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Improving air quality and avoiding pollution costs through low-emission zones: A case study of Chhatrapati Sambhajinagar, India

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INTRODUCTION

Chhatrapati Sambhajinagar (formerly known as Aurangabad), in India's western state of Maharashtra, is among 130 cities identified by the Ministry of Environment, Forest, and Climate Change (MoEFCC) for inclusion in the National Clean Air Programme (NCAP) due to its historically poor air quality (MoEFCC, n.d., 2019). The city's annual average levels of fine particulate matter ($PM_{2.5}$) were recorded at 42 µg/m³ in 2023 and 49 µg/m³ in 2024, exceeding the National Ambient Air Quality Standards (NAAQS) recommended limit of 40 µg/m³; annual average levels of nitrogen dioxide (NO_2) also approached the NAAQS limit of 40 µg/m³ in certain locations in 2023.[1] The World Health Organization's air quality guidelines set annual limits of $PM_{2.5}$ at 5 µg/m³ and of NO_2 at 10 µg/m³.

Although $PM_{2.5}$ concentrations in Chhatrapati Sambhajinagar are lower than in some other cities such as Delhi, where levels exceed the NAAQS limit by 2.5 times (Agarwal, 2025), De Bont et al. (2024) observed that short-term exposure to $PM_{2.5}$ concentrations as low as 28.4 µg/m³, well below the NAAQS limit, was associated with an increased risk of daily mortality. The surfaces of historic monuments in Chhatrapati Sambhajinagar, such as Bibi Ka Maqbara, show signs of pollution-related deterioration and grime, underscoring that dirty air also threatens cultural

1 These data were obtained from the Central Pollution Control Board and Maharashtra State Pollution Control Board database and analyzed by the author.

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heritage sites (Apoorva, 2023). Municipal authorities also have raised concerns over the impacts of pollution on the city's rich biodiversity (Aurangabad Municipal Corporation, n d). A city-level source apportionment study by the Indian Institute of Technology Bombay and Council of Scientific and Industrial Research (CSIR)–National Environmental Engineering Research Institute (2022) found that road transport contributes significantly to pollution in Chhatrapati Sambhajinagar, accounting for 22.5% of $PM_{2.5}$ and 79% of nitrogen oxide (NO_X) emissions.

The Government of India launched the NCAP in 2019 to address unhealthy levels of air pollution in cities.[2] As required by the NCAP, the Maharashtra Pollution Control Board developed a Clean Air Action Plan for the city of Chhatrapati Sambhajinagar aimed at mitigating air pollution across multiple sectors. The action plan includes measures to target vehicle emissions, such as promoting the use of cleaner fuel and public transport, phasing out older commercial vehicles, and retrofitting vehicles with aftertreatment systems (Maharashtra Pollution Control Board, n.d.). In addition, the electric vehicle (EV) policy adopted by the state government of Maharashtra in 2021 tasked Chhatrapati Sambhajinagar, along with five other urban agglomerations, to establish low-emission zones (LEZs) to promote EV use (Government of Maharashtra, 2021).

LEZs are designated geographical areas that restrict older, more polluting vehicles, either by banning them or imposing a fee to operate within the zone. LEZs have been increasingly adopted globally to improve air quality and public health and promote cleaner modes of transport, especially in Europe, where more than 320 such zones have been designated (Kok, 2023). The International Council on Clean Transportation has assisted three cities in Maharashtra to plan and implement LEZs: Chhatrapati Sambhajinagar, Pimpri-Chinchwad, and Pune. The methodology for modeling the LEZ scenarios in this paper follows a previous ICCT LEZ study by Nair (2024) focused on the Pimpri-Chinchwad Municipal Corporation.

In this paper, we examine the impacts that an LEZ could have on citywide tailpipe emissions in Chhatrapati Sambhajinagar. We first explore possible geographical areas within the city that could be suitable for an LEZ based on environmental, social, and infrastructure-related features, identifying two options for consideration. We next present a citywide spatial inventory of current tailpipe emissions and their distribution by vehicle type, focusing on PM, NO_X, hydrocarbons (HC), and carbon monoxide (CO). We then project the level of emissions in 2030 if Chhatrapati Sambhajinagar does not implement an LEZ and if an LEZ were implemented. Finally, we present an assessment of the benefits of establishing an LEZ in terms of reduced emission load, improved air quality, and damage avoided expressed in economic terms, and then highlight policy considerations.

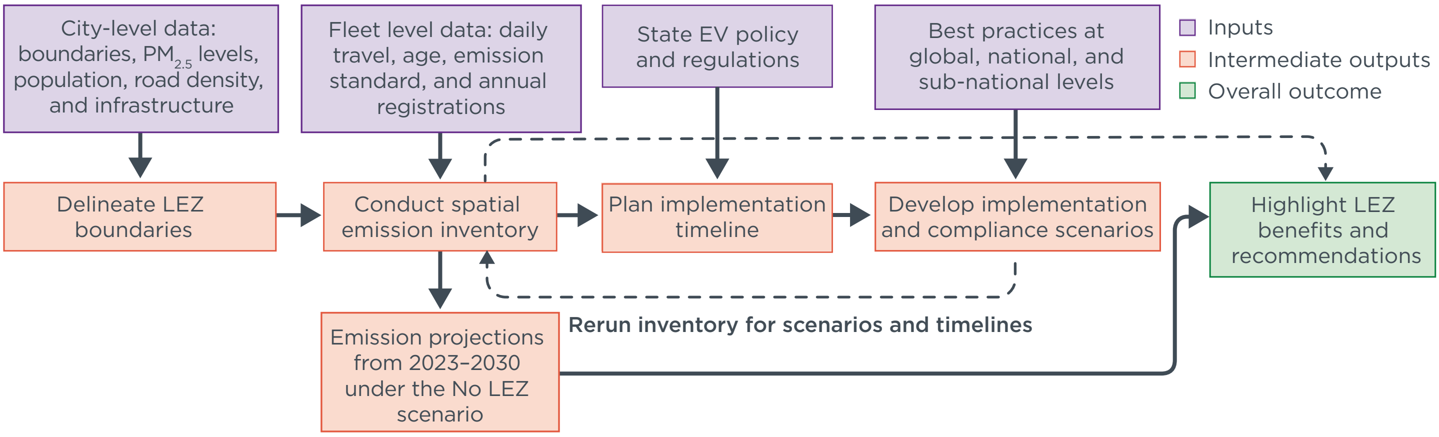
2 The MoEFCC set an initial target for the NCAP of reducing the concentration of particulate matter in 101 cities by 20%–30% from 2017 levels by 2024. The target was later revised to reducing PM_{10} by 40% or achieving the NAAQS limit of 60 µg/m³ for PM_{10} in 131 (now 130) cities by 2026.

METHODOLOGY

Figure 1 shows the inputs and steps involved in modeling the impact of LEZs.

Figure 1

Process flowchart for modeling low-emission zone scenarios



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IDENTIFYING GEOGRAPHIC BOUNDARIES FOR A LOW-EMISSION ZONE

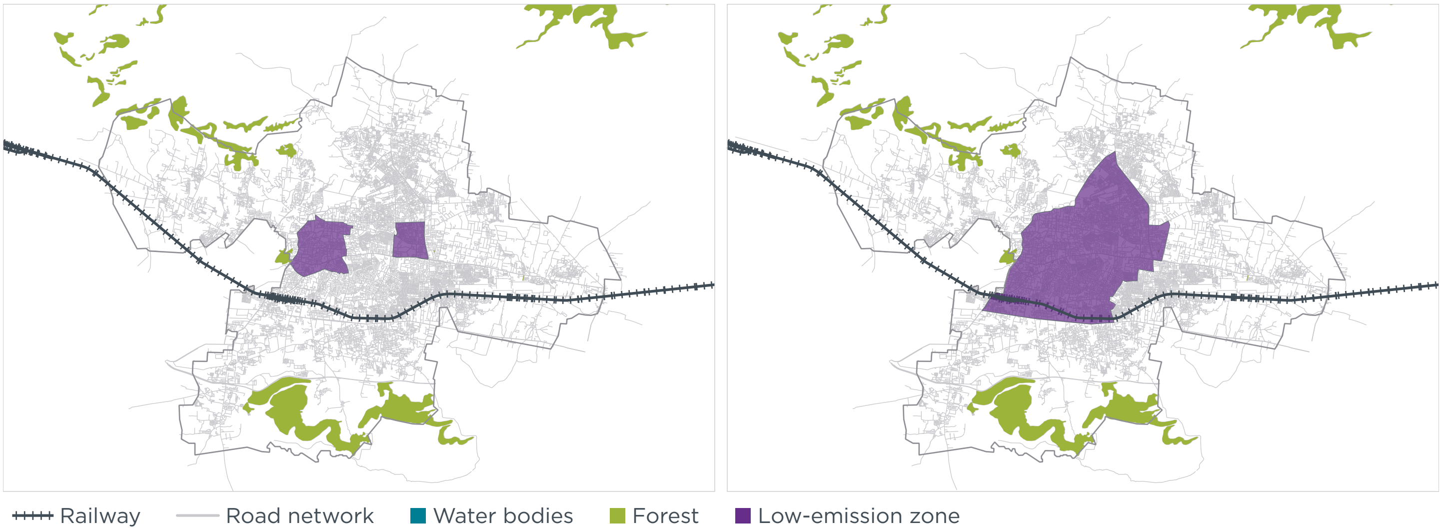
The city area governed by the Chhatrapati Sambhajinagar Municipal Corporation (CSMC) has a population of 1.18 million people, according to India's 2011 census, and covers 179.46 km^2 (WRI India, 2024). Two sets of potential LEZ boundaries were identified using a criteria-based filtering method that considered pollution levels, population, road networks and other infrastructure (e.g., bus stops and nonmotorized networks), EV charging stations, and educational and healthcare facilities. The filtering criteria were based on the proportion of city emissions targeted; a larger LEZ addresses a greater pollution load. Details on these criteria and data sources can be found in our earlier study (Nair, 2024).

Figure 2 shows the two options identified for the LEZ. Option 1 includes two areas totaling a combined 6 km^2, or 3.3% of the CSMC. The larger Option 2 covers 28 km^2, or 15.5% of the CSMC. The selection of these geographic areas aimed to balance emission reductions with practical implementation.

