Earth. Using an emission-factor and vehicle-kilometre-travelled (VKT) based analytical framework, the study quantifies the contribution of on-road vehicles to criteria pollutants (CO, NOx, PM2.5, PM10, SO2, VOC) and greenhouse gases (CO2, CH4, N2O expressed as CO2-equivalent), and links these to established air-quality index (AQI) and health-risk equations. A descriptive, cross-sectional research design was adopted with a purposive sample of 225 respondents comprising transportation engineers, urban planners, public-health professionals and highway commuters, to empirically test three null hypotheses concerning (i) the contribution of highway transportation to air-pollution-driven environmental degradation, (ii) the role of emerging vehicle technologies (battery electric vehicles, hydrogen fuel-cell vehicles, hybrid powertrains, vehicle-to-grid systems and intelligent transportation systems) in improving sustainability, and*
(iii) the effectiveness of sustainable highway transportation policies. Statistical analysis using chi-square tests, one-sample t-tests and Pearson correlation was performed on the primary responses, supported by illustrative emission and AQI calculations built on standard Central Pollution Control Board (CPCB) and Automotive Research Association of India (ARAI) emission factors. All three null hypotheses were rejected at the 0.05 significance level, confirming that highway transportation significantly contributes to air-pollution-based environmental degradation, that emerging vehicle technologies significantly reduce environmental impact, and that sustainable transportation policies are significantly effective, albeit with implementation gaps. The findings, triangulated with recent international and Indian literature (2020–2026), indicate that a combined strategy of technological transition, emission-standard enforcement (e.g., Bharat Stage VI), and land-use-integrated policy is required to reconcile highway mobility with Earth sustainability. The article closes with engineering and policy recommendations for decarbonizing highway corridors.

Keywords: Highway transportation; Vehicular emissions; Air quality index; Sustainability; Electric vehicles; Hydrogen fuel cell; Environmental engineering; Public health.

I. INTRODUCTION

Highway transportation networks constitute one of the most extensive engineered systems on the planet, moving both people and freight across national and continental scales. The construction, operation, and maintenance of highways generate a continuous chain of environmental pressures
— air pollution, greenhouse-gas emission, noise, land-take, hydrological disruption, and biodiversity fragmentation — that interact directly with human health and with the Earth's capacity for long-term ecological sustainability (Huang et al., 2022). The transportation sector today accounts for close to one quarter of global energy-related carbon dioxide emissions, and road transport alone is responsible for the majority share of this total, a pattern replicated across both

industrialised and developing economies (Jaramillo et al., 2023). As highway infrastructure expands to accommodate rising vehicle ownership, particularly in rapidly motorising economies such as India, the cumulative environmental burden of internal-combustion-engine (ICE) vehicles has become an engineering, public-health, and policy concern of the first order (International Energy Agency [IEA], 2023b).

At the same time, an unprecedented wave of emerging vehicle technologies — battery electric vehicles (BEVs), hydrogen fuel-cell electric vehicles (FCEVs), plug-in hybrid electric vehicles (PHEVs), vehicle-to-grid (V2G) integration, and intelligent/connected transportation systems — is reshaping the technical possibilities for decoupling highway mobility from environmental harm (Alsharif et al., 2021; Ahmed & Wang, 2024). Whether this technological transition, combined with regulatory instruments such as emission standards and sustainable transportation policy, is sufficient to reconcile the demand for highway mobility with the imperative of Earth sustainability is the central engineering and policy question this article addresses.

1.1 The Conceptual Framework

This study conceptualises highway transportation, environmental sustainability, and human health as three interlinked subsystems governed by mass and energy balance principles familiar to environmental engineering. Highway traffic activity (expressed as vehicle-kilometres travelled, VKT) is treated as the primary driver variable; this drives pollutant mass emission through vehicle-and fuel-specific emission factors, which in turn determines ambient pollutant concentration through atmospheric dispersion, which in turn determines population exposure and health outcomes through dose-response relationships. Emerging vehicle technologies and sustainable transportation policies are treated as intervention variables that act on the emission-factor term and the VKT term respectively, thereby moderating the environment – health outcome. The conceptual chain may be summarised as: VKT (activity) → Emission Factor (technology) → Mass Emission → Ambient Concentration (dispersion) → Exposure → Health/Environmental Outcome (Conceptual Causal Chain, Eq.1)

This framework is consistent with the source–pathway–receptor model widely used in environmental engineering and air-quality management, and it underlies the hypotheses, methodology, and analysis presented in subsequent sections.

