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Impact of a low-emission zone on air pollutants: A case study of Pimpri-Chinchwad, India

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INTRODUCTION

Air pollution is a major challenge in India, posing a severe threat to human health and the country's economy. Air pollution accounts for 18% of deaths from all causes in the country, lower labor productivity, and reduced consumer foot traffic in stores (Dalberg Advisors, 2021). This costs Indian businesses US$95 billion annually, equivalent to 3% of the country's gross domestic product (GDP) as of 2019 (Dalberg Advisors, 2021). Road transport is responsible for 20%–30% of urban air pollution in India (International Energy Agency, 2023). This paper explores the potential of low-emission zones (LEZs) to reduce emissions at the city level.

LEZs are designated areas within a city where polluting vehicles are restricted from operating or are charged a fee to enter. LEZs are predominantly concentrated in Europe, where there are over 320 active LEZs, but more cities worldwide are considering establishing such zones because of the potential benefits for public health and quality of life. A study by the University of Bath found the Greater London low-emission zone, introduced in stages starting in 2008, has led to a 13% reduction in levels of inhalable particulate matter (PM_{10}), a 4.5% decrease in long-term health issues, an 8% reduction in respiratory problems, and a 14.3% decrease in sick leave (Fichera et al., 2023). The same study found that London's ultra-low emission zone (ULEZ), launched in 2019, achieved an 18.4% reduction in nitrogen dioxide (NO_2) levels, and reported a 3% overall improvement in health and 6% lower anxiety levels. Brussels, Seoul, Lisbon, and Rome—among many other cities—have also introduced LEZs, resulting in significant improvements in air quality (Yanocha et al., 2023). With escalating levels of air pollution in Indian cities, the urgency for implementing effective and results-oriented abatement solutions has become increasingly apparent. Introducing LEZs can be a crucial strategy for controlling air pollution, as well as for

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achieving the broader benefits of more sustainable, healthier urban environments (Wappelhorst et al., 2023).

Many Indian states have established electric vehicle (EV) policies. Seven of these states have included LEZs, also referred to as green zones, in their EV policies as a nonfiscal incentive to promote the adoption of zero-emission vehicles (ZEVs; Anup & Yang, 2023). The western state of Maharashtra designated six urban agglomerations—Mumbai, Pune, Nagpur, Nashik, Chhatrapati Sambhajinagar, and Amravati—as areas for LEZs (Government of Maharashtra, 2021). In support of this initiative, the International Council on Clean Transportation is assisting three cities in Maharashtra currently exploring LEZs: Pimpri-Chinchwad, Pune, and Chhatrapati Sambhajinagar (formerly known as Aurangabad).

This paper evaluates the potential reduction in emissions that could be achieved by establishing an LEZ in Pimpri-Chinchwad, a city of about 2 million people. The Pimpri Chinchwad Municipal Corporation (PCMC) covers 181 square kilometers and is home to numerous automotive plants and other manufacturing facilities. Particulate pollution levels in the city have been found to exceed the government-set air quality standards, with transportation being the primary source of pollution across the Pune Metropolitan Region, which includes the cities of Pune and Pimpri-Chinchwad (SAFAR-India, 2020). Alongside other conventional measures, implementing an LEZ could further enhance the PCMC's efforts to address air pollution.

The structure of the paper is as follows:

» First, we identify the potential geographical areas within the city that could be declared an LEZ and describe the assessment approach.
» Next, we detail the modeling methodology used for developing a spatial inventory of key tailpipe emissions and then project the emission loads for the following air pollutants—particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO) and hydrocarbons (HC)—under a business-as usual scenario with no LEZ through 2030.
» Possible scenarios for restricting certain vehicles from entering an LEZ are then outlined, followed by the assumptions used to model the potential impact of these scenarios on projected emissions.
» Modeling results are discussed, along with an evaluation of the effectiveness of proposed scenarios on emissions.
» Finally, the paper concludes with a discussion of key findings and potential steps that could facilitate an equitable transition to cleaner vehicles and cleaner air.

IDENTIFICATION OF LOW-EMISSION ZONE GEOGRAPHIC BOUNDARIES

The primary objective of the paper is to identify potential areas within the city of Pimpri-Chinchwad to be considered for an LEZ. This section explains the approach we followed to determine these areas, as illustrated in Figure 1.

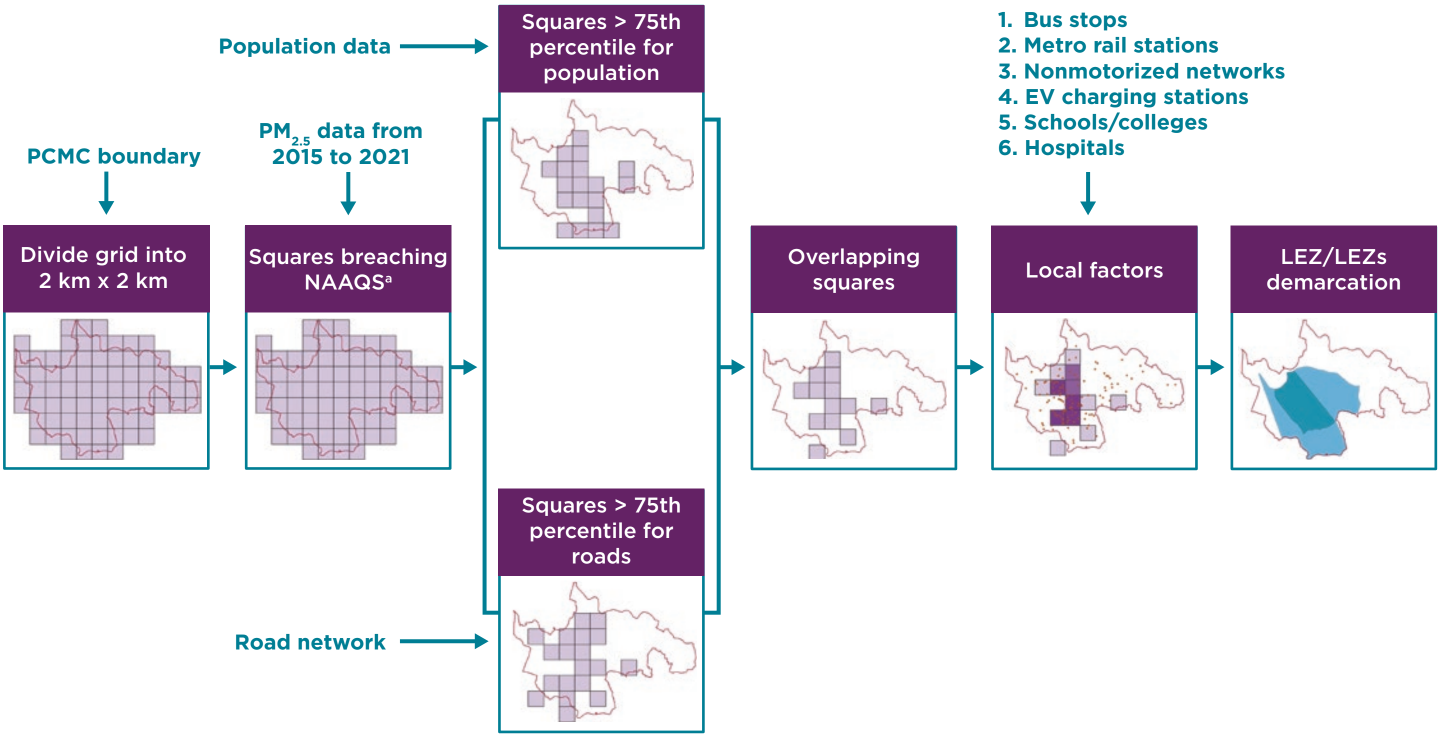
The PCMC was divided into a grid of squares measuring 2 km x 2 km. Relevant data was gathered from various secondary data sources and computed for each square in the grid. This data included levels of fine particulate matter ($PM_{2.5}$), population, kilometers of road categorized by class (arterial, sub-arterial, and minor) and local infrastructure-related factors.

Grid squares were considered for next-stage processing if the annual National Ambient Air Quality Standards for $PM_{2.5}$ levels were breached every year from 2015 to 2021. Next, we identified the squares that ranked above the 75th percentile (or in the top

25%) for population and above the 75th percentile for kilometers of roads.[1] Top-ranked squares that overlapped for population and roads were considered for the next stage of processing. The final demarcation process considered other factors obtained from open-source literature and city records, such as the locations of EV chargers, bus stops, walking and biking paths, schools, and hospitals. Further information about the selection and sources of data used in the evaluation are detailed in Appendix A.

Figure 1

Process flowchart for identifying potential areas for a low-emission zone in Pimpri Chinchwad Municipal Corporation



ª National Ambient Air Quality Standard

Notes: The criteria for filtering can be adjusted depending on the proportion of emissions to be targeted. In this paper, the 75th percentile was used to ensure at least 25% of total emissions from the city would be addressed, which we confirmed through an emissions inventory. These values can vary between cities. A lower percentile value can allow for a larger geographical area resulting in a higher share of emissions being addressed, and vice versa. The final area selection depends on emissions and other factors.

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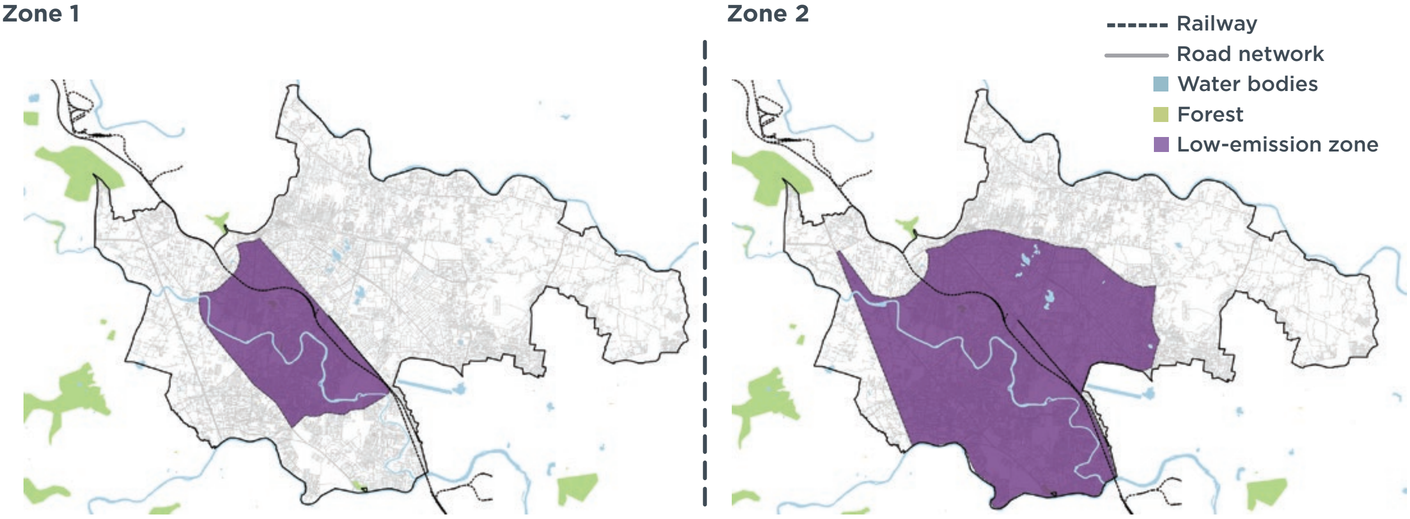
We identified two geographic options for a designated LEZ, one smaller and one larger. Figure 2 shows the boundaries of the PCMC and the potential areas of the LEZ. The total area of Zone 1 is 29 km^2 and covers 15.6% of the PCMC. Zone 2, which includes all of Zone 1 and surrounding areas, is almost 3 times larger at 88 km^2 and covers 47.5% of the PCMC. A smaller geographical area can be a good starting place for the city to establish an LEZ, assess challenges concerning implementation and compliance, and receive feedback. However, the zone with a larger geographical area is more likely to result in the adoption of clean technology vehicles, as commuters are less likely to take alternate routes to avoid entering the zone (Yanocha et al., 2023). Consequently, the larger LEZ will have a greater impact on air quality and public health (Lee et al., 2021). The final selection of the LEZ area will depend on several factors, such as the severity

1 Percentile is a statistical measure that shows the position of a value within a specific dataset, indicating the percentage of data points that are lower. For example, the 75th percentile means that 75% of the values in the dataset are below that point.

of the pollution, the city's readiness or preparedness—including the availability of financial resources—along with willingness to act at administrative and political levels and local support. The legal process for designating an area as an LEZ in Indian cities is detailed in Dhole et al. (2023).