Option 1, given its comparatively limited area, could allow for a quicker rollout. The smaller zone also could provide an opportunity to gather feedback, fine-tune strategies, and provide the city with additional lead time to prepare before expanding the program. Option 2, given its larger area, could achieve greater emission reductions but might require more resources and time to implement. Before enforcement, the city must evaluate multiple factors, including the feasibility of LEZ strategies, technological readiness, regulatory compliance, citizen engagement, infrastructure to support increased walking or transit use, financial resources, and manpower requirements.

Figure 2
Potential low-emission zone boundaries in the Chhatrapati Sambhajinagar Municipal Corporation

Option 1 **Option 2**



Notes: Option 1 includes Cannought Garden and CIDCO. Option 2 includes the areas in Option 1 in addition to Aurangpura, Mill Corner, Paithan Gate, and Gulmandi.

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VEHICLE TAILPIPE EMISSIONS FOR THE BASE YEAR 2023

Information on the primary fleet—such as daily vehicle kilometers traveled (VKT), vehicle age, emission standard, the type of fuel used, and fuel expenses—was collected in surveys conducted at 13 parking lots and fuel stations. Survey locations are mapped in Appendix C. The survey covered more than 4,700 vehicles, spanning seven vehicle categories. Approximately 82% of all vehicles were less than 10 years old, while 5% were more than 15 years old. Around 90% of taxis were less than 10 years old, while 10% of heavy-duty trucks were older than 15 years.

Diesel and gasoline were the primary fuels, powering 86% of the sampled fleet, followed by compressed natural gas (CNG) at 9% and liquefied petroleum gas (LPG) making up the rest. Approximately 70% of three-wheelers were reported to run on gasoline and diesel, 21% on LPG, and 9% on CNG. Bharat Stage (BS) emission standards could be retrieved for 55% of the sampled fleet. Of these vehicles, 88% met BS VI and BS IV norms, 10% met BS III norms, and the remainder consisted of BS I and BS II vehicles.

The survey also highlighted a significant influx of vehicles registered outside the Chhatrapati Sambhajinagar regional transport office (RTO) jurisdiction,[3] primarily from neighboring cities such as Jalna, Pimpri-Chinchwad, Pune, and Thane. These vehicles accounted for 32% of passenger cars, 28% of light commercial trucks, 48% of taxis, 57% of heavy-duty trucks, and 71% of passenger buses. India's national vehicle registry database, VAHAN, shows that the Chhatrapati Sambhaiinagar RTO registered nearly 85,000 vehicles in the 2023 calendar year, 8% of which were electric vehicles (Ministry of Road Transport and Highways, n.d.). Appendix D details the estimates for VKT and vehicle survival rate based on the survey.

3 The Chhatrapati Sambhajinagar RTO is responsible for all vehicle-related functions in Chhatrapati Sambhajinagar district, including vehicle registration, driving license issuance, road tax collection, and fitness and pollution checks, as defined in the rules and regulations of the Motor Vehicle Act, 1988.

Vehicle registrations were projected using a year-over-year growth rate based on registration data from 2001 to 2023. Emissions from various vehicle types were then estimated using the activity-share-intensity-fuel (ASIF) method and distributed spatially across the city at a scale of 2x2 km^2 based on population and road density. The year-over-year registration projection and ASIF methods are detailed in our previous study (Nair, 2024). The emission factors used in the study are based on laboratory conditions and do not represent the real-world emissions.

Table 1 presents the total estimated tailpipe emissions from vehicles operating across the CSMC and within each LEZ option in 2023. This base year was selected to align with the on-the-ground surveys of fleet characteristics conducted in 2023. Option 1 accounted for 9%–10% of all vehicle exhaust emissions in the CSMC, while Option 2 accounted for 41%–43% of total emissions. Appendix B illustrates the spatial distribution of PM load from vehicle exhaust across the city, highlighting higher estimated emission levels and concentrations in the two LEZ options identified, consistent with the criteria-based filtering method used in delineating the two options.

Table 1
Tailpipe emissions in CSMC-governed areas in 2023, in tonnes

Geographical area	PM	NO_x	CO	HC
Option 1	15	203	454	152
Option 2	66	877	1,981	667
Entire CSMC	**161**	**2,157**	**4,734**	**1,568**

Figure 3 illustrates the distribution of emissions by vehicle type. Two-wheelers, which accounted for approximately 75%–80% of total annual registrations from 2007–2023, were the primary contributor to overall tailpipe emissions. The next-highest contributors were light goods vehicles, heavy goods vehicles, and light motor vehicles.[4] Private vehicles, which are two-wheelers and cars purchased for personal use, accounted for 90%–95% of the total annual registrations over the 15-year period.

4 Light motor vehicles refer to motor vehicles, including cars and utility vehicles, with a gross vehicle weight (GVW) of less than 7.5 tonnes. Light passenger vehicles, such as taxis designed to carry passengers, are a category of light motor vehicles. Light goods vehicles include vehicles with a GVW of less than 7.5 tonnes. Medium-duty vehicles have a GVW between 7.5 and 12 tonnes. Heavy-duty vehicles have a GVW above 12 tonnes.

Figure 3

Share of 2023 emissions by vehicle type in the Chhatrapati Sambhajinagar Municipal Corporation