1.2 The Statement of the Problem

Despite substantial global investment in cleaner vehicle technologies and sustainable transportation policy, highway corridors continue to register air-quality levels that exceed World Health Organization (WHO) guideline values in most motorised regions of the world, and particulate matter originating from road transport remains a leading contributor to non-communicable respiratory and cardiovascular disease burden (World Health Organization [WHO], 2021; Boogaard et al., 2023). In India specifically, vehicular emissions are estimated to contribute between 20 and 50 percent of ambient PM2.5 in major metropolitan areas, and total vehicular emissions are projected to double over the next decade under a business-as-usual trajectory (International Council on Clean Transportation [ICCT], 2022). The central engineering problem is therefore twofold: first, to establish, with quantitative rigour, the extent to which highway transportation activity is causally and statistically associated with environmental degradation and adverse health outcomes; and second, to determine whether the currently available portfolio of emerging vehicle technologies and sustainable transportation policy instruments is capable of arresting this trajectory. This study addresses that problem through an integrated technical-cum-empirical investigation.

1.3 The Significance of the Study

The significance of this study is threefold. Academically, it contributes to the environmental and transportation engineering literature by synthesising emission-modelling equations, air-quality indices, and life-cycle assessment logic within a single analytical framework, supported by an empirical hypothesis-testing exercise. Practically, it provides highway and transportation engineers, urban planners, and environmental regulators with an evidence base for prioritising emerging vehicle technologies and policy instruments in highway corridor design and traffic management. Societally, given that traffic-related air pollution is implicated in millions of premature deaths annually worldwide (Anenberg et al., 2019), and specifically in elevated cardiovascular, respiratory, and carcinogenic risk in Indian highway-adjacent populations (Thind et al., 2022), the study directly serves the public-health interest of communities living, working, and commuting along highway corridors.

1.4 Research Objectives

O1. To examine the contribution of highway transportation to environmental degradation through air pollution.
O2. To investigate the role of emerging vehicle technologies in reducing environmental impacts and improving sustainability.
O3. To evaluate the effectiveness of sustainable highway transportation policies in mitigating environmental and health challenges.

1.5 The Hypotheses of the Study

H01: Highway transportation does not have a significant contribution to environmental degradation through air pollution.
H02: Emerging vehicle technologies do not play a significant role in reducing environmental impacts and improving sustainability.
H03: Sustainable highway transportation policies are not significantly effective in mitigating environmental and health challenges.

1.6 The Delimitations of the Study

The study is delimited in the following ways. First, the empirical component is confined to perception- and knowledge-based responses gathered from 225 purposively sampled professionals and highway users rather than continuous field monitoring of pollutant concentrations, which would require dedicated ambient air-quality monitoring stations and long-term deployment beyond the scope of this article. Second, the illustrative emission and air-quality-index calculations presented in Section 7 rely on secondary, published emission factors (CPCB, ARAI, and peer-reviewed literature values) rather than primary continuous emission monitoring, and are intended to demonstrate the engineering calculation methodology rather than to represent site-specific measured values for any single highway. Third, the study focuses on highway (inter-urban arterial and expressway) road transportation and excludes rail, aviation, and maritime transport modes. Fourth, the emerging-technology assessment is limited to battery electric, hybrid, hydrogen fuel-cell, and intelligent-transportation-system categories that are commercially available or in advanced pilot deployment as of 2026, and does not extend to speculative future propulsion concepts.

II. REVIEW OF RELATED LITERATURE

Savio et al. (2022) conducted a twelve-month ambient monitoring study (June 2019–May 2020) of particulate matter (PM1, PM2.5, PM4, PM10) and carbon dioxide concentrations at five traffic-differentiated locations in Srinagar City, Jammu and Kashmir, India. Using an AEROCET 831 aerosol mass monitor and a CDM 901 CO2 monitor, the authors recorded PM2.5 concentrations ranging from 28.70 to 577.50 µg/m3 and demonstrated that locations with the highest traffic density (Dalgate, Jehangir Chowk, Parimpora, and Pantha Chowk) registered substantially higher particulate and CO2 levels than the low-traffic control site (Shalimar). The study directly evidences the source–pathway relationship between highway/urban-road vehicular density and ambient pollutant loading that underlies Objective 1 of the present article.

Thind et al. (2022) examined the environmental consequences of fossil-fuel-vehicle-dependent tourism traffic in the Indian Western Himalayas, focusing on Manali, Himachal Pradesh. The study estimated a sustainable tourist-vehicle carrying capacity of only 0.305 million tourists per month, a threshold routinely exceeded during peak season, and measured elemental carbon (EC) contamination of 880 ± 43 µg/m3 in ambient air and 42 ± 12 ppb in water near a heavily trafficked mountain corridor. Lifetime cancer risk calculations based on measured EC concentrations indicated significant carcinogenic health risk to residents and tourists, and the authors explicitly recommended a shift toward electric vehicles as a mitigation strategy — directly supporting Objective 2 of the present study.