Figure 2

Geographic areas of a potential low-emission zone in the Pimpri Chinchwad Municipal Corporation



Notes: Zone 1 includes Pradhikaran, Pimpri, Chinchwad Gaon, Kalewadi, Theragaon, Rhatani, Pimple Saudgar, and Pimple Gurav. Zone 2 includes the areas in Zone 1 in addition to Nigdi, Ravet, Bhosari, Moshi, Pimple Nilakh, and Wakad.

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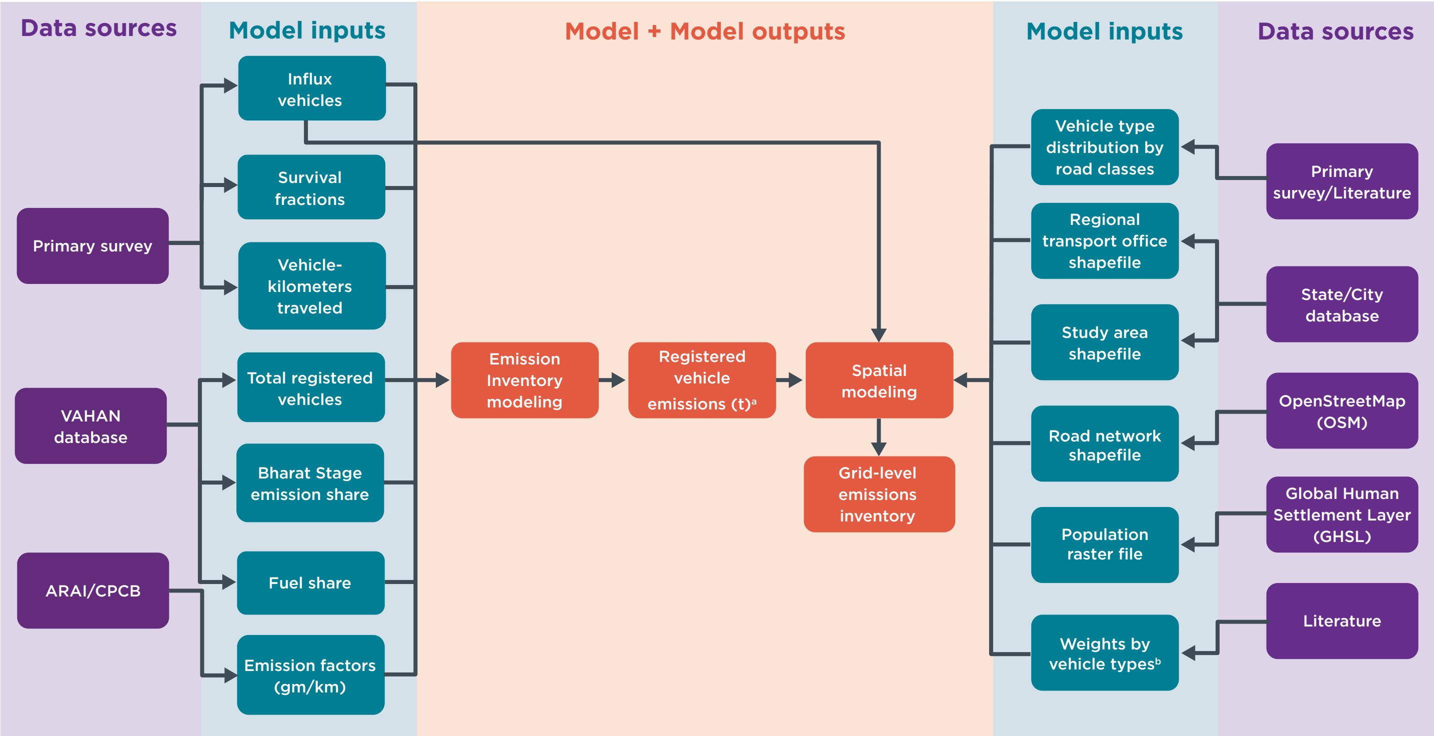
MULTIPOLLUTANT EMISSIONS INVENTORY

This study employed the activity, structure, intensity, and fuel (ASIF) framework (Schipper & Lilliu, 1999) and geospatial modeling techniques to quantify city-level emission loads. The ASIF framework broadly quantifies emissions based on vehicle activity, the structure or share of different modes in the vehicle fleet, the fuel intensity of each mode, and emissions from fuel. Further intricacies of the approach are elaborated in Guttikunda & Calori (2013) and used similarly in this study.

Figure 3 details the methodology and information gathered for developing a comprehensive city-level emission inventory. Interviews were conducted at fuel stations and parking lots as part of a survey to determine the characteristics of internal combustion engine (ICE) vehicles operating in the city. The survey collected information on vehicle type, vehicle age, fuel used, daily distance traveled, fuel economy, and weekly spending on fuel. Information on 4,000 vehicles of all types—in nine categories ranging from heavy trucks to two-wheelers—was collected from eight locations.

Figure 3

Methodology and information flow chart for developing gridded city-level multipollutant emissions inventory



[a] Includes emissions only from vehicles registered within the MH-14 regional transportation office.
[b] Total emissions by vehicle type are allocated to the grid with weights assigned to each vehicle type based on population and road network.
Data sources: Ministry of Road Transport and Highways (n.d.), Automotive Research Association of India (2008), Central Pollution Control Board (2015), OpenStreetMap Contributors (n.d.), Schiavina et al. (2023).

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An F-test was conducted to test the variance of the age distribution of the 4,000 vehicles included in the survey. The results indicated no statistically significant difference, meaning that the F-test did not find strong evidence indicating that the share of sample vehicles in each age interval would differ from the age shares for all vehicles in the city. Therefore the information collected from these eight locations was considered to be representative of the fleets in the PCMC (Goel et al., 2015).

Information about total vehicles registered across all types on an annual basis was retrieved from the VAHAN database, which is the national vehicle registry maintained by the Ministry of Road Transport and Highways, and the MH-14 Regional Transport Office (RTO). The MH-14 RTO is responsible for overseeing vehicle registrations in the PCMC area, along with 10 other regions of Maharashtra state, and these vehicles use the MH-14 registration code. More than 2 million vehicles were registered with the MH-14 code between 2000 and 2023, with two-wheelers consistently making up 57%–77% of total yearly registrations. Electric vehicles accounted for 10% of the total registrations in 2023.

Emission factors for the Indian fleet were sourced from reports by the Automotive Research Association of India (2008) and the Central Pollution Control Board (2015). Missing emission factors were derived using simple machine-learning models, such as ordinary least squares regression and polynomial regression, and the reduction factor method (Raparthi et al., 2021; WWF-India & Automotive Research Association of India, 2022). It is important to note that the emission factors used in the paper are based on chassis dynamometer tests that have shown limitations in accurately reflecting real-world emissions. A recent study by The Real Urban Emissions Initiative used remote-sensing technology to examine emissions from vehicles operating in the Indian cities of Delhi and Gurugram.[2] The study found real-world emissions were up to 14.2 times higher than those recorded under laboratory conditions (Narla et al., 2024).

Estimated emission loads were spatially distributed across the PCMC area to develop a gridded city-level emission inventory. As part of the geospatial modeling, emission shares for each vehicle type were weighted according to population and to information about the length and class of roads in each square of the grid. Road network data was collected from OpenStreetMap (n.d.). Population information was sourced from the Joint Research Centre's Global Human Settlement Layer database for 2020 (Schiavina et al., 2023). Further details on the intricacies of spatial distribution are discussed in Hakkim et al. (2021).

EMISSION LOADS FOR BASE YEAR 2023

Historical data for vehicle registrations from 2000 through 2023 were obtained from the VAHAN database and classified according to nine vehicle types for this paper: two-wheelers, three-wheelers, light motor vehicles (personal cars), light passenger vehicles (taxis), light goods vehicles, medium goods vehicles, heavy goods vehicles, medium passenger vehicles, and heavy passenger vehicles.[3] To eliminate any inconsistencies in the data, a 5-year-moving-window average—a method to smooth out fluctuations in data to reveal the long-term trend—was calculated. In this paper, it involves calculating the average number of total vehicles registered over 5-year windows and progressively moving the window one data point at a time along the time series. The data was then analyzed for trends by computing the year-over-year growth rate. The mean growth rate was used to predict future vehicle registrations. The share of projected registrations for vehicles by fuel type was assumed to be similar to the share for the years 2022 and 2023. The calculations of emission loads for the future years were performed as detailed in the previous section.

Table 1 summarizes the total estimated emission loads emanating from vehicle tailpipes within the Zone 1 and Zone 2 LEZ boundaries for the 2023 baseline year. About 26%–28% of emissions in the PCMC originate in Zone 1. The larger Zone 2 accounts for approximately 62%–64% of total tailpipe emissions in the PCMC. Information on vehicle-kilometers traveled (VKT) and vehicle-specific survival rates used in the emissions inventory analysis are provided in Appendix B.

Table 1
Tonnes of tailpipe emissions in 2023

	Particulate matter	Nitrogen oxides	Carbon monoxide	Hydrocarbons
Zone 1	86	1,393	2,468	690
Zone 2	203	3,150	5,771	1,596
Entire PCMC	327	5,374	9,212	2,517