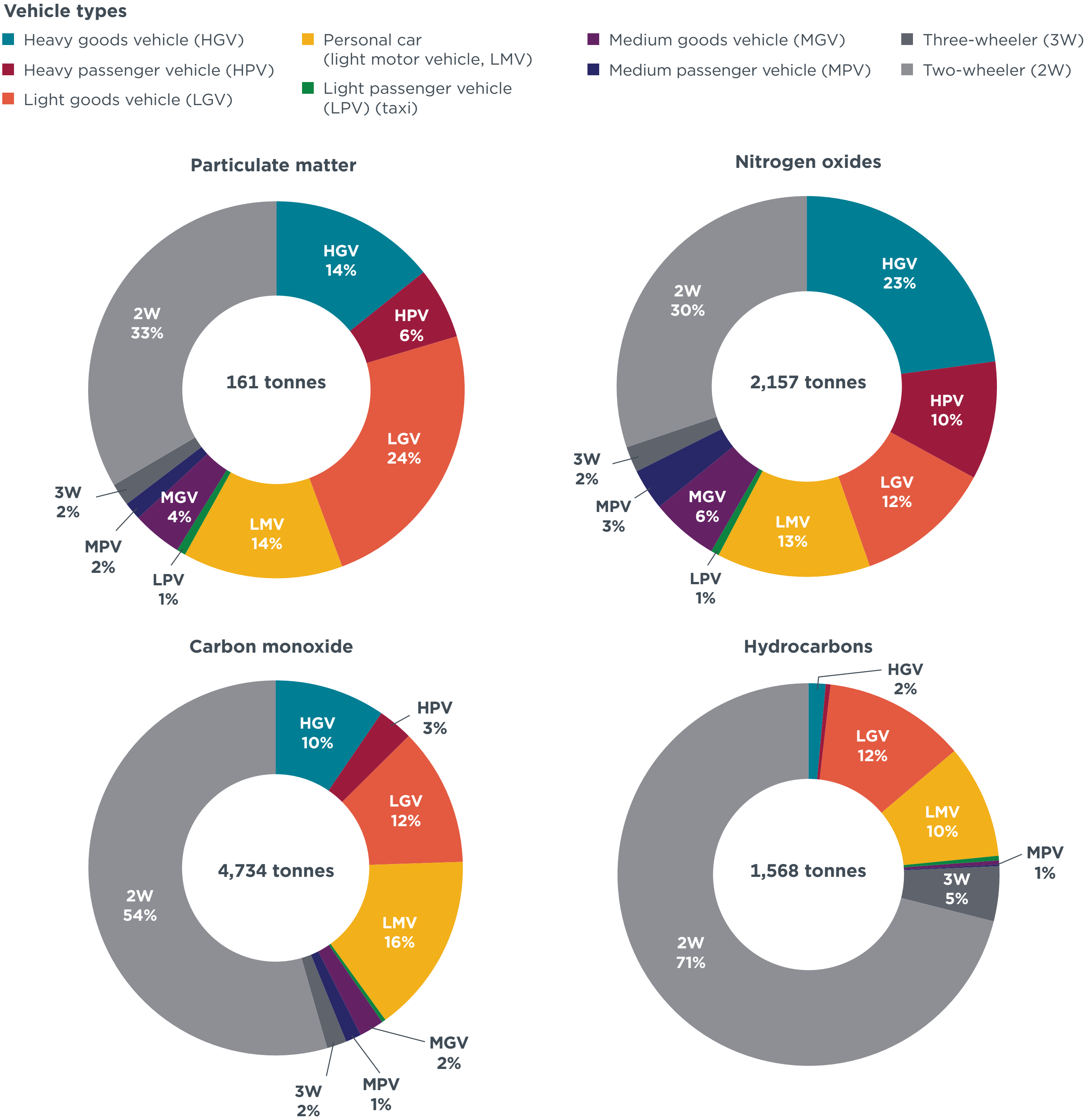

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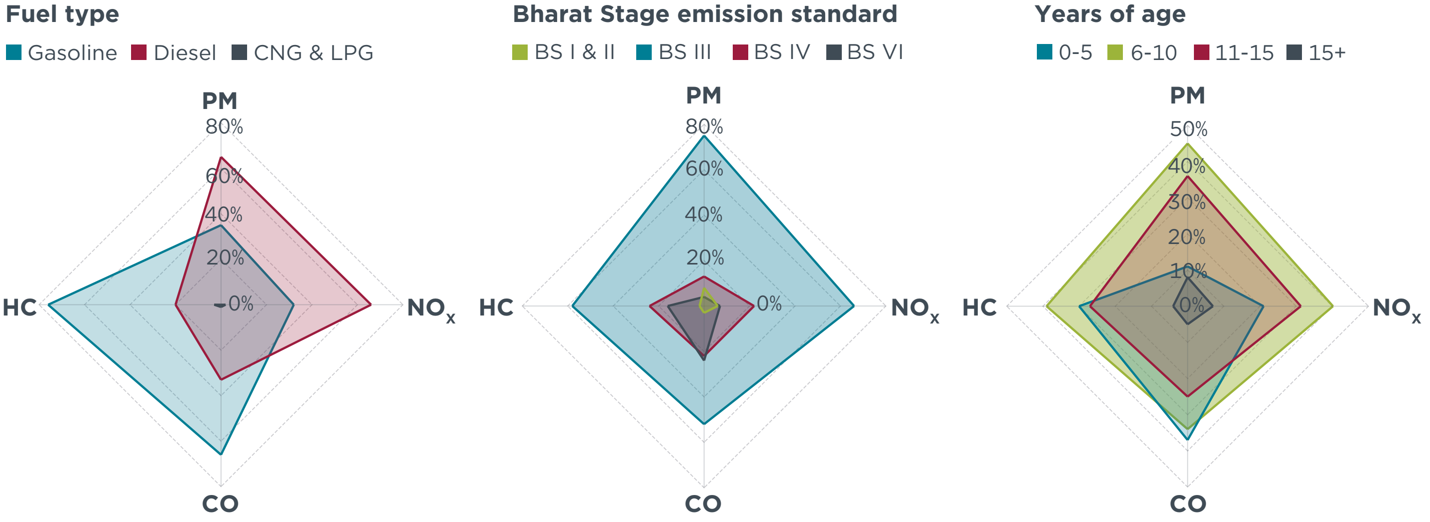
Figure 4 details the share of pollutant emissions by fuel type, emission standard, and age interval in 2023. Diesel-powered vehicles accounted for more than half of PM and NO_x emissions. Diesel vehicles in general emitted higher PM and NO_x than vehicles using any other fuels. Gasoline-powered vehicles contributed two-thirds of CO and HC emissions.

Figure 4

Share of 2023 emissions by vehicle fuel, standard, and age



Note: Vehicles powered by CNG and LPG made up less than 2% of the fleet and 1%–3% of emissions for all four pollutants.

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By BS standard, vehicles approved to BS III accounted for the largest share of emissions across all four pollutants, including three-fourths of PM emissions and two-thirds of NO_x emissions. This is likely due to their prolonged presence in the fleet before the production and sales of BS III vehicles were banned in 2017 in compliance with a judicial ruling. Vehicles aged 6–15 years accounted for 80% of PM emissions, while vehicles up to 10 years old contributed 70% of HC and CO emissions.

MODELING THE IMPACTS OF AN LEZ IN 2030

In this section, we compare vehicle emissions in 2030 in a No LEZ scenario with emissions under two LEZ scenarios: an Age-Based scenario, in which vehicles are restricted from the LEZ based on their age, and a Standard-Based scenario, in which such restrictions are tied to BS standard. For each LEZ scenario, we modeled the emissions impacts under three different compliance approaches. For all scenarios, we projected that annual vehicle registrations would grow at a compounded annual growth rate of 6.9% between 2021 and 2030. The emissions for future years were calculated based on these projected registrations.

TAILPIPE EMISSION PROJECTIONS FOR 2030 UNDER THE NO LEZ SCENARIO

Figure 5 illustrates the changes in emissions of various pollutants between 2023 and 2030 under the No LEZ scenario. As more vehicles complying with the latest emission standards are introduced and older vehicles are retired, we forecast an emissions reduction of 47% in PM, 36% in NO_x, and 13% in HC. Meanwhile, CO emissions were projected to grow by 1.3% as the total number of vehicles increases. Passenger cars (PCs)—which include light motor vehicles (personal cars) and light passenger vehicles (taxis)—medium and heavy passenger vehicles, and heavy goods vehicles are major contributors to higher CO emissions. Despite an overall decline in HC, passenger cars and light goods vehicles exhibited a slight increase in HC emissions by 2030. Two-wheelers remain the dominant contributor in 2030 across all pollutants. Emissions by vehicle type across all pollutants for the year 2030 are detailed in Appendix E.

Figure 5

City-wide emission projections under the No LEZ scenario in 2030 compared with 2023

Note: Blocks show the change in tonnes of emissions for each vehicle category from 2023 to 2030, with steps down indicating decreases in emissions and steps up indicating increases in emissions. The share of emissions from taxis is less than 1% for most pollutants in both 2023 and 2030, so the change in tonnes of emissions for taxis is relatively small compared with other types of vehicles.

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PROJECTED IMPACT OF AN LEZ ON REDUCING VEHICLE TAILPIPE EMISSIONS

We assumed that an LEZ would be implemented in two phases between 2024 and 2030. A planning phase, from 2024 to 2025, would include baseline assessments, setting targets for reducing emissions, stakeholder engagement, defining LEZ boundaries and restriction strategies, setting up fiscal and nonfiscal support measures, and establishing enforcement mechanisms. During the second phase, from 2026 to 2030, the restrictions on vehicles entering the LEZ would be enforced. These timelines align with Maharashtra state's 2021 EV policy, which expired in March 2025.

We evaluated the emissions reduction potential of two types of vehicle restriction scenarios. In the Age-Based scenario, diesel vehicles older than 10 years and other internal combustion engine (ICE) vehicles older than 15 years are barred from the LEZ. In the Standard-Based scenario, restrictions are based on BS standard and strengthen every two years. Beginning in 2026, diesel vehicles below BS III and all others below BS II are prohibited from the LEZ; by 2030, only BS VI diesel vehicles and other vehicles meeting BS IV and above are permitted.

We assumed that vehicle owners shift to vehicles that comply with the proposed LEZ regulations. For each of the LEZ scenarios, we modeled three such compliance approaches:

» Vehicle owners shift to a used vehicle to meet LEZ regulations. In the Age-Based scenario, diesel vehicle owners shift to 5-year-old vehicles while other owners shift to 8-year-old vehicles. In the Standard-based scenario, all vehicle owners shift to vehicles of the minimum BS standard required to comply with the LEZ regulations.

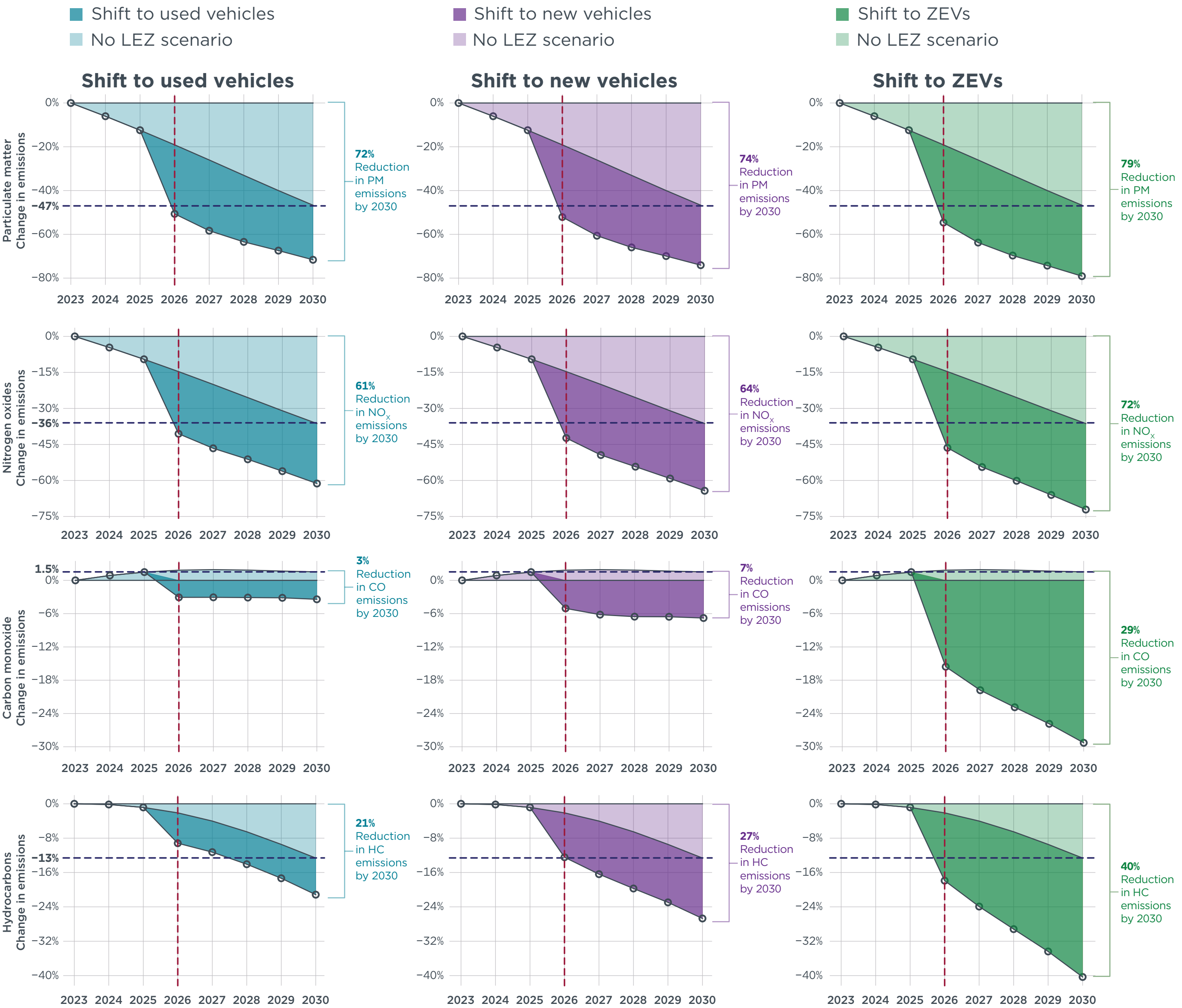
» Vehicle owners shift to new ICE vehicles certified to BS VI.

» Vehicle owners shift to zero-emission vehicles (ZEVs).