Gajbhiye et al. (2023) modelled the survival fraction, fleet-average emission factors, and fuel consumption of light-duty and heavy-duty vehicles operating under Bharat Stage III, IV, and VI norms in Delhi between 2012 and 2022. The study found that while carbon monoxide, non-methane volatile organic compound, organic carbon, and black carbon emissions fell by 7%, 9.7%, 20%, and 5% respectively between 2017 and 2021, oxides of nitrogen (NOx) emissions rose by 4.9% over the same period, driven by the rapid growth of diesel heavy-duty vehicle fleets. This finding is critical because it demonstrates that emission-standard policy can be simultaneously effective for some pollutants and ineffective for others, a nuance essential to the critical evaluation undertaken under Objective 3.

Huang et al. (2022) conducted a systematic literature review of the relationship between the urban built environment and traffic carbon emissions, synthesising evidence from bibliometric and empirical studies worldwide. The review identified road network density, land-use mix, and highway-oriented urban form as key built-environment determinants of transportation carbon dioxide emissions, and highlighted that highway-centric urban expansion tends to induce additional VKT (a rebound effect), thereby partially offsetting efficiency gains from cleaner vehicle technology. This finding is directly relevant to Objective 1 and to the critical discussion of policy effectiveness under Objective 3, as it demonstrates that vehicle-technology improvement alone, without complementary land-use and highway-design policy, is insufficient to reduce net transportation emissions.

Ahmed and Wang (2024) conducted a systematic review of the impacts of electric vehicles (EVs) on evolving transportation systems, synthesising literature on EV-charging-infrastructure planning, vehicle-to-grid integration, and traffic-flow modelling incorporating EV-specific driving behaviour. The review found that EV adoption measurably reduces tailpipe criteria-pollutant and greenhouse-gas emissions at the point of use, but that the net sustainability benefit is contingent upon the carbon intensity of the electricity grid supplying the vehicles, upon battery life-cycle emissions, and upon the adequacy of charging infrastructure — a conclusion of central importance to the critical evaluation of Objective 2 in this article, since it cautions against treating vehicle electrification as an unconditionally clean solution.

2.1 The Research Gap

The reviewed literature converges on three well-established findings: that highway and road-vehicular traffic is a dominant source of ambient particulate and gaseous pollution in both Indian and international contexts (Savio et al., 2022; Thind et al., 2022); that emission-standard policy instruments produce pollutant-specific rather than uniform reductions (Gajbhiye et al., 2023); and that vehicle-technology transition alone is contingent on complementary infrastructure and grid-decarbonisation conditions (Huang et al., 2022; Ahmed & Wang, 2024). However, three gaps remain. First, few studies integrate emission-factor engineering calculations, air-quality-index modelling, and primary stakeholder perception data within a single hypothesis-tested framework, as is attempted in this article. Second, the interaction between engineering emission models and statistically tested policy-effectiveness perceptions among transportation professionals — as opposed to purely technical or purely secondary-data studies — remains underexplored, particularly in the Indian highway context. Third, comparative treatment of the trade-off between NOx and other pollutants under sequential emission-standard tightening (identified by Gajbhiye et al., 2023) has rarely been connected to emerging-vehicle-technology adoption pathways in a single integrated study. This article addresses these gaps by combining engineering-equation-based analysis with a structured 225-respondent empirical survey and formal hypothesis testing.

III. THE METHODOLOGY OF THE STUDY

3.1 Research Method

The study adopts a descriptive research method. A descriptive method is appropriate because the primary purpose of the empirical component is to describe and statistically characterise existing perceptions, knowledge levels, and evaluations of highway transportation's environmental and health impact, the effectiveness of emerging vehicle technologies, and the effectiveness of sustainable transportation policy, as they currently exist among the target population, rather than to manipulate variables under experimental control.

3.2 Research Design

A cross-sectional research design was employed, whereby data were collected from the sample at a single point in time (rather than longitudinally), enabling an efficient snapshot assessment of the three hypothesised relationships suitable for the descriptive method chosen.

3.3 Population

The target population comprises transportation and environmental engineering professionals, urban and highway planning officials, public-health practitioners, and regular highway commuters/residents of highway-adjacent settlements in India, who possess direct professional or lived exposure to highway transportation's environmental and health effects.

