CSTEP

Heavy Duty, High Impact

Mitigating Heavy Commercial Vehicle Emissions in India

Heavy Duty, High Impact:
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Executive Summary

Executive Summary

Background and key findings

Air pollution, a pressing public health crisis in Indian cities, is significantly driven by the transport sector. Heavy commercial vehicles (HCVs; e.g. buses, trucks, water tankers, and dumpers), comprising only 1.74% of all vehicles, contribute to over 70% of vehicular pollution, particularly particulate matter ($PM_{2.5}$ and PM_{10}). Further, trucks, which constitute the majority of HCVs, dominate HCV emissions due to their high registration numbers and vehicle kilometres travelled (VKT). The National Clean Air Programme (NCAP) targets a 40% reduction in PM emissions in non-attainment cities, necessitating focused interventions on HCVs. This report provides a 2022 emission inventory for HCVs, evaluates existing policies, and proposes strategies to curb tailpipe emissions. The report emphasises super-emitters, which have 4–11 times higher emission factors than non-super-emitters. Thus, although super-emitters constitute only 23% of the fleet, they contribute to 62% of $PM_{2.5}$ emissions (154 Gg/year compared with 93 Gg/year from non-super-emitters).

In a business-as-usual scenario, HCV numbers will rise by 27% by 2035; however, emissions will decline owing to the adoption of Bharat Stage VI (BS-VI) norms and scrappage of government HCVs, though super-emitters will continue to dominate fleet emissions. Current policies, including the Voluntary Vehicle Fleet Modernisation Programme (VVMP) and the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME) scheme, lack specific measures for super-emitters or regional coordination for long-distance HCVs.

Key challenges

- Lack of policy focus on super-emitters
- Insufficient infrastructure for scrappage and retrofitting
- High-cost barriers for electric vehicle (EV) and liquefied natural gas (LNG) / compressed natural gas (CNG) adoption
- Regulatory gaps for implementing low-emission zones (LEZs)
- Dependency on road freight for the transportation of goods (the percentage of rail freight transport has declined over the years)

Strategic priorities and actions

Priority	Key action	Expected impact
Target super-emitters	Deploy remote sensing technology and mandate periodic testing.	Reduced HCV emissions by ~60%
Enforce scrappage policies	Mandatory scrappage of private HCVs over 15 years old. To replace nearly 85,000 vehicles, the infrastructure of approximately 28,000 crores would be needed.	Accelerated fleet modernisation
Promote retrofitting	Subsidise partial flow filters and selective catalytic reduction systems for BS-IV HCVs. The estimated cost is INR 1.3 thousand crores for ~3 lakh vehicles.	Immediate reduction in PM and nitrogen oxides emissions
Support EVs and alternative fuels	Increase subsidies (e.g. INR 35 to INR 50 lakh for e-trucks under PM E-DRIVE); develop LNG/CNG/ hydrogen infrastructure. Cleaning up about 70,000 vehicles would require INR 100 thousand crores.	Reduced tailpipe emissions of freight transport
Implement LEZs	Regulatory authority and tech-enabled enforcement.	Localised air quality improvement (15%–30% PM reduction)
Modal shift to rail freight transport	Expand freight corridors and intermodal hubs.	Significant reduction in diesel truck usage

Policy recommendations

- Formalise remote sensing for detecting and repairing super-emitters.
- Scale up scrappage and retrofitting infrastructure and mandate scrappage for persistent polluters (older and poorly maintained vehicles that repeatedly fail the Pollution Under Control [PUC] certification and other fitness tests).
- Enhance subsidies and incentives for fleet transition to cleaner technologies.
- Create enabling regulations for LEZs nationwide.
- Facilitate public–private partnerships for alternative fuel adoption.

Conclusion

Achieving cleaner heavy transportation in India requires targeted regulations, infrastructure investments, industry collaboration, and financial incentives. A phased, pragmatic approach, prioritising super-emitters and transitioning to cleaner fuels, can drive significant air quality benefits and support India's clean transport goals.

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List of Abbreviations

ARAI	Automotive Research Association of India
ATS	Automated testing station
ANPR	Automatic Number Plate Recognition
BAU	Business as usual
BC	Black carbon
BS	Bharat Stage
CO	Carbon monoxide
CEDS	Community Emissions Data System
CTM	Chemical transport models
CNG	Compressed natural gas
DPF	Diesel particulate filter
DOC	Diesel oxidation catalyst
DC	Direct current
EPR	Extended producer responsibility
ELV	End-of-life vehicle
EDGAR-HTAP	Emissions Database for Global Atmospheric Research - Hemispheric Transport of Air Pollution
EDGAR	Emissions Database for Global Atmospheric Research
EI	Emission inventory
EV	Electric vehicle
FAME	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles
FC	Fast charging
FCEV	Fuel cell electric vehicle
GPS	Global Positioning System
GVW	Gross vehicle weight
HCVs	Heavy commercial vehicles
HC	Hydrocarbon
ICE	Internal combustion engine
IBEF	India Brand Equity Foundation