Figures 6a and 6b show the impact of restricting vehicles from the LEZ based on the two scenarios. Percentages reflect the reductions in vehicle emissions within the boundaries of the of the LEZ only, rather than the entire CSMC; percentage reductions in emissions are the same for both the Option 1 and Option 2 LEZs, although the tonnes of emissions abated will be higher in the larger LEZ. From the start of enforcement in 2026, the Age-Based scenario shows a greater reduction in emissions compared with the Standard-Based scenario, as many drivers shift to more efficient vehicles to enter the LEZ. However, the trend reverses by 2030, with the Standard-Based scenario achieving the highest reduction that year as more vehicles adhering to less-stringent emission standards are phased out. Overall, the Age-Based scenario still shows the greatest improvement over the entire implementation period. The results for each restriction scenario are explored in more detail below.

Figure 6a

Age-Based scenario: Impact on emission loads under three compliance approaches compared with the No LEZ scenario



Notes: The light-shaded portions of each figure indicate the emissions load under the No LEZ scenario, with the horizontal dark blue line indicating the emissions level in 2030 in that scenario. The red vertical line indicates the start year for LEZ enforcement.

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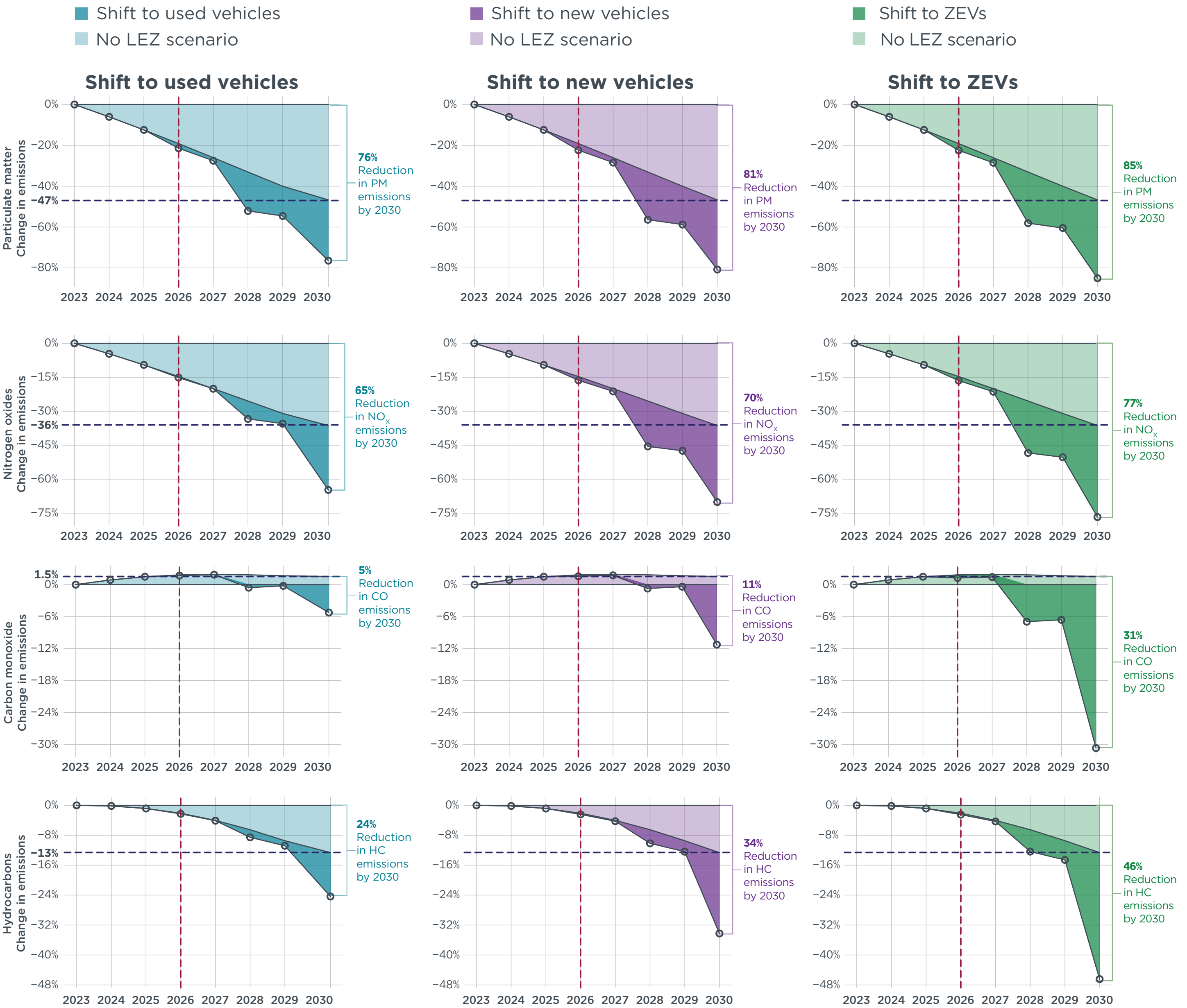
Figure 6b

Standard-Based scenario: Impact on emission loads under three compliance approaches compared with the No LEZ scenario



Notes: The light-shaded portions of each figure indicate the emissions load under the No LEZ scenario, with the horizontal dark blue line indicating the emissions level in 2030 in that scenario. The red vertical line indicates the start year for LEZ enforcement.

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Age-Based scenario

The Age-Based scenario projects substantive emission reductions during the entire LEZ enforcement period from 2026 to 2030. PM emissions decrease by 44%–53%, NO_x by 34%–46%, CO by 5%–24%, and HC by 8%–24%. For PM, NO_x, and CO, under all three compliance approaches, the emission reductions in 2026 (the start year of LEZ enforcement) exceed reductions projected for 2030 under the No LEZ scenario. This is also the case for HC under two of the compliance approaches: shift to new vehicles and shift to ZEVs. For the other compliance approach, which assumes a shift to used vehicles, reductions exceed those under the No LEZ scenario in 2030 by 2028.

In 2030, additional emission reductions (on top of reductions under the No LEZ scenario) range from 25%–32% for PM, 25%–36% for NO_x, and 8%–27% for HC, depending on the compliance approach. The most extensive reductions occurred when noncompliant vehicles were replaced with ZEVs; under this compliance approach, total reductions ranged from 29%–79% across all pollutants in 2030 compared with the 2023 base year.

Between 2026 and 2030, relative to the No LEZ scenario, emissions of all four pollutants combined would decrease by an additional 12% if vehicle owners shift to used vehicles, 15% if owners shift to new vehicles, and 29% if owners transition to ZEVs. These cumulative values are intended to provide a simplified comparison across compliance approaches and should be interpreted as indicative rather than scientifically precise, as they do not account for varying impacts or interactions of individual pollutants.

Standard-Based scenario

Relative to the No LEZ scenario, cumulative emission reductions over the enforcement period in the Standard-Based scenario were projected to range from 20%–27% for PM, 11%–23% for NO_x, 2%–10% for CO, and 3%–10% for HC.

For PM, the Standard-Based scenario achieves the same level of emissions observed in the No LEZ scenario in 2030 two years earlier (i.e., in 2028) for all three compliance approaches; for NO_x, this is the case for two of the compliance approaches. Additional reductions in emissions in 2030 (on top of reductions under the No LEZ scenario) were projected to range from 29%–38% for PM, 25%–36% for NO_x, and 8%–27% for HC, depending on the compliance approach. Replacing noncompliant vehicles with ZEVs produced the greatest total decrease in emissions: The reductions in 2030 compared with the 2023 base year range from 31%–85%, depending on the pollutant.

Between 2026 and 2030, relative to the No LEZ scenario, emissions of all four pollutants combined would decrease by an additional 4% if vehicle owners shift to used vehicles, 7% if they shift to new vehicles, and 13% if vehicle owners shift to ZEVs.

IMPACT OF AN LEZ ON AIR QUALITY

In addition to emissions, urban air quality is influenced by environmental factors such as atmospheric conditions and geographical features (Jayaraman et al., 2025). The effectiveness of policy measures aimed at reducing emissions is likely to vary from city to city, largely due to these other factors.

To investigate the impact of LEZ measures on air quality, we conducted an air quality modeling simulation focused on tailpipe $PM_{2.5}$ and NO_x for 2026 and 2030 across the different vehicle restriction scenarios and compliance approaches. We used the Intervention Model for Air Pollution (InMAP), a reduced-complex numerical air quality model that requires less computational time and has lower operational complexity than alternative models. This analysis aims to provide insights for decision-makers regarding the expected improvements at the start and end of the proposed LEZ intervention. Details on our model selection and the methodology for this analysis are detailed in Appendix A.

Figures 7a and 7b present the results of our reduced-complex modeling of tailpipe $PM_{2.5}$ and NO_x emissions for the No LEZ scenario and the Age-Based and Standard-based LEZ scenarios for the two identified LEZ boundary options.

Figure 7a

Change in citywide tailpipe concentration of $PM_{2.5}$ under different LEZ scenarios compared with the 2023 base year