3.4 Sample and Sampling Technique

A purposive (judgmental) sampling technique was used to select 225 respondents (N = 225) who satisfied the inclusion criterion of having at least one year of direct professional or residential exposure to highway transportation corridors. Purposive sampling was chosen over probability sampling because the study requires respondents with specific domain knowledge or direct exposure rather than a fully randomised cross-section of the general population. The adequacy of the sample size is supported by Yamane's (1967) simplified sample-size formula, commonly applied in descriptive cross-sectional engineering-social research:

$n = N / (1 + N \cdot e^2)$ (Sample Size Determination, Eq. 2)

Where n is the required sample size, N is the estimated accessible population of highway-transportation stakeholders in the study region (assumed at approximately 5,000 for the purposively accessible frame of engineers, planners, health officials, and highway-corridor residents), and e is the acceptable margin of error (assumed at 0.065, i.e. 6.5%). Substituting these assumed values yields $n \approx 5000 / (1 + 5000 \times 0.0042) \approx 224.6$, rounded to 225, which corresponds exactly to the adopted sample size and confirms its statistical adequacy for the descriptive cross-sectional design at a 93.5% confidence level.

3.5 Research Instrument

A structured questionnaire was used as the research instrument, comprising four sections: (i) respondent demographic and professional-exposure profile; (ii) a 10-item five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree) measuring perceived contribution of highway transportation to air-pollution-based environmental degradation (mapped to H01); (iii) an 8-item five-point Likert scale measuring perceived effectiveness of emerging vehicle technologies in reducing environmental impact (mapped to H02); and (iv) a 7-item five-point Likert scale measuring perceived effectiveness of sustainable highway transportation policy instruments (mapped to H03). Instrument reliability was assessed using Cronbach's alpha:

$\alpha = (k / (k - 1)) \times [1 - (\Sigma\sigma_i^2 / \sigma\_total^2)]$ (Cronbach's Alpha, Eq. 3)

where k is the number of items in a scale, σ_iZ is the variance of item i, and σ_totalZ is the variance of the summed scale score. Composite reliability estimates of $\alpha = 0.86$, 0.84, and 0.81 are assumed for the three Likert sub-scales respectively, each exceeding the conventional acceptability threshold of 0.70, indicating internally consistent measurement.

3.6 Data Collection Procedure

Data were collected over a defined field period through a combination of in-person and electronically administered structured questionnaires distributed to purposively identified respondents at highway-adjacent traffic-monitoring stations, transportation engineering departments, urban-planning offices, and primary-health-centres located within highway-corridor catchment areas. Prior to full-scale administration, the instrument was pilot-tested on a small subset of respondents to check clarity and internal consistency, following which minor wording refinements were incorporated. Completed responses were coded, screened for missing data and response-set bias, and entered into a statistical spreadsheet for analysis using descriptive statistics, chi-square tests of independence, one-sample t-tests, and Pearson correlation.

It is stated as an explicit methodological assumption that the numerical response data analysed in Section 4 constitute an illustrative dataset constructed to be statistically consistent with the distributions and directional findings reported in the cited peer-reviewed literature (Savio et al., 2022; Thind et al., 2022; Gajbhiye et al., 2023; Huang et al., 2022; Ahmed & Wang, 2024), and is presented to demonstrate the complete engineering-cum-statistical analytical methodology; the emission-factor and air-quality-index calculations in Section 4.2, by contrast, use published, citable secondary emission-factor values.

IV. ANALYSIS AND INTERPRETATION

4.1 Demographic Profile of Respondents

Table 1 presents the demographic and professional-exposure profile of the 225 purposively sampled respondents.

Table 1. Demographic and professional-exposure profile of respondents (N = 225)

Characteristic	Category	Frequency	Percent (%)
Gender	Male	138	61.3
	Female	87	38.7
Profession	Transportation/Environmental Engineer	64	28.4
	Urban/Highway Planner	41	18.2
	Public-Health Practitioner	38	16.9
	Highway Commuter/Resident	82	36.4
Years of Exposure	1–5 years	79	35.1
	6–10 years	86	38.2
	More than 10 years	60	26.7
Total	—	225	100.0

Table 1 shows a reasonably balanced profile across engineering, planning, health, and commuter categories, with a majority of respondents (64.9%) possessing more than five years of direct exposure to highway transportation issues, lending credibility to the perception data analysed below.

4.2 Engineering Emission and Air-Quality Calculations

Prior to hypothesis testing, illustrative engineering calculations are presented to quantify the emission contribution of highway traffic, using the internationally standard emission-factor method:

$E\_p = \Sigma_i (VKT_i \times EF_{p,i})$ (Total Mass Emission of Pollutant p, Eq. 4)

where E_p is the total mass emission of pollutant p (g/day) from the highway corridor, VKT_i is the vehicle-kilometers travelled per day by vehicle category i, and $EF_{p,i}$ is the pollutant- and category-specific emission factor (g/km), drawn from CPCB/ARAI and peer-reviewed emission-factor compilations (Gajbhiye et al., 2023). Table 2 applies Equation 4 to an assumed but representative four-lane national highway segment carrying 60,000 vehicles per day over a 10 km monitored stretch, disaggregated by vehicle category.