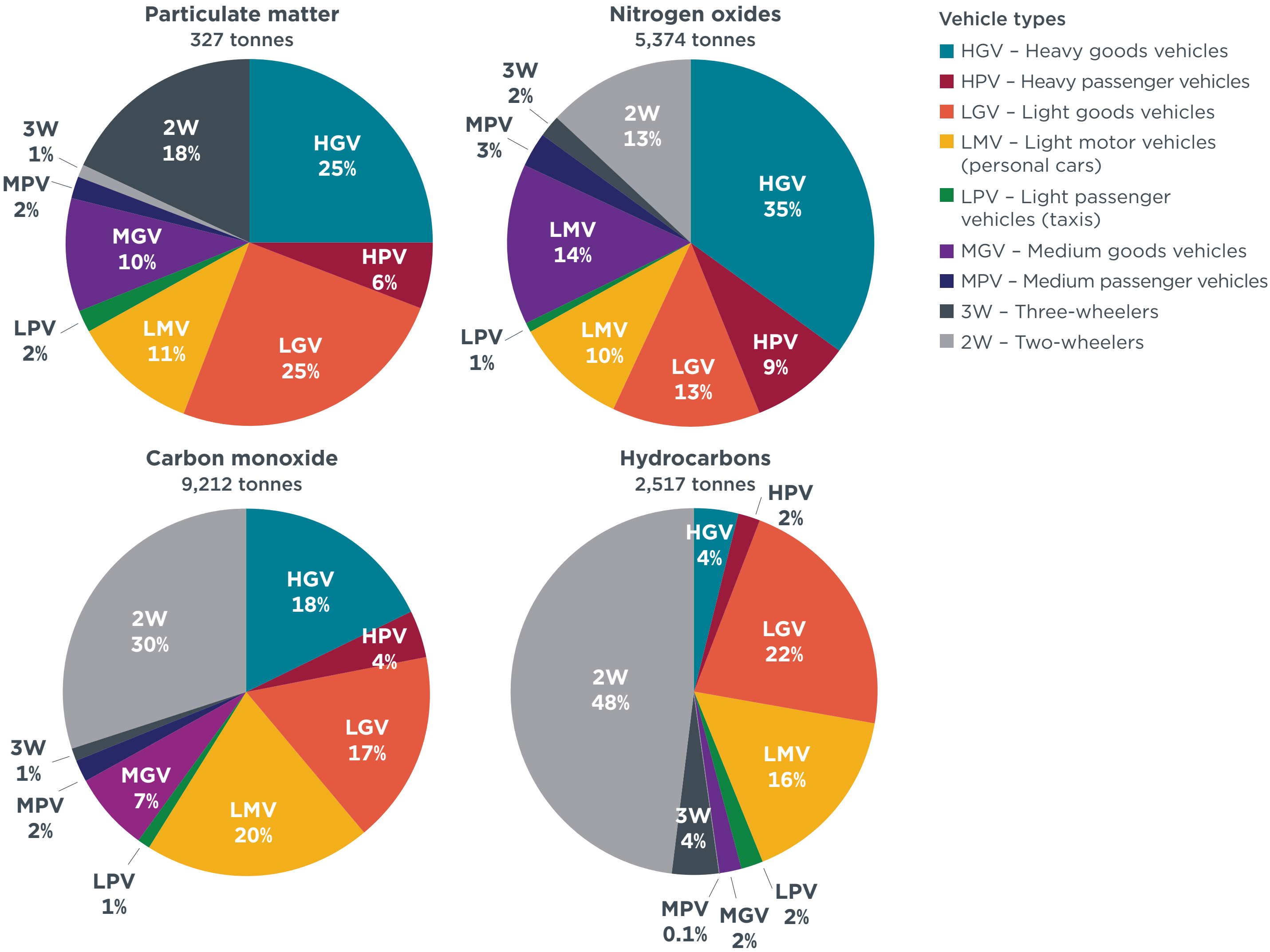
Figure 4 shows the share of air pollutants attributable to each vehicle type in 2023. Heavy goods vehicles, light goods vehicles, and two-wheelers were the top contributors to pollution among the nine categories. Heavy goods vehicles accounted for a significant share of PM and NO_x emissions as the vehicles are powered by diesel.

2 Remote-sensing technology is a nonintrusive method for collecting a snapshot of tailpipe emissions from a vehicle driving past a sampling location. The technology uses absorption spectroscopy to measure emissions accurately. Information about vehicle speed, acceleration, and license plate are also captured (Narla et al., 2024).

3 For both passengers and goods, light-duty vehicles have a gross vehicle weight (GVW) of less than 3.5 tonnes, medium-duty vehicles have a GVW above 3.5 tonnes but below 12 tonnes, and heavy-duty vehicles have a GVW exceeding 12 tonnes.

The primary survey showed that approximately 75% of all heavy goods vehicles operating in the study area are registered with RTOs other than MH-14. To avoid underestimating the emission loads, we consider the contribution of emissions from these vehicles—in addition to the emissions from vehicles registered by the MH-14 RTO—to the total loads.

Figure 4
Share of 2023 emission loads by vehicle type in the Pimpri Chinchwad Municipal Corporation



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The survey also found that over 90% of three-wheelers in operation within the city use compressed natural gas (CNG). The three-wheelers are responsible for a minimal emissions share, despite their high VKT and relative age compared with other vehicle categories, because they account for fewer than 5% of registrations. This preference for CNG can be attributed to its high fuel efficiency and to a well-developed CNG refueling infrastructure throughout the city. Likewise, light passenger vehicles, which is the category for taxis, also contributed minimally to emissions; these vehicles must be retired after completing 9 years of service, as mandated by the Maharashtra City Taxi Rules (Khatua, 2017), resulting in higher turnover and the introduction of newer and more efficient models.

Most CO and HC emissions came from gasoline-powered vehicles, such as two-wheelers and passenger cars in the light motor vehicle category. Although the emission standards for two-wheelers have become more stringent over the years (Dallmann & Bandivadekar, 2016), these vehicles still accounted for most of the CO and HC emissions, mainly because of their larger share of the vehicle stock. The higher proportion of CO coming from light- and heavy-duty vehicles can be attributed to the unchanged emission limit from Bharat Stage (BS) IV to BS VI standards (Dallmann & Bandivadekar, 2016; Sathiamoorthy et al., 2021).

Further, it was observed that diesel vehicles—particularly heavy goods vehicles, light goods vehicles and light motor vehicles—contributed disproportionately higher levels of PM and NO_x compared to their gasoline and CNG counterparts. In the case of CO, both diesel and gasoline vehicles exhibited similar contributions. Among gasoline vehicles, two-wheelers and light motor vehicles were the main contributors to CO, while heavy goods vehicles and light goods vehicles were the primary sources among the diesel vehicles. Although diesel vehicles generally emit less CO than gasoline vehicles, the diesel vehicles here show higher levels of CO emissions because there has been no improvement in CO standards for diesel vehicles. In the case of HC, two-wheelers stand out as the disproportionately higher contributor. A detailed breakdown of emissions share by vehicle and fuel type is provided in Appendix C.

Figures 5a and 5b show the share of the emission loads based on vehicle age and BS emission standards for each vehicle type. To help understand the relative proportions of emissions attributable to each vehicle type, we normalized emissions loads across pollutants to a consistent scale of 0 to 10. Using the min-max scaling technique, emissions were then aggregated across the categorical variables for age and emissions standard. The results are summarized below.

Results by age:

» Approximately 36% of vehicles in operation were between 5 and 10 years old. These vehicles were responsible for 42% of the total normalized emissions.

» Vehicles 10–15 years old accounted for 28% of total vehicles and 32% of total normalized emissions.

» Vehicles 0–5 years old accounted for 26% of the total vehicles but were responsible for 18% of total normalized emissions.

» Vehicles more than 15 years old were 10% of the total number of vehicles but contributed 8% of total normalized emissions.

Results by emission standard:

» The greatest share of all vehicles, 39%, are certified to BS IV emission standards; these vehicles contributed 27% of normalized emissions.

» About 34% of vehicles are certified to BS III standards and contribute 53% of the normalized emissions.

» Another 14% of the vehicles are certified to the most recent BS VI standards, and they contributed 14% of normalized emissions.

» The remaining vehicles, 13%, are certified to BS II and BS I standards, and they contribute 6% of the normalized emissions.

Figure 5a

Share of emission loads for each vehicle type by standard in 2023

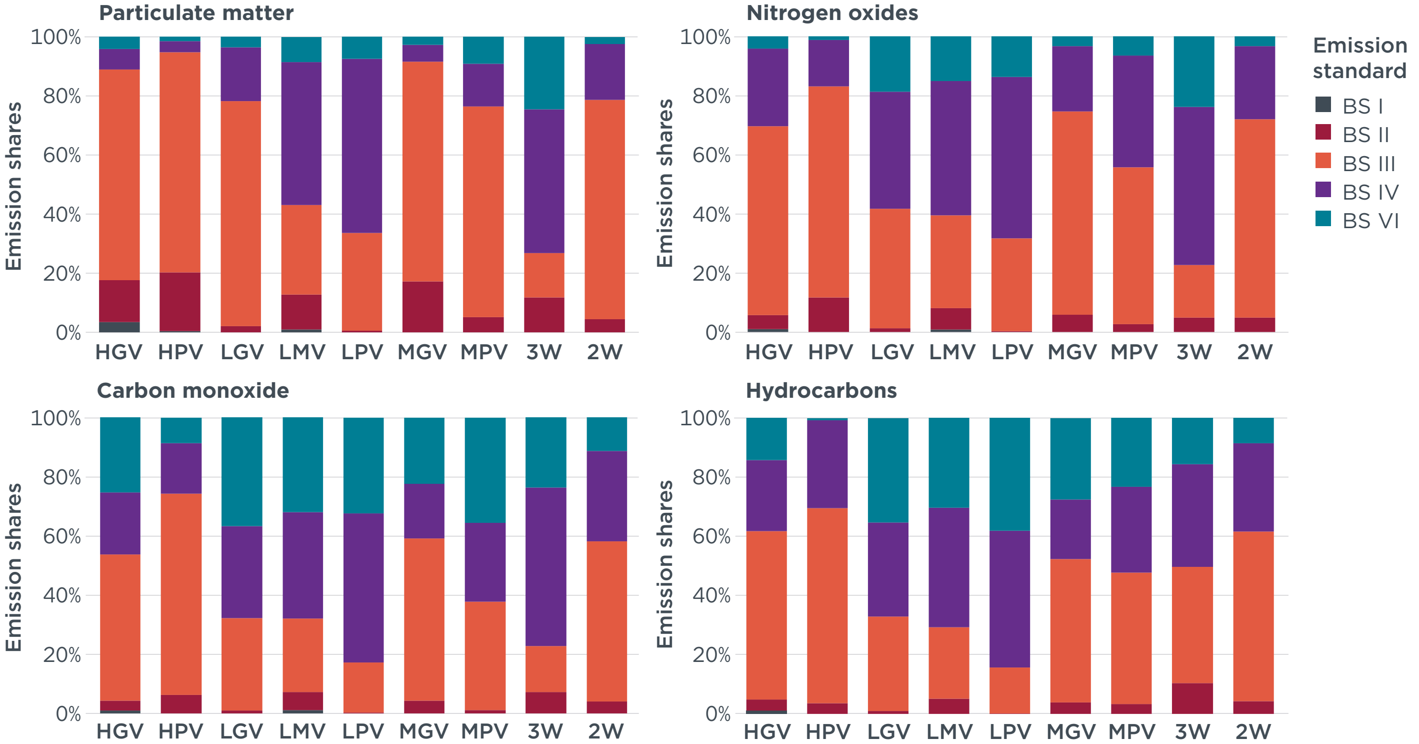
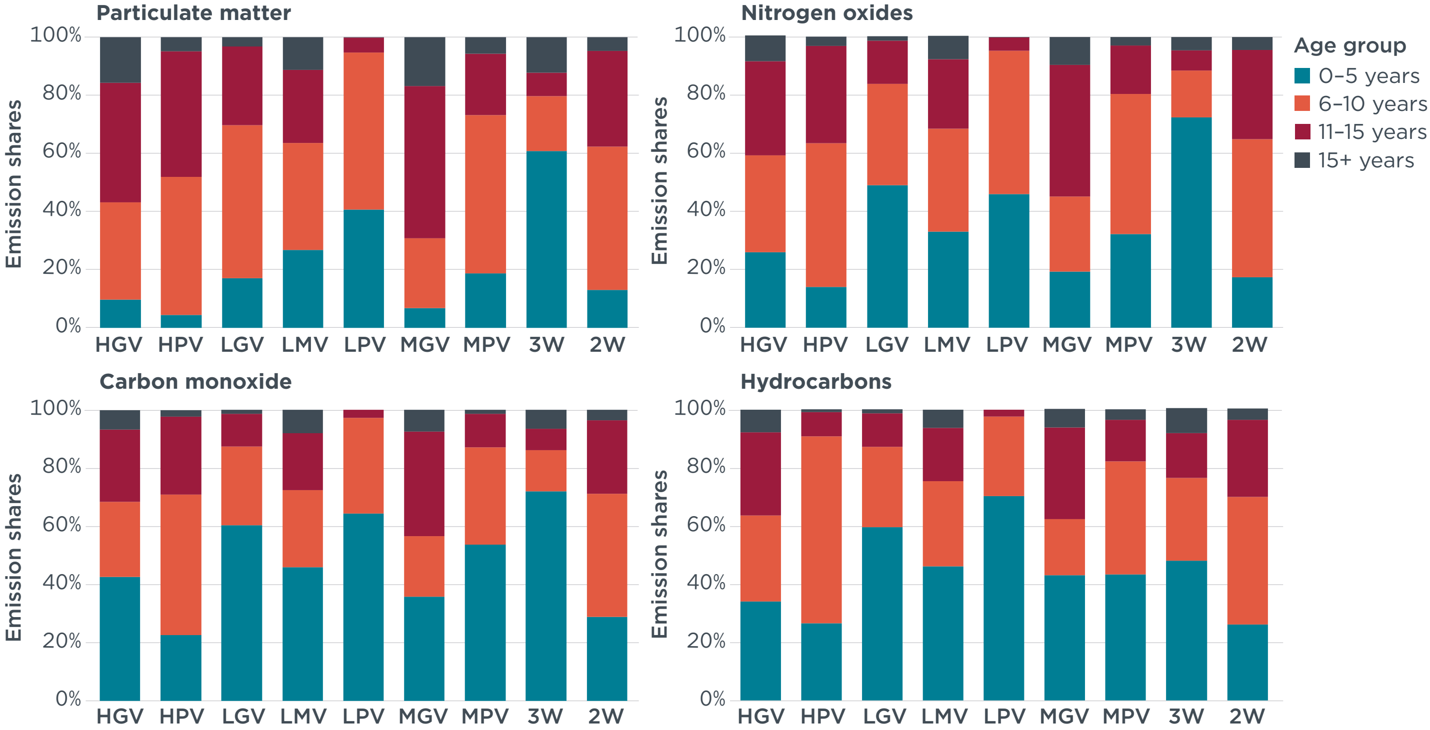