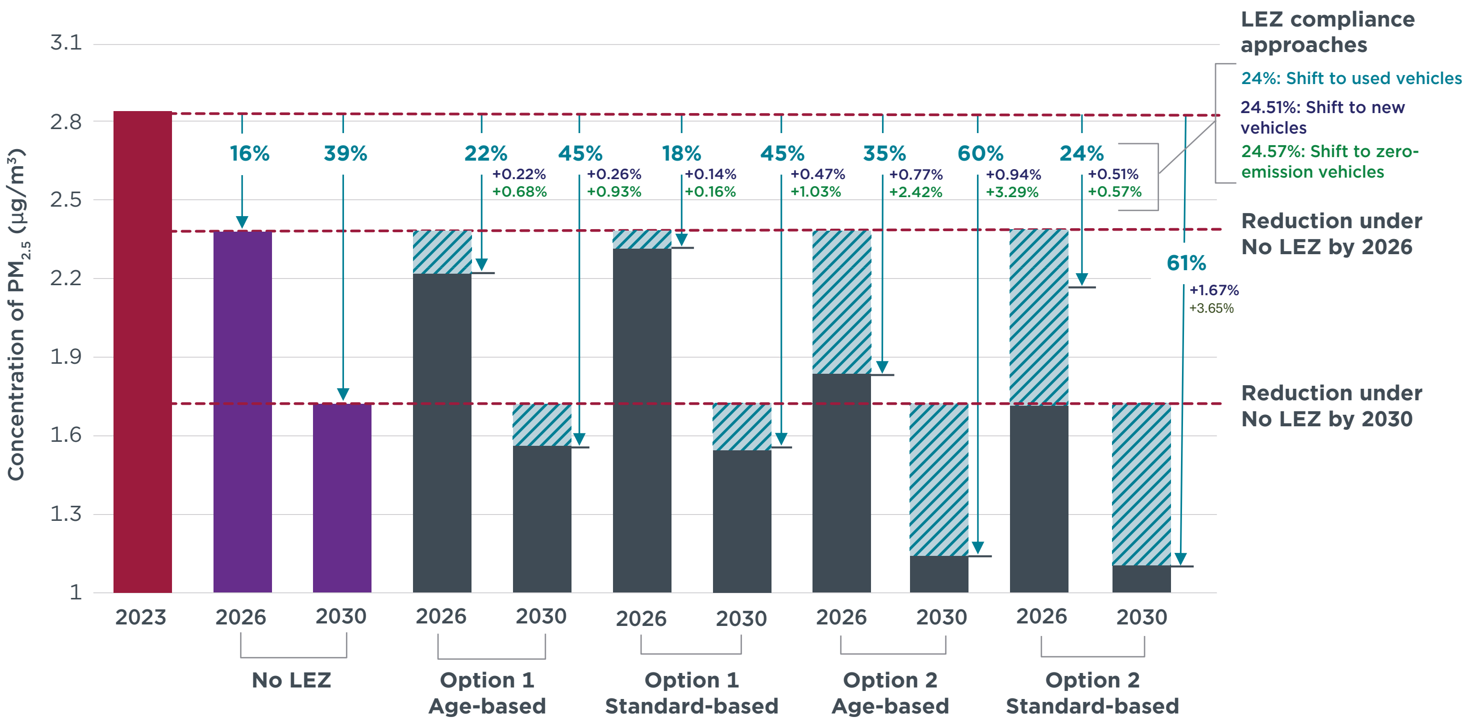

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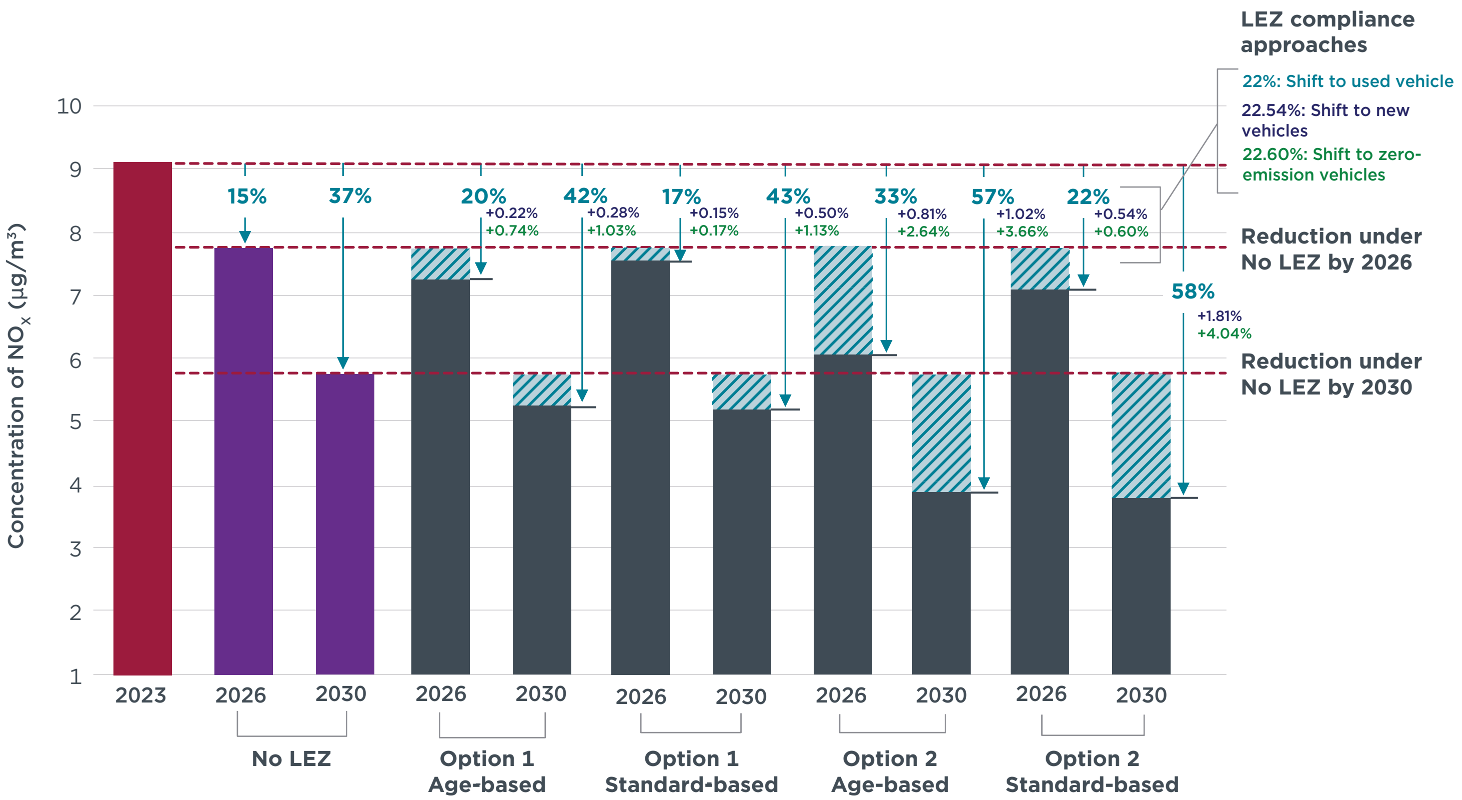
Figure 7b

Change in citywide tailpipe concentration of NO_x under different LEZ scenarios compared with the 2023 base year



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Comparing these results with on-ground air quality data from continuous and manual air quality monitoring conducted by the state government (see Appendix C), our reduced-complex modeling indicated that tailpipe emissions accounted for 6.8% of average citywide $PM_{2.5}$ levels in 2023, or 2.8 μg/m³ out of 42 μg/m³. The spatial variation in $PM_{2.5}$ levels in 2023, shown in Figure B2, indicates that the areas we identified as potentially suitable options for LEZs are pollution hotspots. In terms of NO_X, the model results showed that vehicle emissions accounted for 28% of the citywide average in 2023, or 9.1 μg/m³ out of 32.5 μg/m³.

According to the modeling, in the No LEZ scenario, citywide concentrations of $PM_{2.5}$ and NO_X from vehicle emissions decline by 0.45 μg/m³ (16%) and 1.4 μg/m³ (15%), respectively, in 2026, and by 1.1 μg/m³ (39%) and 3.3 μg/m³ (37%) in 2030, compared with the 2023 baseline. These reductions are primarily driven by the natural turnover of the fleet to newer vehicles meeting the most recent emission standard.

Greater average reductions are achieved with an LEZ in place. Under LEZ Option 1 with standard-based restrictions and a shift to used vehicles, $PM_{2.5}$ concentrations decline by 0.5 μg/m³ (18%) in 2026 and 1.3 μg/m³ (45%) in 2030, while NO_X concentrations decline by 1.54 μg/m³ (17%) in 2026 and 3.9 μg/m³ (43%) in 2030. Under an age-based scenario with the same compliance approach, $PM_{2.5}$ declines by 0.6 μg/m³ (22%) in 2026 and 1.3 μg/m³ (45%) in 2030, while NO_X concentrations decline by 1.83 μg/m³ (20%) in 2026 and 3.8 μg/m³ (42%) in 2030.

The impacts of the LEZ depend on its geographical size, with larger zones yielding greater year-over-year benefits. Under LEZ Option 2 with standard-based restrictions and a shift to used vehicles, $PM_{2.5}$ concentrations decline by 0.6 μg/m³ (24%) in 2026 and 1.7 μg/m³ (61%) in 2030, while NO_X concentrations decline by 2.0 μg/m³ (22%) in 2026 and 5.3 μg/m³ (58%) in 2030. With age-based restrictions under the same compliance scenario, $PM_{2.5}$ declines by 1.0 μg/m³ (35%) in 2026 and 1.7 μg/m³ (60%) in 2030, while NO_X concentrations decline by 3.0 μg/m³ (33%) in 2026 and 5.3 μg/m³ (57%) in 2030. With LEZ Option 2, the benefits are 1.3 to 1.6 times higher than LEZ Option 1.

The citywide benefits of a larger LEZ would be even greater if vehicle owners shift to ZEVs. While the city may start with a smaller zone such as Option 1, higher air quality benefits are achievable by expanding the LEZ boundaries.

MONETARY VALUATION OF LEZ ENVIRONMENTAL BENEFITS

Next, we evaluated the environmental benefits of reducing tailpipe emissions under the LEZ scenarios. Environmental benefits represent the societal costs avoided, quantified in Indian rupees per kilogram of pollutant abated, because there is less exposure to the harmful pollutant. Table 4 displays environmental valuations for pollutant emissions in the EU-28 from de Bruyn et al. (2018) and van Essen et al. (2019) derived using the shadow pricing method and expressed in euros per kilogram. Details on the shadow pricing method are presented in Appendix A. Transport emissions are more damaging to human health than average emissions as they occur closer to the ground so higher proportions of emissions are likely to enter the human body. Hence, the monetary benefits of reducing transport emissions, especially $PM_{2.5}$ and $NO_{X,}$ are likely to be higher than the benefits of reducing average emissions from other sources.

Euro prices were translated to 2023 rupees using the value transfer approach (VTA). The VTA procedure involves transferring value estimates from an original location to a new location with adjustments to economic indicators such as income, inflation, and exchange rates. Details about VTA and the economic indicators used for the assessment are provided in Appendix F. We acknowledge that the prices in Table 2 are conservative estimates and may not fully capture the true extent of benefits. The aim of this estimation is to encourage a broader discussion among relevant stakeholders on the potential implications of implementing an LEZ.