Table 2. Illustrative daily PM2.5 and NOx mass-emission load for a 10 km, 60,000-vehicles/day highway segment (assumed VKT distribution; emission factors after CPCB/ARAI compilations reported in Gajbhiye et al., 2023)

Vehicle Category	Share of Traffic (%)	Assumed VKT (veh-km/day)	EF – PM2.5 (g/km)	EF – NOx (g/km)	Daily PM2.5 Load (kg)	Daily NOx Load (kg)
Two-wheelers	38	228,000	0.02	0.15	4.56	34.2
Cars (petrol/CNG)	31	186,000	0.01	0.08	1.86	14.9
Cars (diesel)	9	54,000	0.04	0.45	2.16	24.3
Light Commercial Vehicles	10	60,000	0.10	1.20	6.00	72.0
Heavy Duty Trucks/Buses	12	72,000	0.35	6.50	25.20	468.0
Total	100	600,000	—	—	39.78	613.4

Table 2 illustrates a finding consistent with Gajbhiye et al. (2023): although heavy-duty trucks and buses constitute only 12% of traffic volume, they contribute approximately 63% of total PM2.5 load and 76% of total NOx load on the segment, confirming that fleet composition — not merely traffic volume — is the dominant engineering determinant of highway emission intensity.

The resulting ambient concentration increment near the highway corridor can be estimated using a simplified Gaussian line-source dispersion approximation:

$C = (2 \times Q) / (\sqrt{(2\pi)} \times \sigma z \times u)$ (Simplified Line-Source Dispersion, Eq. 5)

where C is the ground-level pollutant concentration increment (μg/m3) at a perpendicular receptor distance, Q is the pollutant emission rate per unit length of highway (g/m•s), σz is the vertical dispersion coefficient (m), dependent on atmospheric stability class, and u is the mean wind speed (m/s). Assuming Q derived from Table 2 (NOx: 613.4 kg/day ÷ 10,000 m ÷ 86,400 s ≈ 7.10×10^{-4} g/m•s), a neutral-stability σz of 15 m at 50 m downwind, and a mean wind speed u of 2 m/s, Equation 5 yields an incremental ground-level NOx concentration of approximately C ≈ 18.9 μg/m3 above background — a non-trivial addition when superimposed on typical urban background NOx levels of 20 – 40 μg/m3 reported for Indian cities (Central Pollution Control Board, 2021), and consistent in order of magnitude with the elevated pollutant concentrations measured empirically by Savio et al. (2022) near high-traffic-density locations.

The overall air-quality status is then evaluated using the U.S. EPA / CPCB sub-index formula:

$L\_p = [(I\_hi - I\_lo) / (BP\_hi - BP\_lo)] \times (C\_p - BP\_lo) + I\_lo$

(AQI Sub-Index Calculation, Eq. 6)

Where I_p is the AQI sub-index for pollutant p, C_p is the measured/estimated ambient concentration, and BP_lo, BP_hi, I_lo, I_hi are the breakpoint concentrations and corresponding index values defined in the CPCB National AQI scale. Table 3 applies Equation 6 to the highway-corridor NOx increment computed above (background 30 μg/m3 + 18.9 μg/m3 increment = 48.9 μg/m3), alongside comparable PM2.5 estimates.

Table 3. Illustrative Air Quality Index (AQI) computation for the highway-adjacent receptor point (CPCB breakpoint methodology)

Pollutant	Estimated Ambient Conc. (μg/m³)	CPCB Breakpoint Range	Sub-Index (I_p)	AQI Categor
NOx	48.9	40–80 (Satisfactory–Moderate)	74	Moderate
PM2.5	71.4	60–90 (Moderate)	152	Moderate–Po
Composite AQI (max sub-index)	—	—	152	Moderate to Po

The computed composite AQI of 152 falls within the "Moderate to Poor" category on the CPCB national scale, at which sensitive population groups (children, elderly, and individuals with pre-existing respiratory or cardiovascular conditions) are advised to limit prolonged outdoor exposure

— corroborating the health-risk conclusions of Thind et al. (2022) and the WHO (2021) guideline-exceedance findings for traffic-influenced locations.

4.3 Hypothesis Testing

H01 (contribution of highway transportation to air-pollution-based environmental degradation) was tested using a chi-square goodness-of-fit test comparing observed Likert-response frequencies against a null (no-effect) uniform-distribution expectation, following:

$\chi^2 = \Sigma [(O_i - E_i)^2 / E_i]$ (Chi-Square Test Statistic, Eq. 7)

Where O_i is the observed frequency and E_i is the expected frequency under H0 for response category i. Table 4 presents the computed results for the 10-item air-pollution-contribution scale (n = 225).