Figure 5b

Share of emission loads for each vehicle type by age group in 2023



Note for Figure 5a and Figure 5b: Bars show how much vehicles of different ages and standards contribute to the total emission loads for each vehicle type. For example, heavy goods vehicles certified to BS III standards are responsible for 71% of the total particulate matter emissions generated by all vehicles in the heavy goods vehicle segments.

Abbreviations: HGV – heavy goods vehicles; HPV – heavy passenger vehicles; LGV – light goods vehicles; LMV – light motor vehicles (personal cars); LPV – light passenger vehicles (taxis); MGV – medium goods vehicles; MPV – medium passenger vehicles; 3W – three-wheelers; and 2W – two-wheelers.

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The high share of vehicles certified to BS III and BS IV standards is related to the early rollouts of these models and the continued availability of BS III vehicles for purchase until 2017. In the PCMC, vehicles being registered for the first time had to adhere to nationwide BS IV standards beginning in 2017. However, a judicial ruling ordered the neighboring city of Pune, along with 13 other cities and the National Capital Region, to end BS III vehicle registrations in 2010. As a result, BS IV models started operating in Pune and surrounding areas years earlier than in other parts of the country. Nevertheless, the initiative to end BS III sales in Pune did not gain momentum as expected, primarily due to the lack of available fuel compatible with BS IV vehicles. The operation of BS IV vehicles with BS III fuel can severely degrade vehicle performance (Shah, 2017). The nationwide rollout of emission standards, including in major Indian cities, is detailed in Narla et al. (2024).

The results summarized above by vehicle age and emission standards reveal two key factors influencing the total emissions: the total number of vehicles and the pollution levels per vehicle. A large fleet of clean vehicles can have a similar or even greater effect on emissions than a smaller fleet of highly polluting vehicles. This emphasizes the benefits of transitioning to zero-emission vehicles rather than solely relying on advancements in ICE technologies. These results suggest putting a priority on phasing out older vehicles within an LEZ would be beneficial for improving air quality. This is because the exhaust after-treatment systems of the older vehicles are likely to degrade with their use, making them less effective at controlling emissions; mechanical wear and tear accumulates with age and further contributes to emissions; and vehicles approaching end-of-life experience a general decline in emission performance (Borken-Kleefeld & Chen, 2015).

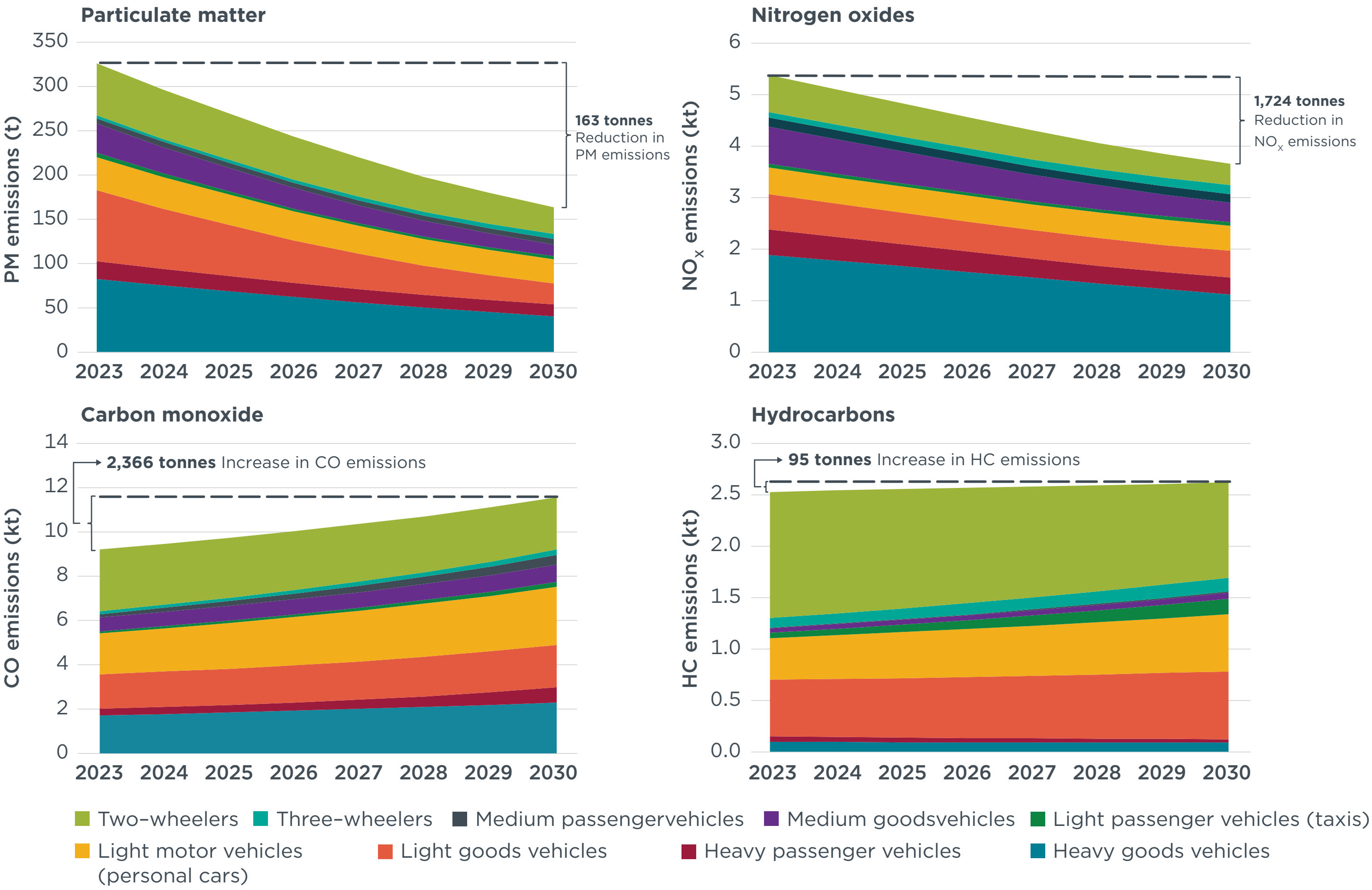
NO LEZ SCENARIO: PROJECTED EMISSION LOADS THROUGH 2030

Emission loads are projected until 2030 using the base year of 2023. Projections beyond 2030 were avoided to prevent potential anomalies stemming from future vehicle-related policies, such as possible improved emission standards in the coming years. Also, over the last two years, EV sales have increased to account for approximately 10%–11% of total registrations of all vehicles in the MH-14 RTO, though the percentage may vary for individual vehicle types. With the push toward policies and strategies promoting EVs at both national and subnational levels, EVs are likely to make up an increasingly significant portion of the total operational fleet. Therefore, projecting emissions beyond 2030 based on current conditions may not yield accurate results.

The projected emission loads show levels of PM and NO_x diminishing between 2023 and 2030, even under the No LEZ Scenario. However, a different trend is observed for HC and CO, with these levels staying nearly flat or rising. These projections are consistent with changes in India's emission standards for vehicles. The BS VI standard resulted in improvements in PM and NO_x emissions for all vehicles in India. However, CO emissions improved only for two-wheelers under the BS VI standard, and HC emissions improved only for heavy-duty vehicles (Dallmann & Bandivadekar, 2016). Figure 6 provides a breakdown of emission load projections by pollutant and vehicle type if an LEZ is not established in the PCMC. By 2030, emissions of PM are reduced by up to 50%, while NO_x exhibits a decrease of up to 32% compared to the base year. Conversely, CO emissions increase by 25% and HC emissions increase by 3%.

Figure 6

Projected emission loads in the Pimpri Chinchwad Municipal Corporation through 2030 under the No LEZ Scenario



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The projected relative contribution of different vehicle types to pollutant emissions varies for the year 2030 compared with 2023. Light motor vehicles exhibit an increase in relative emissions share across all pollutants, due to their increased vehicle share. However, two-wheelers exhibit a decreasing relative share of pollutants, even though two-wheeler registrations are twice the share of light motor vehicles. This can be attributed to the higher proportion of two-wheelers on the road that are certified to the more recent emission standards. Conversely, three-wheelers show increasing emissions across all pollutants because these vehicles tend to stay in use much longer than other vehicle types. (See Figure B1). Although heavy goods vehicles are projected to remain primary contributors to PM and NO_x emissions, their contribution to PM remains stable, while their relative contribution to NO_x emissions decreases compared to the base year due to the share of the vehicles certified to BS VI emission standards. Despite an overall increasing trend in CO and HC emissions, two-wheelers are projected to remain the primary contributor for CO and HC, but emissions of these gaseous pollutants by two-wheelers declined 15% and 24%, respectively. Further details are provided in Appendix D.

Figures 7a and 7b depict the relative share of emissions from 2023 to 2030 categorized by emission standards and age intervals. In 2023, BS VI vehicles accounted for 4%–24% of emissions for the four pollutants, and this share is projected to rise to 35%–73% by 2030. Despite improvements in PM and NO_x emission limits in the BS VI standards across all vehicle types, their relative share of emissions is projected to increase gradually over the years, albeit with a reduction in absolute value. However, this improvement eventually plateaus, leading to a resurgence in absolute emissions. This indicates the need to consider enhanced emission standards and stronger incentives to encourage the adoption of ZEVs. Conversely, the emission shares of vehicles not certified to BS VI emission standards is projected to decline over the years (Figure 7a), along with the number of pre-BS VI vehicles, due to fleet turnover. For emissions categorized by vehicle age group (Figure 7b), vehicles aged 15 years or older are projected to be responsible for an increasing share of emissions over the years, while vehicles under 15 years old exhibit a fluctuating trend.