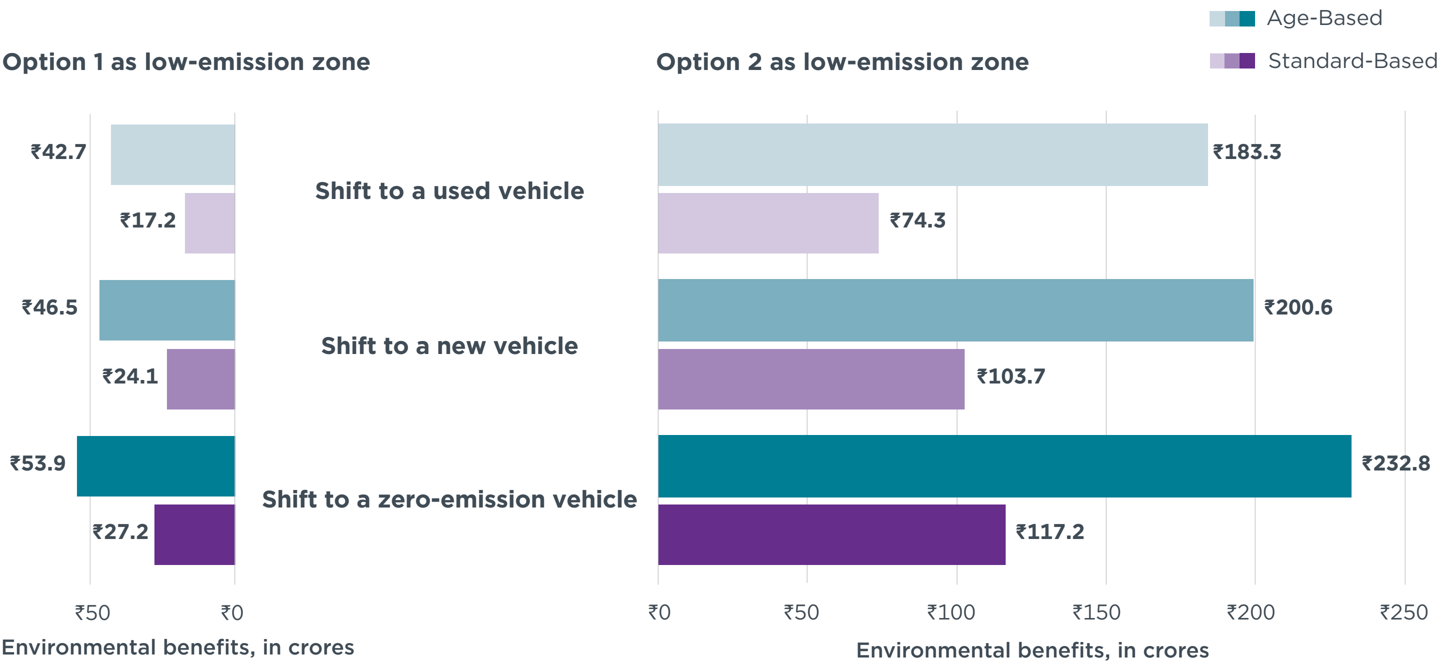
Table 2
Environmental prices for air pollutants

Air pollutants	€/kg	2023₹/kg	Midpoint (M) and endpoint (E) impact of pollutants
$PM_{2.5}$	€381 (2016€)[a]	₹11,434	M: Particulate matter formation E: Harm to human health and building and material damage
NO_x	€21.3 (2016€)[a]	₹639.2	M: Particulate matter formation, smog formation, and acidification E: Harm to human health, crop damage, biodiversity loss, and building and material damage
CO	€0.0526 (2015€)[b]	₹1.6	M: Smog formation E: Harm to human health
HC	€1.25 (2015€)[c]	₹36.8	M: Smog formation E: Harm to human health, crop damage, biodiversity loss, and building and material damage

[a] de Bruyn et al. (2018).
[b] van Essen et al. (2019).
[c] Environmental pricing for hydrocarbons was unavailable. Because hydrocarbons are a subset of volatile organic compounds (VOCs), we used the price of VOCs as a proxy. To avoid overestimation, weights of 0.9 and 0.1 were assigned to the prices for non-methane VOCs and methane, respectively, with values from van Essen et al. (2019).

Figure 8 illustrates the estimated environmental benefits resulting from the implementation of an LEZ. The benefits vary depending on the size of the LEZ, the policy intervention applied and the vehicles that users choose to comply with the restrictions.

Figure 8
Monetary valuation of an LEZ's environmental benefits for 2026–2030 in Chhatrapati Sambhajinagar Municipal Corporation



Note: Values are rounded to the nearest digit.

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The environmental benefits for 2026–2030 ranged from a minimum of ₹17.2 crores assuming LEZ Option 1, standard-based restrictions, and a shift to used vehicles to a maximum of ₹232.8 crores assuming LEZ Option 2, age-based restrictions, and a shift to ZEVs. Shifting to ZEVs yielded the most significant benefits, particularly in reducing CO, HC, and NO_x emissions. Notably, the larger LEZ Option 2 offered 3.3 times higher benefits compared with Option 1.

By share of the overall monetary value of environmental benefits, the reduction in $PM_{2.5}$ accounted for 57%–68%, NO_x 31%–41%, HC 0.5%–1.2%, and CO 0.04%–0.16%. Benefits depend on the LEZ size, the type of restrictions, and the compliance strategies adopted by vehicle owners. Appendix G details the environmental benefits expressed in rupees by pollutant, LEZ option, and scenario. LEZs could yield additional benefits outside the scope of this work, including reduced noise pollution, avoided greenhouse gas emissions, enhanced public health from more walking and transit use, fewer service delays caused by congestion, and a rise in real estate values.

CONCLUSION

This paper examined the possible impacts, on air quality and avoided societal costs, of implementing an LEZ in the Chhatrapati Sambhajinagar Municipal Corporation. We found that an LEZ could yield considerable benefits, with the extent of the impact depending on the geographical scope of the LEZ and the type of vehicle restrictions adopted. This analysis informs the following conclusions and policy considerations:

Boundaries of LEZs can be drawn to target high-emission areas. Two options for an LEZ were identified. The two areas making up the smaller zone accounted for about 10% of the city's estimated emissions from vehicle tailpipes, while the single larger zone accounted for 42%. The choice of LEZ may depend on several factors, including the city's preparedness, resource availability, and capacity at the political, administrative, and local levels. Larger LEZ boundaries would achieve greater emission reductions and air quality improvements in the CSMC. Compared with 2023 levels, the projected improvements from reducing transport sector emissions ranged from a low end of 0.5 $\mu g/m^3$ for $PM_{2.5}$ and 1.5 $\mu g/m^3$ for NO_x in the smaller option up to 1.7 $\mu g/m^3$ for $PM_{2.5}$ and 5.3 $\mu g/m^3$ for NO_x in the larger option, depending on the restriction type and compliance strategy.

Restrictions based on vehicle age and BS standard can be effective. Implementing vehicle restrictions across all vehicle categories would maximize reductions in emissions. Compared with the No LEZ scenario, age-based restrictions yielded estimated reductions of up to 29% over the entire enforcement period while standard-based measures resulted in reductions of up to 13%. The greatest emission reductions were observed when owners of noncompliant vehicle shifted to ZEVs. This underscores the importance of incentivizing ZEV adoption as a key policy strategy.

An LEZ can result in substantial economic value from the avoided social cost of air pollution. The avoided social cost—including harmful impacts on health, reductions in crop productivity, building and material damage, and biodiversity loss—ranged from ₹17.2 crores to ₹232.8 crores (US$2 million to US$27 million), depending on the size of the LEZ, type of vehicle restriction, and the vehicle owners' compliance strategy.

An LEZ can be one piece of an effective policy mix toward improved air quality. Transport-related pollutants can be more harmful to human health because the emissions occur close to the ground. While an LEZ in Chhatrapati Sambhajinagar would deliver targeted reductions in tailpipe emissions, its effectiveness as part of the city's air quality strategy depends on complementary actions addressing other pollution sources, such as industrial activities, open waste burning, and dust from construction and unpaved roads. These other pollution sources, as well as meteorological and geographical factors, could mean that an LEZ does not immediately result in lower pollutant measurements. Therefore, additional ways to measure the effectiveness of LEZs could be considered, such as the LEZ compliance rate, number of noncompliant vehicles scrapped, increased EV adoption, and higher public transport ridership.

The benefits of LEZs extend beyond air quality improvements to include reductions in greenhouse gas emissions, fewer traffic delays, and improved health as people opt for more physically active modes of transport. Direct economic gains could materialize from increased real estate values and business activity from improved foot traffic in a cleaner, more attractive urban environment.

As the CSMC progresses toward achieving its air quality and climate goals, integrating LEZs as part of its demand-side regulation strategies can accelerate these efforts. Regular monitoring, timely updates, and robust support measures through demand-side incentives—such as improved public transport and infrastructure for walking and cycling, subsidies for scrapping polluting vehicles, and ZEV purchase incentives—can help ensure the successful implementation and transition to a sustainable LEZ.

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APPENDIX A

METHODOLOGY AND ASSUMPTIONS

Modeling air quality

To evaluate air quality improvements from LEZ implementation, we used the Intervention Model for Air Pollution (InMAP), a reduced-complex numerical air quality model, to simulate the various scenarios under each of the proposed LEZ options. Unlike the conventional Chemical Transport Models (CTMs), InMAP requires less computational time and has lower operational complexity. InMAP takes spatially gridded emission load as input and “combines spatially-resolved annual-average physical and chemical information derived from a state-of-the-science CTM (WRF-Chem) with simplifying assumptions regarding atmospheric chemistry” to compute the annual average pollutant concentration (Tessum et al., 2017).

Air quality dispersion modeling was based on vehicle exhaust emissions from the entire Chhatrapati Sambhajinagar district to account for pollutants transported from neighboring regions to the CSMC area. We computed the improvement in $PM_{2.5}$ and NO_x concentrations annually using the InMAP model. The resulting concentration isopleths were validated against on-ground air quality data from continuous and manual air quality monitoring stations operated by the Government of Maharashtra and analyzed by the author. The on-ground station locations are mapped in Appendix C.