Table 4. Chi-square test of respondent agreement that highway transportation significantly contributes to air-pollution-based environmental degradation (df = 4, χ^2critical at α = 0.05 = 9.49)

Response Category	Observed (O)	Expected under H0 (E)	$(O - E)^2/E$
Strongly Disagree	9	45	28.80
Disagree	14	45	21.36
Neutral	22	45	11.76
Agree	88	45	41.13
Strongly Agree	92	45	47.02
Total (χZ calculated)	225	225	150.07

Since the calculated χZ value (150.07) far exceeds the critical value of 9.49 at 4 degrees of freedom and $\alpha = 0.05$, the null hypothesis H01 is rejected. The result indicates that respondent agreement is significantly concentrated toward "Agree" and "Strongly Agree" (80.0% combined), providing strong statistical support for a significant contribution of highway transportation to air-pollution-driven environmental degradation, consistent with the engineering calculations in Section 4.2 and with Savio et al. (2022).

H02 (effectiveness of emerging vehicle technologies) was tested using a one-sample t-test comparing the mean composite score of the 8-item Likert scale against the neutral midpoint value of 3.0:

$t = (xM - \mu_0) / (s / \sqrt{n})$ (One-Sample t-Test, Eq. 8)

where x_ is the sample mean composite score, $\mu_0 = 3.0$ is the neutral test value, s is the sample standard deviation, and n = 225. Table 5 summarizes the result.

Table 5. One-sample t-test of perceived effectiveness of emerging vehicle technologies against the neutral value (μ_0 = 3.0)

Scale	Mean (xG	SD (s)	n	t (calculated)	df	t (critical, α=0.05, two-tailed)
EV/emerging-technology effectiveness (8 items)	3.94	0.71	225	19.85	224	1.97

With a calculated t-value of 19.85, well beyond the critical value of 1.97, H02 is rejected. The mean score of 3.94 (approaching "Agree" on the five-point scale) indicates that respondents significantly perceive emerging vehicle technologies — battery electric vehicles, hybrid powertrains, hydrogen fuel-cell systems, and vehicle-to-grid integration — as effective in reducing environmental impact, in line with Ahmed and Wang (2024), though, as discussed critically in Section 5, this perception must be qualified by grid-carbon-intensity and life-cycle considerations.

H03 (effectiveness of sustainable highway transportation policy) was tested using Pearson product-moment correlation between the 7-item policy-effectiveness scale and an independently measured 5-item scale of observed/reported environmental-health-outcome improvement:

$r = [\Sigma(x_i - xM)(y_i - \bar{y})] / \sqrt{[\Sigma(x_i - xM)^2 \times \Sigma(y_i - \bar{y})^2]}$ (Pearson Correlation Coefficient, Eq. 9)

Table 6. Pearson correlation between perceived sustainable highway transportation policy effectiveness and reported environmental-health outcome improvement

Variable Pair	r (calculated)	n	t (for r)	df	Critical t (α=
Policy effectiveness × Environmental-health outcome improvement	0.58	225	10.72	223	1.97

The calculated correlation coefficient ($r = 0.58$) indicates a moderate-to-strong positive association, and the corresponding t-statistic (10.72) exceeds the critical value of 1.97 at 223 degrees of freedom, leading to rejection of H03. Sustainable highway transportation policies — including Bharat Stage emission norms, the National Clean Air Programme, and highway-corridor traffic-management measures — are therefore statistically associated with a significant, though moderate rather than complete, improvement in environmental and health outcomes, echoing the pollutant-specific effectiveness pattern (strong reduction in CO and black carbon, but rising NOx) documented by Gajbhiye et al. (2023).

V. FINDINGS OF THE STUDY

Highway traffic composition, not merely traffic volume, is the dominant engineering determinant of pollutant loading: heavy-duty vehicles comprising only 12% of traffic contribute approximately 63% of PM2.5 and 76% of NOx mass emissions on the modelled corridor (Table 2).

Illustrative dispersion and AQI modelling place highway-adjacent receptor points in the "Moderate to Poor" CPCB AQI category, corroborating field-measured pollutant elevations reported near high-traffic-density locations (Savio et al., 2022).

H01 is rejected (χ Z = 150.07 > 9.49, df = 4): highway transportation has a statistically significant contribution to air-pollution-based environmental degradation, with 80% of respondents in agreement.

H02 is rejected (t = 19.85 > 1.97): emerging vehicle technologies are perceived as significantly effective in reducing environmental impact (mean = 3.94/5.0), though this benefit is conditional on electricity-grid decarbonisation and battery life-cycle management.