Figure 7a

Projected share of emissions by standard for each year across all vehicle types in the No LEZ Scenario

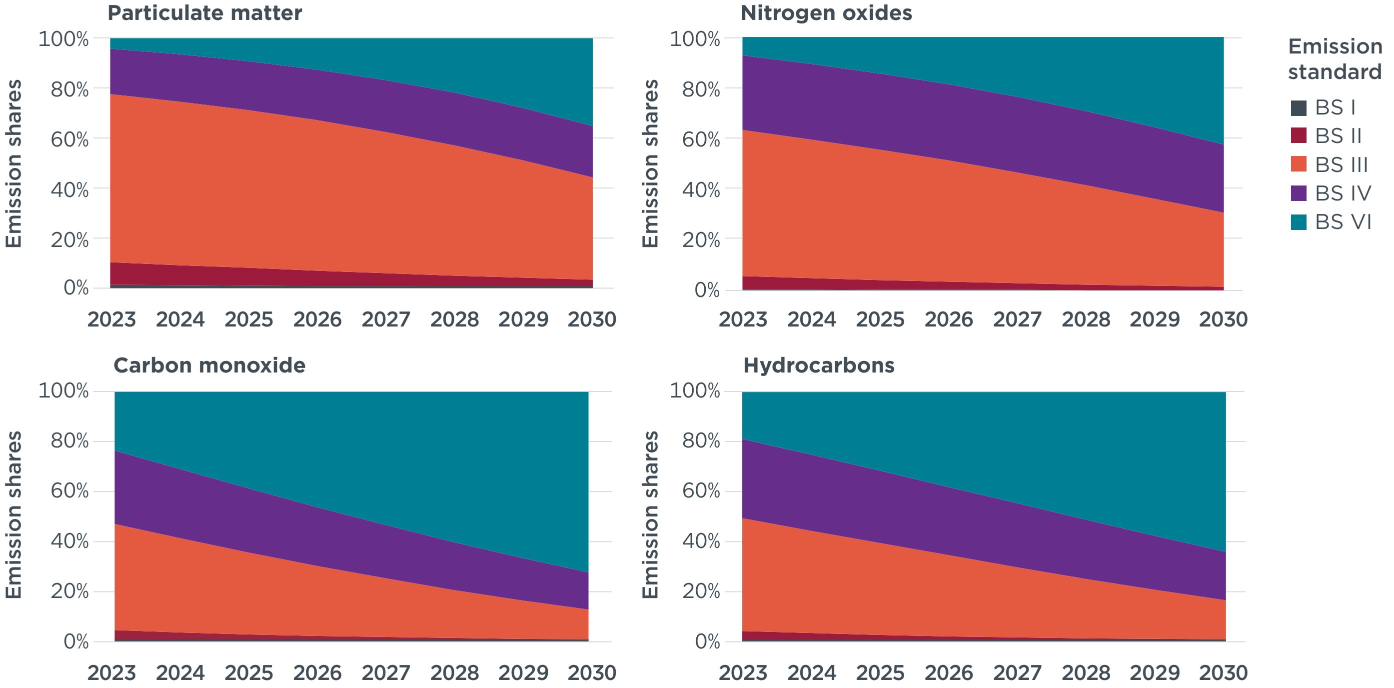
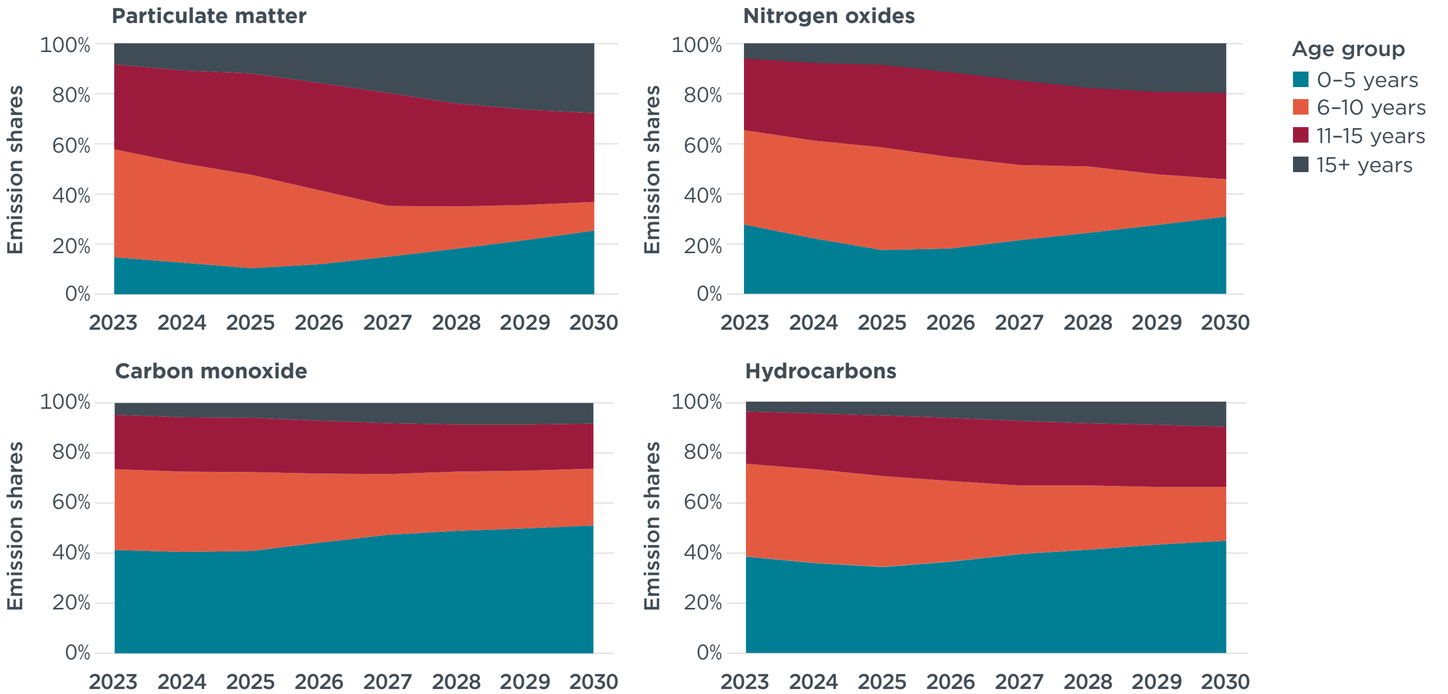


Figure 7b

Projected emission shares by age group for each year across all vehicle types in the No LEZ Scenario

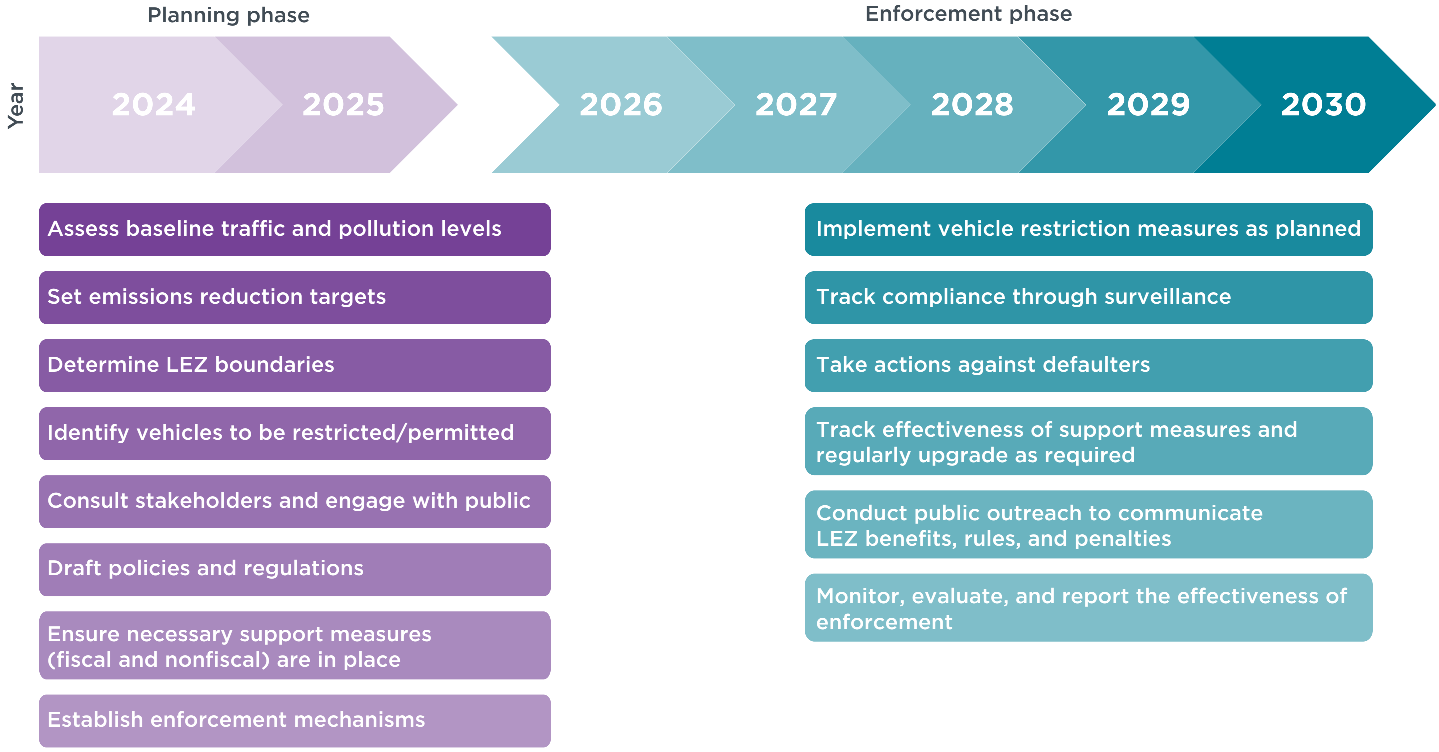


LOW-EMISSION ZONE SCENARIOS: TIMELINE AND RESTRICTIONS

Figure 8 details a potential roadmap for the timeline of actions to be taken for implementing an LEZ. For this study, the enforcement of an LEZ is assumed to begin in 2026. Planning for LEZ implementation would occur during 2024 and 2025. During this planning phase, the city would need to define the objectives for creating an LEZ, map the boundary, develop a policy framework and regulations, establish fiscal and nonfiscal measures to encourage compliance, and install signage and surveillance technology. As part of this process, the city would consult with stakeholders, conduct outreach, and build up its own capacity for implementing and administering the LEZ. Although the allocated timeline in this roadmap may be insufficient, an ambitious model timeline was selected because of the urgency of addressing air pollution.

Figure 8

Roadmap of timeline and actions to be considered for implementing a low-emission zone



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To comprehend the impact of LEZ measures on emissions, two sets of vehicle restriction scenarios were analyzed—one based on vehicle age and the other based on emission standards. Both scenarios have three sub-scenarios. These restrictions were contemplated by considering similar measures implemented in other Indian cities.

The Age-Based Scenario bars older vehicles of all types from the LEZ starting in 2026, including vehicles more than 15 years old if they use gasoline, compressed natural gas (CNG), or liquefied petroleum gas (LPG), and diesel vehicles more than 10 years old (see Table 2). The age restrictions are tighter for diesel vehicles because of their expected higher pollutant emissions. The Delhi government implemented similar restrictions starting January 1, 2022, in adherence to a judicial ruling (Government of National Capital Territory of Delhi, 2021).