We made several assumptions in modeling the impacts of the LEZs:

- The implementation of the LEZ does not impact the vehicle stock or the makeup of the vehicle fleet in the city.
- Vehicle owners that do not yet comply with LEZ regulations will not seek alternate routes to avoid violating these regulations. Instead, they will replace noncompliant vehicles with compliant ones of the same type.
- The proportion of vehicles registered outside of the city but operating within the city, also known as influx vehicles, is assumed to remain constant throughout the study.
- The physical-chemical processes and meteorological and geographical conditions used in the InMAP simulation are considered unchanged for the study duration.
- We modeled air quality dispersion of $PM_{2.5}$ by assuming that the PM emission load from vehicle exhaust is composed of fine particles of 2.5 µm, given that particles of this size or smaller mainly originate from combustion sources, and on-road transport is one of the primary sources of $PM_{2.5}$ (Li & Managi, 2021).
- We applied a correction factor by increasing emissions by 25% (Automotive Research Association of India & The Energy and Resources Institue, 2018) along the major roads of the Chhatrapati Sambhajinagar district to account for high-emitting vehicles and influx vehicles. This adjustment was incorporated only in the air quality dispersion modeling for both $PM_{2.5}$ and NO_x to minimize the risk of underestimation and better represent the spatial distribution of pollution levels, capturing transported emissions from areas outside the CSMC.

Estimating economic benefits of pollution reduction

We used the shadow pricing method to estimate the benefits of pollution reduction by assigning a monetary value to goods and services lacking a market price. This approach evaluates how changes in environmental quality affect social welfare, quantifying the impact these changes have on health, crop productivity, building materials, and biodiversity.

In this paper, shadow prices were calculated through multiple techniques, including the damage-cost, replacement-cost, and restoration-cost approaches. For example, when assessing the health impacts of pollutants, where direct market prices for damages were absent, an individual's willingness to pay to avoid the damage or willingness to accept compensation for are proxy measures for valuation. In cases of material and building damage, the replacement-cost method—which estimates the value of externality based on the costs of replacing or repairing the damage caused by externality—was applied, though this may lead to underestimates because some damaged assets cannot fully be restored or replaced. Similarly, for biodiversity loss, the restoration-cost method was used, although this approach may not fully capture biodiversity value, given that genetic diversity may be permanently lost even after recovery. The external cost of air pollutants and associated methodology are detailed in reports by de Bruyn et al (2018) and van Essen et al (2019).

Importantly, these estimates are conservative and may not reflect the full extent of benefits. The average emission valuations are based on EU-28 estimates and are generalized for the CSMC without accounting for spatial and temporal variations. Although there are limitations, this approach is useful as it offers a preliminary assessment of pollution cost relative to economic benefit, aiding in decision-making.

APPENDIX B

Figure B1

Load distribution of particulate matter from vehicle exhaust across the Chhatrapati Sambhajinagar Municipal Corporation for the 2023 base year

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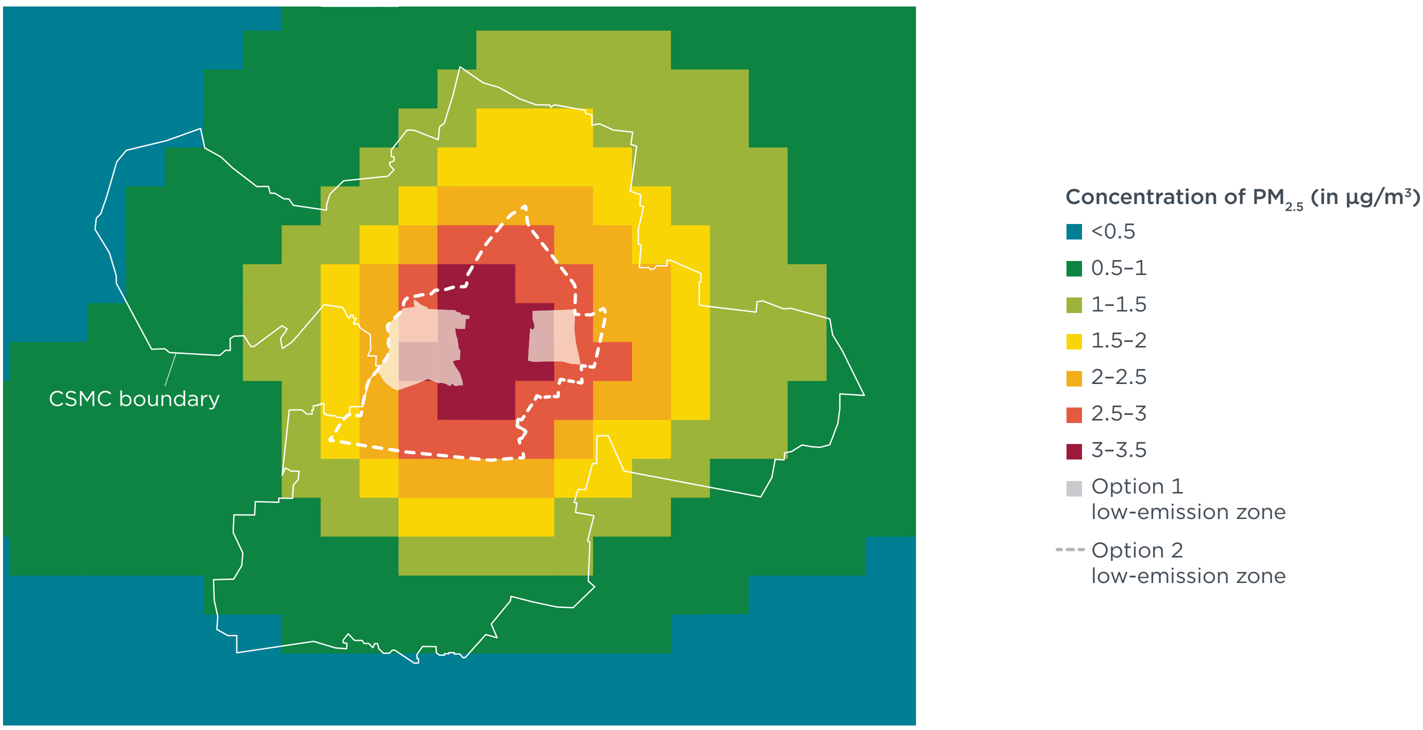
Figure B2

Isopleths of modeled annual average $PM_{2.5}$ concentrations from vehicle exhaust for the Chhatrapati Sambhajinagar Municipal Corporation for the 2023 base year



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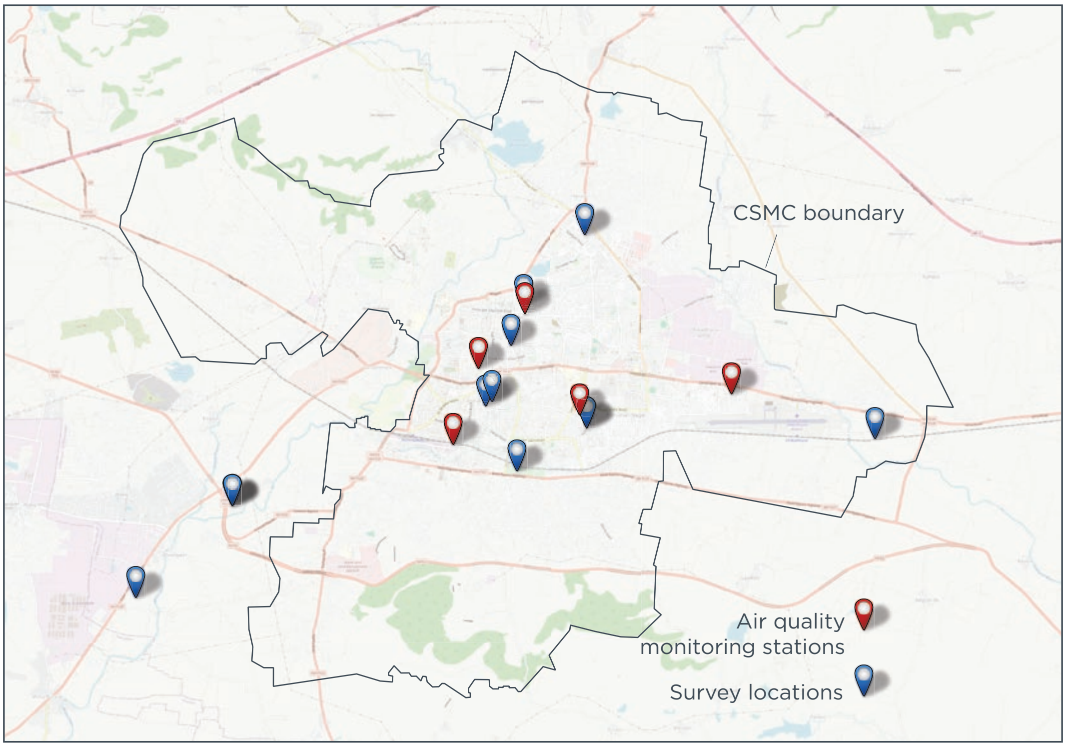
APPENDIX C

Figure C1

Geolocations of survey sites and state-run ambient air quality (AQ) monitoring stations, including both continuous and manual monitoring stations



Source: Base map from OpenStreetMap (n.d.). Locations of air quality monitoring stations obtained from the Central Pollution Control Board and Maharashtra Pollution Control Board platforms.

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APPENDIX D

Table D1, Table D2, and Figure D1 detail the parameters derived through primary surveys conducted at fuel stations and parking lots to understand city-specific fleet characteristics. The survey included questions about vehicle age, trip length, trip frequency, and weekly amount spent on fuel. These independent variables were used to develop the city-specific air pollutants emission inventory.

Table D1
Vehicle-kilometers traveled (VKT) by vehicle type

Vehicle types	VKT per day
Two-wheelers	42
Three-wheelers	60
Light motor vehicles (personal cars)	50
Light passenger vehicles (taxis)	73
Medium and heavy passenger vehicles	122
Medium and heavy goods vehicles	56

Note: Survey information on VKT and fuel expenditures were used to estimate the final VKT values for specific vehicle types based on the highest density function. We applied the kernel density function (KDF) to identify where the majority of responses were concentrated. For each vehicle type, the peak of KDF represents the most probable value based on the distribution of the data, which in this case is VKT recorded and analyzed through fuel-expenditure data from the survey. The lowest values at the peak were selected as representative VKT for each vehicle type.