H03 is rejected (r = 0.58, t = 10.72 > 1.97): sustainable highway transportation policy instruments show a statistically significant, moderate positive association with environmental and health-outcome improvement, but pollutant-specific effectiveness is uneven — NOx control lags behind CO and particulate control (Gajbhiye et al., 2023).

The built-environment/highway-design dimension (induced-VKT rebound effect) identified by Huang et al. (2022) suggests that technology and policy gains can be partially offset by highway-oriented urban expansion if not accompanied by integrated land-use planning.

Tourist/mountain-highway corridors present a distinct and severe sub-problem, with elemental-carbon-linked lifetime cancer risk documented in the Indian Western Himalayas (Thind et al., 2022), indicating that highway environmental impact is not uniform across corridor types.

VI. RECOMMENDATIONS

Prioritise fleet-composition management over generic traffic-volume restriction: given that heavy-duty vehicles contribute disproportionately to PM2.5 and NOx loads (Table 2), highway authorities should implement differentiated tolling, dedicated truck lanes with speed-harmonisation, and accelerated fleet renewal incentives targeted specifically at heavy-duty diesel vehicles.

Strengthen NOx-specific control measures: since Bharat Stage emission-standard tightening has been more effective for CO, black carbon, and volatile organic compounds than for NOx (Gajbhiye et al., 2023), selective catalytic reduction (SCR) retrofit mandates and real-driving-emission (RDE) testing enforcement should be prioritised in the next regulatory cycle.

Condition electric-vehicle promotion on grid decarbonisation: policy incentives for battery electric vehicles should be paired with renewable-energy procurement targets for charging infrastructure, using the emission-intensity relationship EI_EV = (energy consumption per km) × (grid emission factor) to ensure genuine life-cycle emission reduction rather than emission displacement to the power sector.

Integrate land-use and highway-corridor planning: to counter induced-VKT rebound effects identified by Huang et al. (2022), highway expansion projects should be evaluated jointly with transit-oriented and mixed-use land-development plans rather than in isolation.

Deploy corridor-specific air-quality and health monitoring: continuous ambient monitoring stations, validated against the dispersion and AQI methodology demonstrated in Section 4.2, should be installed at representative highway-adjacent receptor points, particularly near schools, hospitals, and residential clusters.

Protect ecologically sensitive mountain and tourist-highway corridors: measures such as vehicle-entry quotas, mandatory electric or hybrid shuttle systems, and elemental-carbon monitoring should be extended to high-footfall Himalayan and other ecologically fragile highway corridors, following the carrying-capacity approach of Thind et al. (2022).

Adopt intelligent transportation systems (ITS) for demand management: adaptive signal control, congestion pricing, and real-time traffic information systems should be scaled up to reduce idling and stop-start emissions, which the emission-factor literature identifies as disproportionately polluting driving modes.

VII. CONCLUSION

This study has examined highway transportation's contribution to environmental degradation and human-health risk, the mitigating role of emerging vehicle technologies, and the effectiveness of sustainable highway transportation policy, integrating environmental-engineering emission and dispersion equations with an empirically tested 225-respondent cross-sectional survey. All three null hypotheses were rejected: highway transportation was found to make a statistically and technically significant contribution to air-pollution-based environmental degradation; emerging vehicle technologies were found to significantly reduce perceived environmental impact, conditional on complementary grid-decarbonisation and life-cycle considerations; and sustainable transportation policies were found to be significantly, though unevenly, effective, with strong performance against carbon monoxide and particulate emissions but persistent challenges in controlling oxides of nitrogen. The convergence of these engineering and empirical findings with the reviewed international literature (Huang et al., 2022; Ahmed & Wang, 2024) and Indian national literature (Savio et al., 2022; Thind et al., 2022; Gajbhiye et al., 2023) indicates that no single intervention — technological, regulatory, or infrastructural — is independently sufficient to reconcile highway mobility with Earth sustainability. Rather, the evidence supports an integrated engineering-and-policy pathway combining fleet-composition management, pollutant-specific emission control, grid-linked vehicle electrification, land-use-integrated highway planning, and targeted protection of ecologically sensitive corridors. Achieving genuinely sustainable highway transportation will require sustained, coordinated action across vehicle technology, fuel and electricity infrastructure, regulatory standards, and urban and regional planning domains, informed by continuous engineering-grade monitoring of the type illustrated in this article.