The Standard-Based Scenario restricts vehicles across all categories based on BS emission standards (see Table 2). Each stage of the scenario restricts vehicles of progressively newer emission standards to target older and more polluting vehicles. This approach is similar to that in LEZ studies conducted by the ICCT for European cities (Lee et al., 2021; Nepali et al., 2023). In Delhi, a comparable regulation was enforced for a limited time as a component of the Graded Response Action Plan for 2023, an emergency response mechanism designed to combat poor air quality in the region (Commission for Air Quality Management, 2023). Under this plan, only diesel vehicles certified to the latest BS VI standards, along with gasoline vehicles of BS IV standards and above, were permitted to operate when the pollution levels breach the set limits.

Table 2

Age-based and emission standard-based restriction scenarios considered for the low-emission zone

Year of enforcement	Age-Based Scenario: Oldest vehicle year to be permitted in LEZ		Standard-Based Scenario: Minimum Bharat Stage to be permitted in LEZ	
	Gasoline/CNG/LPG[a]	Diesel	Gasoline/CNG/LPG[a]	Diesel
2026	2011	2016	BS II	BS III
2027	2012	2017	BS II	BS III
2028	2013	2018	BS III	BS IV
2029	2014	2019	BS III	BS IV
2030	2015	2020	BS IV	BS VI

[a] CNG is compressed natural gas; LPG is liquified petroleum gas.

Table 3 outlines three sub-scenarios based on how vehicle owners might respond following the restriction of their noncompliant vehicles from the LEZ. These sub-scenarios were considered based on previous LEZ studies by the ICCT (Bernard et al, 2020; Lee et al., 2021; Nepali et al., 2023; Lee et al., 2024).

Table 3

Sub-scenarios applied under each restriction scenario

Sub-scenarios	Description	Age-Based Scenario	Standard-Based Scenario
No LEZ	Business as usual with natural fleet turnover		
Sub-scenario 1 (SS1)	Vehicle owners **shift to used ICE vehicles** of the same fuel type to ensure the bare minimum requirement of the LEZ.	Owners of gasoline, CNG, and LPG vehicles shift to 8-year-old models; owners of diesel vehicles shift to 5-year-old models.	Owners shift to the newest pre-owned vehicle meeting the required standard; if BS VI is required, owner shifts to oldest pre-owned vehicle.[a]
Sub-scenario 2 (SS2)	Vehicle owners **shift to new ICE vehicles** of same fuel type. All new vehicles meet BS VI standards.		
Sub-scenario 3 (SS3)	Vehicle owners **shift to zero-emission vehicles**.		

Note: Noncompliant ICE vehicles are those that are restricted from entering the LEZ.

[a] Beginning in April 2020, all new vehicles sold in India must meet BS VI standards, ending new-vehicle sales of BS IV and earlier models. (There is no BS V.) In our LEZ scenario, for example, if the owner of a noncompliant vehicle must shift to BS IV, then a pre-owned BS IV model from 2020 is procured. If the noncompliant vehicle must be swapped for a BS VI, a pre-owned model from 2020 is assumed.

We make several assumptions in the LEZ impact analysis. We assume the overall vehicle stock remains constant for all scenarios and sub-scenarios and is not impacted by the LEZ. In addition, we assume owners of vehicles that do not comply with the restrictions will not seek alternate routes to avoid violating the LEZ regulations. Instead, the owners and drivers will acquire vehicles that comply with the restrictions and continue operating within the LEZ. The percentage of vehicles continuing to operate, rather than be retired or scrapped, is assumed to remain the same for first-owner vehicles, second-owner or used vehicles, and EVs. In addition, the influx of vehicles registered with RTOs other than the MH-14 RTO into the study area does not alter the relative mix of vehicle ages and of vehicles meeting different emission standards. Finally, the proportion of influx vehicles registered outside the MH-14 RTO area is assumed to remain constant throughout the projected years.

LOW-EMISSION ZONE SCENARIOS: PROJECTION OF EMISSION LOADS THROUGH 2030

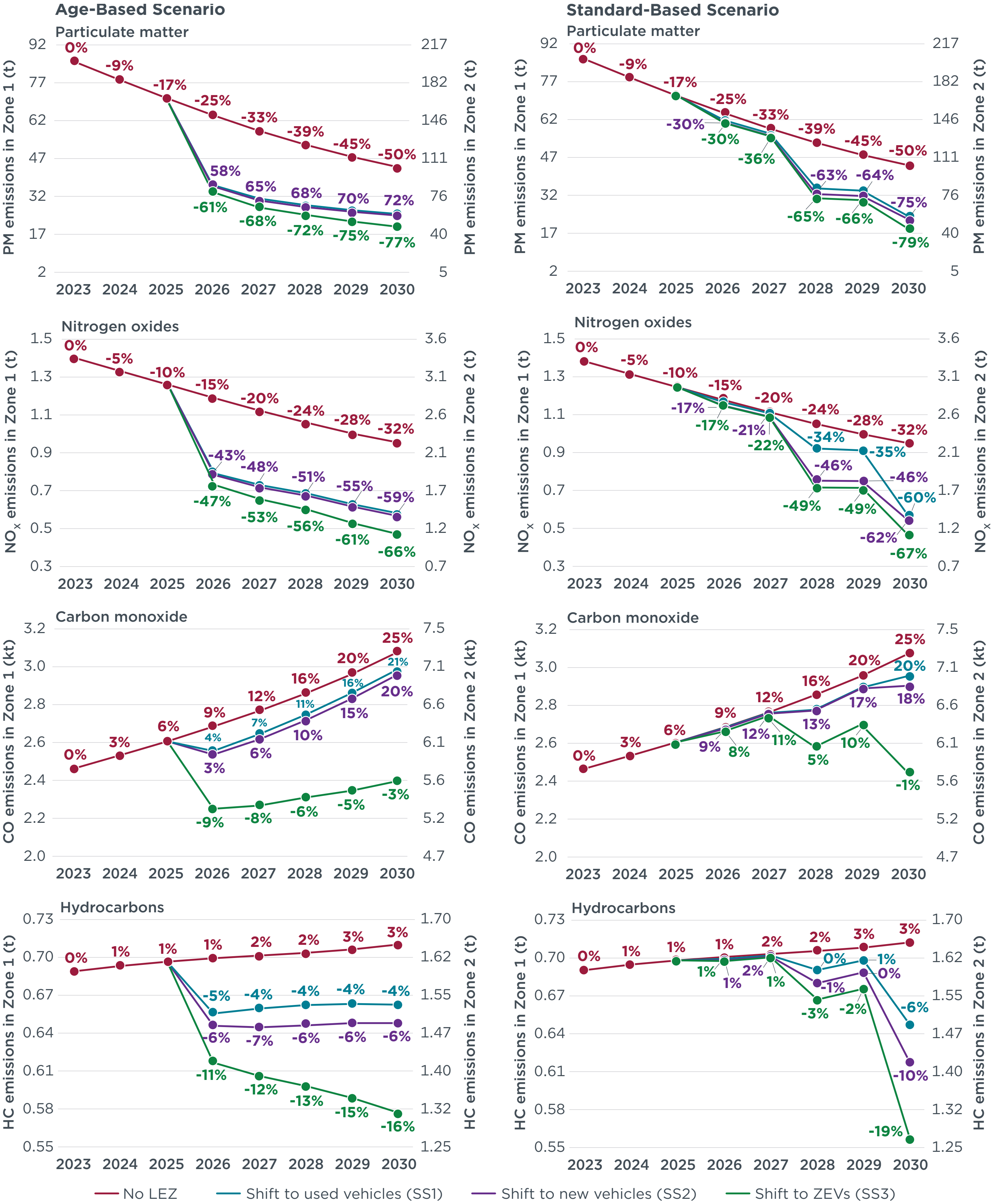
Figure 9 illustrates the impact of implementing vehicle restriction measures on emission loads. The values in the figure correspond to the results within the identified LEZ, Zone 1 or Zone 2, rather than the entire PCMC area. Under both restriction scenarios, the most significant improvements are observed for PM and NO_x. Emissions from these two pollutants would decline in the No LEZ Scenario, but an LEZ could lead to further reductions of up to 30% for PM and 35% for NO_x in 2030, for a total reduction up to 79% for PM and 67% for NO_x compared with the 2023 base year.

The emission loads of CO increase over the years, even when owners replace their compliant vehicles with used vehicles (SS1) and new vehicles (SS2). Nevertheless, the CO emission loads are 5%–7% less in 2030 than it would be under the No LEZ Scenario. If vehicle owners were to replace their noncompliant ICE vehicles with ZEVs (SS3), CO emission loads would drop by 22%–24% in 2030 compared with the No LEZ scenario.

A similar trend is observed for HC. For the year 2030, the improvement in HC emissions because of the shift in ICE vehicles ranges from 7% to 9% in the Age-Based Scenario and from 9% to 13% in the Standard-Based Scenario compared with the No LEZ Scenario. If owners of noncompliant vehicles switch to ZEVs (SS3), the HC emission load would be 20%–22% lower in 2030 compared with the No LEZ Scenario.

Figure 9

Impact on emission loads under the Age-Based and Standard-Based scenarios



Notes: All percentage changes in emissions are relative to 2023 and are the same for both zones. Changes in tonnes of emissions are greater in Zone 2.

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Figure 9 and Table 4 show that the Age-Based Scenario achieves a greater reduction in total emissions compared with the Standard-Based Scenario. The term "total emissions" refers to the total combined mass of all the individual pollutants. The greater improvement can be attributed to the initial high turnover of vehicles that are too old to enter the LEZ; approximately 61 times more vehicles are swapped for a more efficient technology at the outset of the Age-Based Scenario in 2026 compared with the Standard-Based Scenario. The situation is reversed by 2030, with a higher number of vehicles being swapped under the Standard-Based Scenario, leading to higher emission reductions across most pollutants for that year. Nevertheless, when considered at an aggregate level, the Age-Based Scenario still results in approximately 5% more vehicle transitions from 2026 to 2030 when compared with the Standard-Based Scenario.

Table 4

Potential emission reductions from 2026 to 2030 under different low-emission zone scenarios compared with the No LEZ Scenario

Restriction scenario	Sub-scenario	Reduction in emissions				Total reduction in emissions
		Particulate matter	Nitrogen oxides	Carbon monoxide	Hydrocarbons	
Age-Based Scenario	SS1—shift to used vehicles	45%	35%	4%	6%	12%
	SS2—shift to new vehicles	46%	36%	5%	8%	13%
	SS3—shift to ZEVs	52%	43%	19%	15%	24%
Standard-Based Scenario	SS1—shift to used vehicles	22%	12%	2%	3%	4%
	SS2—shift to new vehicles	25%	19%	2%	4%	7%
	SS3—shift to ZEVs	28%	22%	8%	6%	11%

Note: Percentage reductions in emissions are based on the mass of the pollutants.

In the early years of the LEZ, interventions under the Standard-Based Scenario have a minimal effect on vehicle turnover and on reducing emissions, primarily because there are few pre-BS III vehicles on the road. Restrictions under this scenario do not change in 2027 and 2029, resulting in higher emissions during this period. It is not until 2030—when the dominant BS III gasoline vehicles and BS IV diesel vehicles are exchanged for more efficient alternatives—that the highest reduction in emissions is achieved under the Standard-Based Scenario. In contrast, the Age-Based Scenario consistently reduces emissions from the beginning of the LEZ, driven by a significant number of noncompliant vehicles transitioning to cleaner alternatives every year. Furthermore, among the three sub-scenarios, the transition to ZEVs (SS3) demonstrates the greatest potential for reducing emissions across all pollutants.

The results in Table 4 focus on emissions within the LEZ. However, an LEZ would improve air quality throughout the PCMC. The smaller Zone 1 LEZ would reduce total emissions in the PCMC by 1%–6% between 2026 and 2030, depending on the scenario and sub-scenarios, while the larger Zone 2 LEZ would reduce emissions by 3%–15%. The greatest benefit shown here, a 15% improvement in emissions, comes from the larger Zone 2 LEZ implementing age-based restrictions, and from the assumption that noncompliant vehicles are replaced with ZEVs. A detailed breakdown of these citywide improvements is provided in Appendix E.