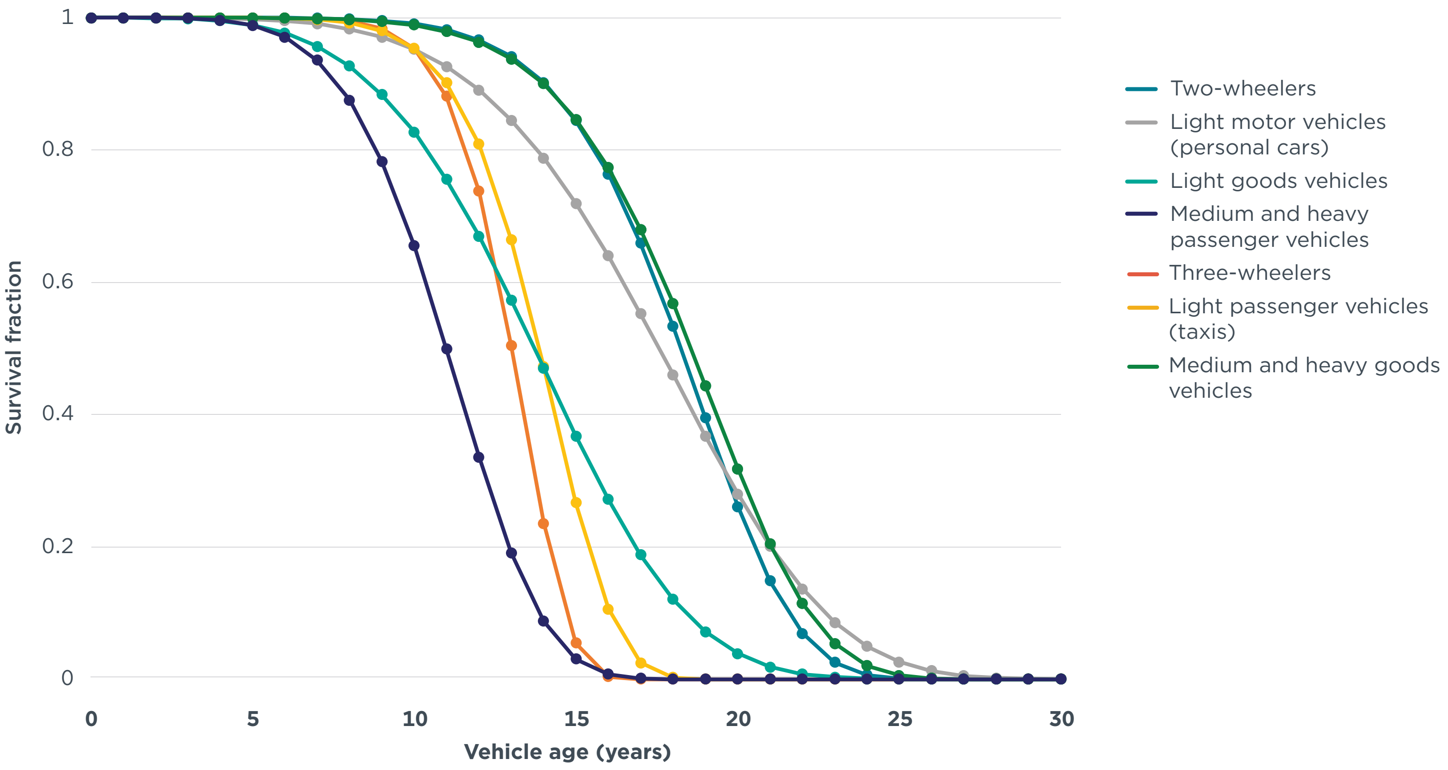
Table D2
Mean survival life by vehicle type

Vehicle types	Survival life in years
Two-wheelers	15
Three-wheelers	11
Light motor vehicles (personal cars)	15
Light passenger vehicles (taxis)	12
Medium and heavy passenger vehicles	9
Medium and heavy goods vehicles	15

Note: The values were derived using the survival probability elastic function. The details of the methodology are discussed in Malik et al. (2019).

Figure D1

Survival fraction of vehicles with age



Note: The survival rate of a vehicle is the fraction or percentage of registered vehicles still in use at a certain vehicle age. The modified Weibull probability distribution method was used to generate the curves. More details on the methodology are discussed in Goel et al. (2015).

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APPENDIX E

Table E1

Share of 2030 emissions by vehicle type in the Chhatrapati Sambhajinagar Municipal Corporation under the No LEZ scenario

Vehicle type	$PM_{2.5}$	NO_x	CO	HC
Two-wheelers	43.2%	34.5%	51.8%	72.6%
Three-wheelers	1.7%	1.9%	0.6%	1.6%
Light motor vehicles (personal cars)	17.1%	16%	17.2%	11.2%
Light passenger vehicles (taxis)	0.6%	0.5%	0.3%	0.3%
Light goods vehicles	15.7%	11.4%	11.2%	11.7%
Medium goods vehicles	3.0%	4.2%	1.7%	0.3%
Heavy goods vehicles	15.4%	25.4%	10.9%	1.4%
Medium passenger vehicles	1.3%	2.5%	2.3%	0.15%
Heavy passenger vehicles	2.0%	3.4%	3.9%	0.7%
Total emissions in tonnes	85	1,365	4,822	1,371

APPENDIX F

Indian prices for the environmental price of pollutant emissions were estimated by applying a value transfer approach (Maji et al., 2017) using the following equation:

$$EP_{p,i,y} = EP_{p,EU28,k} \times \left[\frac{G_{i,k}}{G_{EU28,k}}\right]^{\epsilon} \times \left[1 + \%\Delta G_{i,k\rightarrow y} + \%\Delta P_{i,k\rightarrow y}\right]^{\beta} \times PPP_{EU28\rightarrow i,y}$$

Definitions and sourcing for each variable are presented in Table F1.

Table F1

Descriptions of equation variables and assigned values

Equation variables	Description	Values considered/assigned	Source
$EP_{p,i,y}$	Environmental price in ₹/kg for pollutant *p*, region *i*, and year *y*	p = $PM_{2.5}$, NO_X, CO, and HC; i = India; y = 2023	
$EP_{p,EU28,k}$	Environmental price of pollutant *p* in €/kg in EU-28 prices for year *k*	k = 2016 for $PM_{2.5}$ and NO_X; k = 2015 for CO and HC	
$G_{i,k}$	Gross domestic product (GDP) per capita in terms of purchasing power parity (PPP) for the region *i* and year *k*	\$6.94 thousand for k = 2016; \$6.49 thousand for k = 2015; \$9.16 thousand for k = 2023	World Bank (n.d.)
$G_{EU28,k}$	GDP per capita in terms of PPP for the region EU-28 and year *k*	\$48.22 thousand for k = 2016; \$47.38 thousand for k = 2015	World Bank (n.d.)
ϵ	Elastic coefficient of willingness to pay (WTP)	1.0	Maji et al. (2017)
$\%\Delta G_{i,k\rightarrow y}$	Percentage change in GDP per capita in terms of PPP for the region *i* for the years *k* to *y*	$\%\Delta G_{India,2016\rightarrow 2023}$ = 0.32 $\%\Delta G_{India,2015\rightarrow 2023}$ = 0.41	
$\%\Delta P_{i,k\rightarrow y}$	Percentage change in the consumer price index for the region *i* for the years *k* to *y*	$\%\Delta P_{India, 2016\rightarrow 2023}$ = 0.40 $\%\Delta P_{India,2015\rightarrow 2023}$ = 0.47	Ministry of Statistics and Programme Implementation (2025)
β	Income elasticity for WTP of environmental and health-related goods	0.8	Organisation for Economic Co-operation and Development (2014)
$PPP_{i,y}$	Exchange rate in terms of PPP from € to currency in the region *i* for the year *y*	135	International Monetary Fund (n.d.), Eurostat (n.d.)

Note: GDP (PPP) values, expressed in constant 2021 international dollars, are sourced from the World Bank database. These values may be subject to revision due to improvements in estimation techniques, enhanced data collection methods, recent surveys, or advancements in methodology and data sources. Additionally, the consumer price indices used in this analysis originally pertained to the year 2012. To ensure consistency with the base year of 2021 for GDP per capita, the CPI values were rescaled to align with the 2021 base year.

APPENDIX G

Table G1

Environmental benefit, in crores of rupees, from implementing a low-emission zone in the Option 1 geographical area, by pollutant

Pollutant	Age-Based scenario			Standard-Based scenario		
	Shift to used vehicles	Shift to new vehicles	Shift to zero-emission vehicles	Shift to used vehicles	Shift to new vehicles	Shift to zero-emission vehicles
$PM_{2.5}$	₹25.7	₹27.7	₹30.9	₹11.8	₹14.4	₹15.7
NO_x	₹16.8	₹18.4	₹22.3	₹5.4	₹9.6	₹11.2
CO	₹0.017	₹0.03	₹0.09	₹0.008	₹0.013	₹0.04
HC	₹0.2	₹0.4	₹0.6	₹0.09	₹0.1	₹0.3
Total	**₹42.7**	**₹46.5**	**₹53.9**	**₹17.3**	**₹24.1**	**₹27.2**

Table G2

Environmental benefit, in crores of rupees, from implementing a low-emission zone in the Option 2 geographical area, by pollutant

Pollutant	Age-Based scenario			Standard-Based scenario		
	Shift to used vehicles	Shift to new vehicles	Shift to zero-emission vehicles	Shift to used vehicles	Shift to new vehicles	Shift to zero-emission vehicles
$PM_{2.5}$	₹110.8	₹119.2	₹133,5	₹50.7	₹61.9	₹67.8
NO_x	₹72.0	₹79.6	₹96.2	₹23.2	₹41.1	₹48.1
CO	₹0.08	₹0.1	₹0.4	₹0.04	₹0.06	₹0.2
HC	₹0.9	₹1.5	₹2.7	₹0.4	₹0.7	₹1.1
Total	**₹183.8**	**₹200.6**	**₹232.8**	**₹74.301**	**₹103.7**	**₹117.2**

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