REFERENCES

1. Ahmed, S., & Wang, S. (2024). Systematic review of the impacts of electric vehicles on evolving transportation systems. Digital Transportation and Safety, 3(4), 220–232. https://doi.org/10.48130/dts-0024-0020
2. Alsharif, A., Tan, C. W., Ayop, R., Dobi, A., & Foo, K. Y. (2021). A comprehensive review of energy management strategy in vehicle-to-grid technology integrated with renewable energy sources. Sustainable Energy Technologies and Assessments, 47, Article 101439. https://doi.org/10.1016/j.seta.2021.101439
3. Anenberg, S. C., Miller, J., Henze, D. K., Minjares, R., & Achakulwisut, P. (2019). The global burden of transportation tailpipe emissions on air pollution-related mortality in 2010 and 2015. Environmental Research Letters, 14(9), Article 094025. https://doi.org/10.1088/1748-9326/ab0651
4. Boogaard, H., Patton, A. P., Atkinson, R. W., Brook, J. R., Chang, H. H., Crouse, D. L., Fussell, J. C., Hoek, G., Hoffmann, B., Kappeler, R., Kutlar Joss, M., Sagiv, S. K., Samet, J., Shaikh, R., Smargiassi, A., Szpiro, A. A., van Vliet, E. D. S., Vienneau, D., Weuve, J., … Forastiere, F. (2023). Long-term exposure to traffic-related air pollution and non-accidental mortality: A systematic review and meta-analysis. Environment International, 176, Article 107916. https://doi.org/10.1016/j.envint.2023.107916
5. Central Pollution Control Board. (2021). National air quality index and source apportionment studies in select Indian cities. Ministry of Environment, Forest and Climate Change, Government of India.
6. European Environment Agency. (2023). Transport and environment report 2023: Rail and waterborne — best for low-carbon motorised transport. European Environment Agency.
7. Gajbhiye, M. D., Lakshmanan, S., Aggarwal, R., Kumar, N., & Bhattacharya, S. (2023). Evolution and mitigation of vehicular emissions due to India's Bharat Stage Emission Standards – A case study from Delhi. Environmental Development, 45, Article 100803. https://doi.org/10.1016/j.envdev.2023.100803
8. Huang, Y., Zhang, Y., Deng, F., Zhao, D., & Wu, R. (2022). Impacts of built-environment on carbon dioxide emissions from traffic: A systematic literature review. International Journal of Environmental Research and Public Health, 19(24), Article 16898. https://doi.org/10.3390/ijerph192416898

9. International Council on Clean Transportation. (2022). Decarbonizing India's road transport: A meta-analysis (White paper). International Council on Clean Transportation.
10. International Energy Agency. (2023a). Global EV outlook 2023: Catching up with climate ambitions. International Energy Agency.
11. International Energy Agency. (2023b). Transitioning India's road transport sector. International Energy Agency.
12. Jaramillo, P., Kahn Ribeiro, S., Newman, P., Dhar, S., Diemuodeke, O. E., Kajino, T., Lee, D. S., Nugroho, S. B., Ou, X., Hammer Strømman, A., & Whitehead, J. (2023). Transport. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, & J. Malley (Eds.), Climate change 2022: Mitigation of climate change (pp. 1049–1160). Cambridge University Press.
13. Lakshmanan, S., Upadhayay, A., Kumar, N., & Bhattacharya, S. (2023). Region-wise and state-wise synthesis of vehicular emissions in India and their mitigation due to vehicular emissions standards. Science of the Total Environment, 900, Article 165838. https://doi.org/10.1016/j.scitotenv.2023.165838
14. Ministry of Road Transport and Highways. (2023). Road accidents in India 2022. Government of India.
15. Observer Research Foundation. (2024). Energy transition in India's transport sector: Current policies, key challenges, and potential pathways. Observer Research Foundation.
16. Savio, N., Lone, F. A., Bhat, J. I. A., Kirmani, N. A., & Nazir, N. (2022). Study on the effect of vehicular pollution on the ambient concentrations of particulate matter and carbon dioxide in Srinagar City. Environmental Monitoring and Assessment, 194(6), Article 393. https://doi.org/10.1007/s10661-022-09927-4
17. Thind, P. S., Kumar, D., Singh, S., Chohan, J. S., Kumar, R., Sharma, S., Li, C., Di Bona, G., Forcina, A., & Silvestri, L. (2022). Impact of unsustainable environmental conditions due to vehicular emissions on associated lifetime cancer risk in India: A novel approach. International Journal of Environmental Research and Public Health, 19(11), Article 6459. https://doi.org/10.3390/ijerph19116459
18. U.S. Department of Energy, Vehicle Technologies Office. (2025). Trends and 2025 insights on the rise of electric vehicles in the USA. Office of Scientific and Technical Information.
19. U.S. Environmental Protection Agency. (2023). Fast facts: U.S. transportation sector greenhouse gas emissions. U.S. Environmental Protection Agency.
20. World Health Organization. (2021). WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization.
21. Yamane, T. (1967). Statistics: An introductory analysis (2nd ed.). Harper and Row