DISCUSSION AND NEXT STEPS

If an LEZ is to be established in Pimpri-Chinchwad, the PCMC will need to make decisions regarding the geographic boundaries, the implementation timeline, and the restriction scheme for older or more polluting vehicles. The analysis provides information on the emission reductions that could be achieved under different LEZ restriction and compliance scenarios. In this section, we summarize key findings and potential next steps for achieving better air quality.

Potential LEZ boundaries: The study identified two potential boundaries for an LEZ that would encompass the most heavily populated areas of the PCMC along with the largest network of roads. The smaller, centralized Zone 1 would cover 29 km^2. The larger, expanded Zone 2 would cover 88 km^2, nearly half of the PCMC. The larger LEZ would result in an overall emission reduction that is 2.3 times greater than limiting the LEZ to Zone 1. Emissions could be reduced even further in the established LEZ by transitioning to a zero-emission zone that prohibits all ICE vehicles.

Implementation timeline: Given the condition of air pollution in the city and the recommendations of the Maharashtra EV policy, an ambitious timeline of 2024 to 2030 is suggested for implementing the LEZ. After successfully implementing the actions in the set timeline, the city could consider further enhancements post-2030 to meet stricter air quality goals.

Emissions by vehicle type: In 2023, the share of total emissions was greatest for two-wheelers, followed by heavy goods vehicles and light goods vehicles. By 2030, under the No LEZ Scenario, the order shifted slightly with light motor vehicles (passenger cars) rising to the top three. Despite this, the results of this study suggest that imposing restrictions on vehicles across all categories, regardless of their emission shares, would achieve the highest emission reductions. However, the PCMC may wish to consider the emission shares and overall emission reduction objectives when deciding which vehicles to restrict.

Age-based versus standard-based restrictions: Excluding vehicles from the LEZ based on age results in more reductions in emissions than an exclusion based on BS standards. Between 2026 and 2030, the Age-Based Scenario would result in a 12%–24% reduction in emissions within the LEZ, compared with 4%–11% under the Standard-Based Scenario. Using standards for the basis of restrictions affects fewer vehicles during the early years of enforcement, which could facilitate an earlier launch of an LEZ. However, as total demand for vehicles increases, the Standard-Based Scenario will require incremental adjustments to the LEZ restrictions to consistently reduce more emissions over time. In contrast, the Age-Based Scenario addresses the issue to a certain extent through the continual phase out of older vehicles each year regardless of emission standards.

Equitable incentives: To translate these LEZ strategies into tangible action, demand-side management measures, as outlined in Roychowdhury et al. (2023), should be considered. European cities such as London, Paris, and Brussels have offered financial support based on the economic situation of private individuals and business entities, along with other equity components, to assist with replacing noncompliant vehicles in LEZs (Wappelhorst et al., 2023). Adopting a similar approach could help achieve a socially equitable LEZ in the PCMC area.

Possible future actions: This study showed that switching from noncompliant vehicles to zero-emission alternatives offers the highest potential for reducing emissions under both restriction scenarios. Our analysis also showed that CO and HC emissions will continue to increase without an LEZ, despite natural turnover in the fleet. This underscores the importance of considering higher emission thresholds in forthcoming BS emission standards across all vehicle types. To mitigate emissions from expected fleet growth in coming years, the adoption of ZEVs as opposed to ICE vehicles could be encouraged through demand-side policies to boost consumer interest and supply-side measures such as a ZEV sales regulation (Anup & Rokadiya, 2024), complementing the LEZ initiative. Appealing and effective support mechanisms can accelerate the switch to cleaner alternatives like EVs and public transport.

Following the establishment of a successful LEZ in Pimpri-Chinchwad, city and state authorities could aim to expand the LEZ to encompass the entire PCMC, and eventually extend it to multiple cities and districts in the region. Creating a regional-level LEZ would help address cross-boundary movement of pollutants and allow for more effective control of emissions, ultimately improving overall air quality in the region.

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APPENDIX A

Table A1

Details of secondary datasets used to perform the analysis

Datasets	Purpose of using dataset	Source
$PM_{2.5}$ levels	Prominent pollutant released from tailpipe with substantial implication for air quality in India	van Donkelaar et al. (2021)
Road network	A proxy for locating potential traffic hotspots; more kilometers of road lead to more vehicular operations and higher emission levels	OpenStreetMap Contributors (n.d.)
Population	Identification of areas with greater population density so that the selected LEZ can benefit more people with better air quality	Schiavina et al. (2023)
Local infrastructure and facilities	Ensure that the selected area possesses basic complementary amenities, such as nonmotorized transport networks, charging infrastructure, and accessible public transit.	Government repositories and websites

Additional information:

» $PM_{2.5}$ levels were selected as a factor in the LEZ identification process because this is the prominent pollutant deteriorating India's urban air quality, posing a serious threat to human well-being. Other harmful gaseous pollutants such as NO_2 and CO in the ambient air are mostly within the set limits.

» The area with optimum complementary amenities available, such as EV charging stations and mass transit, was selected to ensure that the city can adhere to the timelines considered in Figure 8. Cities without complementary amenities will need to invest substantial time in developing them first before enforcing an LEZ.

» Targeting areas where more pollution-vulnerable populations may be found—such as schools, colleges, and hospitals—was considered in the analysis, providing more compelling evidence for the need for LEZ.

APPENDIX B

Table B1, Figure B1, and Table B2 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 refueling. These independent variables were used to develop the city-specific air pollutants emission inventory.

Table B1

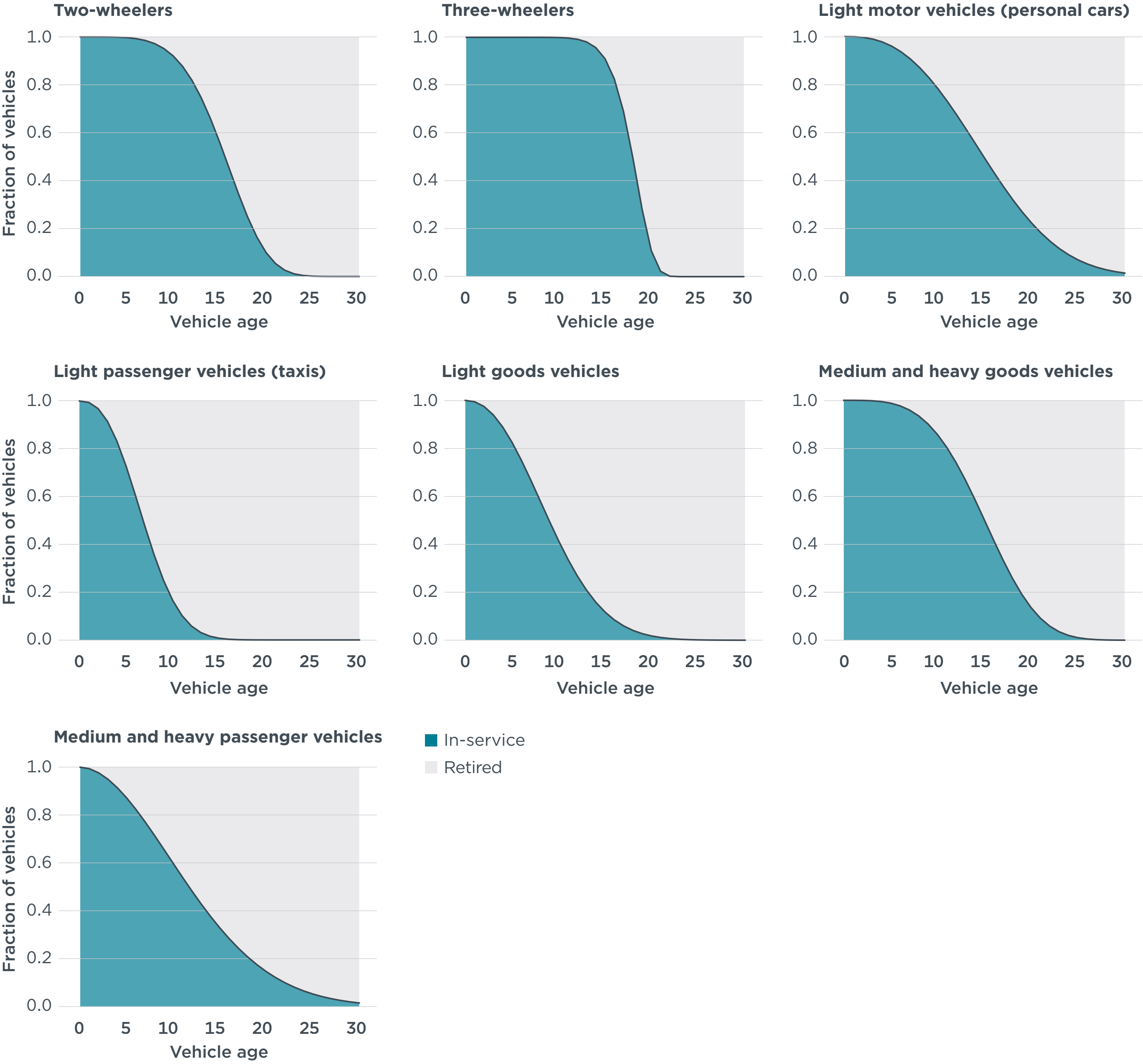
Vehicle-kilometers traveled (VKT) for each vehicle type

Vehicle types	VKT per day
Two-wheelers	30
Three-wheelers	85.7
Light motor vehicles (personal cars)	54
Light passenger vehicles (taxis)	114
Light goods vehicles	76.3
Medium and heavy passenger vehicles	129.1
Medium and heavy goods vehicles	74.1

Note: Survey information on VKT and fuel expenditures were used to estimate—based on the highest density function—the final VKT values for specific vehicle types. 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.

Figure B1

Survival/retirement rate of vehicle types by age



Note: The survival rate of a vehicle is described as the fraction or percentage of registered vehicles still in use at a certain vehicle age. As the vehicle ages, the survival rate of the vehicle tends to decline. The rate depends on several factors, including the consumer's economic decisions, vehicle quality, maintenance and fuel costs, motor vehicle tax policies, and any restrictions on operating the vehicle (Zheng et al., 2019). The modified Weibull method was used to derive the curves. More details on the methodology are discussed in Goel et al., (2015).

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Table B2
Survival life by vehicle type

Vehicle types	Mean survival life (years of age)
Two-wheelers	13
Three-wheelers	17
Light motor vehicles (personal cars)	14
Light passenger vehicles (taxis)	8
Light goods vehicles	15
Medium and heavy passenger vehicles	12
Medium and heavy goods vehicles	17

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

APPENDIX C

This section of the appendix details the share of pollutant emission based on vehicle and fuel type in Table C1. Table C2 specifically highlights the contribution of individual fuel types to pollutant emissions in the area. This is to provide further insights into emission contributions at a finer level, which can be used for better decision-making.

Table C1
Emission shares by vehicle and fuel type in the Pimpri Chinchwad Municipal Corporation for the base year 2023

Fuel type	Vehicle type	Particulate matter	Nitrogen oxides	Carbon monoxide	Hydrocarbons
Gasoline	Two-wheelers	18.1%	13.5%	30.2%	48.5%
	Three-wheelers	0.1%	0.0%	0.1%	0.4%
	Light motor vehicles (personal cars)	1.0%	1.7%	14.6%	5.4%
	Light passenger vehicles (taxis)	0.0%	0.0%	0.1%	0.0%
	Light goods vehicles	0.0%	0.1%	0.3%	0.1%
Diesel	Three-wheelers	0.6%	0.1%	0.1%	0.1%
	Light motor vehicles (personal cars)	9.8%	6.8%	3.9%	5.6%
	Light passenger vehicles (taxis)	1.5%	1.1%	0.6%	0.9%
	Light goods vehicles	24.5%	11.8%	15.6%	19.1%
	Medium passenger vehicles	1.8%	3.2%	1.6%	0.2%
	Medium goods vehicles	10.0%	13.4%	6.5%	1.3%
	Heavy passenger vehicles	6.1%	8.2%	3.0%	0.5%
	Heavy goods vehicles	25.1%	35.0%	18.1%	3.3%
Compressed natural gas	Three-wheelers	0.3%	1.6%	1.2%	3.4%
	Light motor vehicles (personal cars)	0.7%	1.1%	1.5%	4.9%
	Light passenger vehicles (taxis)	0.2%	0.2%	0.3%	1.2%
	Light goods vehicles	0.1%	0.9%	0.9%	2.8%
	Medium passenger vehicles	0.0%	0.0%	0.0%	0.0%
	Medium goods vehicles	0.0%	0.1%	0.4%	0.6%
	Heavy passenger vehicles	0.1%	1.0%	0.5%	1.7%
	Heavy goods vehicles	0.0%	0.1%	0.2%	0.3%

Table C2

Emission shares by fuel type in the Pimpri Chinchwad Municipal Corporation for the base year 2023

Fuel	Particulate matter	Nitrogen oxides	Carbon monoxide	Hydrocarbons
Gasoline	19.2%	15.3%	45.4%	54.4%
Diesel	79.5%	79.6%	49.4%	30.8%
CNG	1.3%	5.0%	5.2%	14.8%

APPENDIX D

Projections of emission loads were evaluated based on the year-over-year new vehicle registration estimates. Based on the analysis, from 2021 to 2030, vehicle registration will grow at an overall compounded annual growth rate of 8.7%.

The projected emissions depicted in Table D1, when considered with Figures 7a and 7b, offer a basic insight into the implications of the proposed LEZ scenarios. This information also serves as a valuable tool for refining recommendations to align with the emission reduction objectives established by state- and city-level authorities.

Table D1

Percentage of each pollutant emitted by vehicle type in 2030 under the No LEZ Scenario

Vehicle type	Particulate matter	Nitrogen oxides	Carbon monoxide	Hydrocarbons
Heavy goods vehicles	24%	31%	20%	3%
Heavy passenger vehicles	8%	9%	6%	1%
Light goods vehicles	14%	14%	17%	25%
Light motor vehicles (personal cars)	17%	13%	23%	21%
Light passenger vehicles (taxis)	2%	2%	2%	6%
Medium goods vehicles	8%	10%	7%	2%
Medium passenger vehicles	4%	4%	4%	0.5%
Three-wheelers	3%	5%	2%	5%
Two-wheelers	19%	11%	20%	35%

Notes: Green cells indicate a reduction in the emissions share of greater than 1 percentage point compared with the 2023 base year; red cells indicate an increase in the emissions share of greater than 1 percentage point; blue cells indicate no change in the emissions share or a change within plus or minus 1 percentage point compared with the base year. The sum of emission shares for each pollutant may not equal 100% because of rounding.

APPENDIX E

Tables E1 though E3 detail the impact of LEZ restriction scenarios on emission loads for the entire PCMC area compared with the base year of 2023. According to the timeline outlined for LEZ implementation (Figure 8), enforcement is assumed to begin in 2026.

Table E1

Potential reduction in emissions across the Pimpri Chinchwad Municipal Corporation from 2026 to 2030 under different LEZ scenarios compared with the No LEZ Scenario

Zones	Restriction scenario	Sub-scenario	Emissions reduction by pollutant				Total emissions reduction
			Particulate matter	Nitrogen oxides	Carbon monoxide	Hydrocarbons	
Zone 1	Age-Based	SS1	12%	9%	1%	2%	3%
		SS2	12%	9%	1%	2%	3%
		SS3	14%	11%	5%	4%	6%
	Standard-Based	SS1	6%	3%	0%	1%	1%
		SS2	7%	5%	1%	1%	2%
		SS3	7%	6%	2%	2%	3%
Zone 2	Age-Based	SS1	28%	22%	2%	4%	7%
		SS2	29%	23%	3%	5%	8%
		SS3	33%	27%	12%	10%	15%
	Standard-Based	SS1	14%	7%	1%	2%	3%
		SS2	16%	12%	1%	3%	4%
		SS3	17%	14%	5%	4%	7%

Note: Emission reductions are in terms of the mass of the pollutants. In sub-scenario SS1, owners of noncompliant vehicles shift to used vehicles. In SS2 the owners shift to new vehicles and in SS3 they shift to zero-emission vehicles. The sub-scenarios are further explained in Table 3.

Table E2

Age-Based Scenario: Impact of an LEZ on emission loads for the entire Pimpri Chinchwad Municipal Corporation, compared with the 2023 base year

LEZ area	Pollutant	No LEZ and LEZ sub-scenarios	2024	2025	2026	2027	2028	2029	2030
Zone 1	Particulate matter	No LEZ	-9%	-17%	-25%	-33%	-39%	-45%	-50%
		SS1	-9%	-17%	-34%	-41%	-47%	-51%	-56%
		SS2	-9%	-17%	-34%	-41%	-47%	-52%	-56%
		SS3	-9%	-17%	-35%	-42%	-48%	-53%	-57%
	Nitrogen oxides	No LEZ	-5%	-10%	-15%	-20%	-25%	-29%	-32%
		SS1	-5%	-10%	-22%	-27%	-31%	-35%	-39%
		SS2	-5%	-10%	-23%	-27%	-32%	-36%	-39%
		SS3	-5%	-10%	-24%	-29%	-33%	-37%	-41%
	Carbon monoxide	No LEZ	+3%	+6%	+9%	+13%	+16%	+21%	+26%
		SS1	+3%	+6%	+8%	+11%	+15%	+20%	+25%
		SS2	+3%	+6%	+8%	+11%	+15%	+19%	+24%
		SS3	+3%	+6%	+4%	+7%	+11%	+14%	+18%
	Hydrocarbons	No LEZ	+1%	+1%	+2%	+2%	+3%	+3%	+4%
		SS1	+1%	+1%	0	0	+1%	+1%	+2%
		SS2	+1%	+1%	0	0	0	+1%	+1%
		SS3	+1%	+1%	-2%	-2%	-2%	-2%	-2%
Zone 2	Particulate matter	No LEZ	-9%	-17%	-25%	-33%	-39%	-45%	-50%
		SS1	-9%	-17%	-46%	-53%	-57%	-60%	-63%
		SS2	-9%	-17%	-46%	-53%	-57%	-61%	-64%
		SS3	-9%	-17%	-48%	-55%	-60%	-64%	-67%
	Nitrogen oxides	No LEZ	-5%	-10%	-15%	-20%	-25%	-29%	-32%
		SS1	-5%	-10%	-33%	-37%	-41%	-45%	-48%
		SS2	-5%	-10%	-33%	-38%	-41%	-45%	-49%
		SS3	-5%	-10%	-35%	-40%	-44%	-49%	-53%
	Carbon monoxide	No LEZ	+3%	+6%	+9%	+13%	+16%	+21%	+26%
		SS1	+3%	+6%	+6%	+9%	+14%	+18%	+23%
		SS2	+3%	+6%	+5%	+9%	+13%	+18%	+23%
		SS3	+3%	+6%	-2%	0	+3%	+5%	+8%
	Hydrocarbons	No LEZ	+1%	+1%	+2%	+2%	+3%	+3%	+4%
		SS1	+1%	+1%	-2%	-2%	-1%	-1%	-1%
		SS2	+1%	+1%	-3%	-3%	-3%	-2%	-2%
		SS3	+1%	+1%	-6%	-7%	-7%	-8%	-9%

Notes: Purple shading represents no change in emissions, the blue shading indicates a reduction in emissions, and red shading indicates an increase in emissions from 2023. In sub-scenario SS1, owners of noncompliant vehicles shift to used vehicles. In SS2 the owners shift to new vehicles and in SS3 they shift to zero-emission vehicles. The sub-scenarios are explained further in Table 3.

Table E3

Standard-Based Scenario: Impact of an LEZ on emission loads for the entire Pimpri Chinchwad Municipal Corporation, compared with the 2023 base year

LEZ area	Pollutant	No LEZ and LEZ sub-scenarios	2024	2025	2026	2027	2028	2029	2030
Zone 1	Particulate matter	No LEZ	-9%	-17%	-25%	-33%	-39%	-45%	-50%
		SS1	-9%	-17%	-26%	-33%	-45%	-50%	-56%
		SS2	-9%	-17%	-27%	-34%	-46%	-50%	-57%
		SS3	-9%	-17%	-41%	-46%	-50%	-54%	-57%
	Nitrogen oxides	No LEZ	-5%	-10%	-15%	-20%	-25%	-29%	-32%
		SS1	-5%	-10%	-15%	-20%	-27%	-30%	-39%
		SS2	-5%	-10%	-16%	-20%	-30%	-33%	-40%
		SS3	-5%	-10%	-30%	-33%	-36%	-39%	-41%
	Carbon monoxide	No LEZ	+3%	+6%	+9%	+13%	+16%	+21%	+26%
		SS1	+3%	+6%	+9%	+13%	+16%	+20%	+24%
		SS2	+3%	+6%	+9%	+13%	+16%	+20%	+24%
		SS3	+3%	+6%	+4%	+8%	+13%	+17%	+23%
	Hydrocarbons	No LEZ	+1%	+1%	+2%	+2%	+3%	+3%	+4%
		SS1	+1%	+1%	+2%	+2%	+2%	+3%	+1%
		SS2	+1%	+1%	+2%	+2%	+2%	+2%	0
		SS3	+1%	+1%	-8%	-7%	-5%	-4%	-2%
Zone 2	Particulate matter	No LEZ	-9%	-17%	-25%	-33%	-39%	-45%	-50%
		SS1	-9%	-17%	-28%	-34%	-53%	-56%	-65%
		SS2	-9%	-17%	-25%	-35%	-55%	-57%	-66%
		SS3	-9%	-17%	-28%	-35%	-56%	-58%	-68%
	Nitrogen oxides	No LEZ	-5%	-10%	-15%	-20%	-25%	-29%	-32%
		SS1	-5%	-10%	-16%	-20%	-31%	-32%	-50%
		SS2	-5%	-10%	-17%	-21%	-38%	-40%	-51%
		SS3	-5%	-10%	-17%	-21%	-40%	-42%	-54%
	Carbon monoxide	No LEZ	+3%	+6%	+9%	+13%	+16%	+21%	+26%
		SS1	+3%	+6%	+9%	+13%	+14%	+19%	+23%
		SS2	+3%	+6%	+9%	+12%	+14%	+19%	+21%
		SS3	+3%	+6%	+9%	+12%	+9%	+14%	+10%
	Hydrocarbons	No LEZ	+1%	+1%	+2%	+2%	+3%	+3%	+4%
		SS1	+1%	+1%	+2%	+2%	+1%	+2%	-2%
		SS2	+1%	+1%	+1%	+2%	0	+1%	-5%
		SS3	+1%	+1%	+1%	+2%	-1%	0	-10%

Notes: Purple shading represents no change in emissions, the blue shading indicates a reduction in emissions, and red shading indicates an increase in emissions from 2023. In sub-scenario SS1, owners of noncompliant vehicles shift to used vehicles. In SS2 the owners shift to new vehicles and in SS3 they shift to zero-emission vehicles. The sub-scenarios are explained further in Table 3.