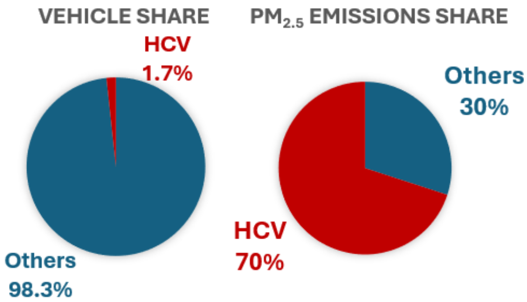
LNG	Liquefied natural gas
LEZ	Low-emission zone
MoRTH	Ministry of Road Transport and Highways
NCAP	National Clean Air Programme
NO_x	Nitrogen oxides
NH_3	Ammonia
MNVOC	Non-methane volatile organic compound
OEM	Original equipment manufacturer
OBDs	On-board diagnostics
PFF	Partial flow filter
PCD	Pollution control device
PLI	Production-Linked Incentive
PUC	Pollution Under Control
PM_{10}	Particulate matter with a diameter of 10 microns or less
$PM_{2.5}$	Particulate matter with a diameter of 2.5 microns or less
RCM	Reduced Complexity Model
REACH	Rapid Estimation of Air Concentrations for Health
RORO	Roll-on/Roll-off
RVSF	Registered Vehicle Scrapping Facility
SF	Survival fraction
SC	Slow charging
SCR	Selective catalytic reduction
SO_2	Sulphur dioxide
TCO	Total cost of ownership
UT	Union territory
VKT	Vehicle kilometres travelled
VVMP	Voluntary Vehicle-Fleet Modernisation Programme

Introduction

1. Introduction

Air pollution in India is now a major public health crisis, with several Indian cities featuring in the world's top 10 most polluted cities list. In 2019, India launched the National Clean Air Programme (NCAP), which targeted a reduction of 20%–30% (later increased to 40%) of air pollution (particulate matter [PM] with an aerodynamic diameter of 10 microns or less [PM_{10}]) from non-attainment cities in India.

***Figure 1**: Disproportionate emissions from HCVs*



Across 76 Indian cities, 34% of $PM_{2.5}$ emissions are from vehicular exhaust. Heavy commercial vehicles (HCVs) contribute more than 70% of these emissions.

The transport sector is a major polluter in Indian cities; it adds to PM_{10} and $PM_{2.5}$ levels through tailpipe emissions and resuspension of dust. On average, 55% (interquartile range 29%–82%) of PM_{10} emissions are attributed to traffic-related air pollution (tailpipe emissions and resuspended road dust). Meanwhile, 34% (interquartile range 22%–49%) of urban $PM_{2.5}$ emissions are attributed to vehicular exhaust (CSTEP's Emission Inventory, n.d.). Controlling emissions from the transport sector is essential for air quality improvement in Indian cities. Hence, around 38% of all the control measures prescribed in the city-level clean air action plans in 2020 targeted the mitigation of transportation emissions (Ganguly et al., 2020).

Heavy commercial vehicles make up only 1.74% of the vehicle population, but contribute to more than 70% of vehicular pollution (Bhalerao et al., 2024). The relative contribution is higher for older and poorly maintained HCVs. However, no city other than Delhi has targeted interventions in place for reducing HCV emissions. HCVs (specifically long-distance buses and trucks) travel across borders. City-level control measures only affect HCVs within city limits and are largely inadequate in controlling emissions from the larger fleet of HCVs. Thus, it is imperative to plan emission reduction measures at the regional and national levels.

This study developed a state-wise HCV emission inventory (EI) and assessed the existing policy measures. Further, it investigated the emission reduction potential of different control strategies focused on HCVs across four categories: buses, trucks, water tankers, and dumpers. The study concludes with a set of policy interventions and strategies for reducing HCV emissions.

Understanding HCV Emissions in India

2. Understanding HCV Emissions in India

Emissions are a function of the number of HCVs on the road, as well as their age, condition, fuel type, and vehicle kilometres travelled (VKT; Appendix A).

Some HCVs might emit much more than the recommended standards owing to poor maintenance or age. These are called super-emitters. Their mean emission factor is estimated to be 4–11 times higher than that of non-super-emitters (Prakash et al., 2020).

The study estimated that super-emitters compose 23% of the total HCV fleet (see Appendix B for the calculations). The baseline emissions estimated in this study were derived using a vehicle survival function, as described in the literature (Pandey & Venkataraman, 2014a). Further, a survival function was derived using our 2022 HCV survey data, which showed a higher prevalence of trucks older than 10 years compared to what the survival fraction (SF) prevalent in the literature would suggest. This function was fitted using a Weibull distribution function (Li et al., 2024a). The study used a survival function derived from a CSTEP survey to better understand uncertainties regarding HCV emissions. A sensitivity analysis was performed based on uncertainties in SFs, and the resulting changes in the number of vehicles plying on the road can be found in Appendix H. For scenario development, we considered the more widely used survival function as described in the literature (assuming that older vehicles are well-regulated and phased out).

Based on the literature, we considered daily VKT for different types of HCVs (e.g. buses, trucks, dumpers, and water tankers; Appendix A). However, feedback from stakeholder consultations and reports indicated that a VKT of 300 km/day is more appropriate for trucks (India Brand Equity Foundation [IBEF], 2024). In our baseline scenario, we assumed a VKT of 142 km/day; however, we also considered the alternative 300 km/day scenario throughout this report (numbers will be in parentheses).

Estimated $PM_{2.5}$ emissions due to wear and tear (i.e. non-tailpipe emissions) in 2022 stand at 0.86 Gg/yr, while those from tailpipe emissions are 201 ± 46 Gg/yr.

The study estimated baseline HCV emissions for the year 2022 (Figure 2 and Table 1) using the latest emission factors (Table A2, Appendix A). Given the relatively small PM contribution estimated for non-tailpipe emissions, the rest of this report focuses on tailpipe emissions from HCVs. Therefore, 'emissions' refer to tailpipe emissions hereinafter.

For the base year 2022 (Table 1), particulate emissions from 77% of normal (non-super-emitter) HCVs are estimated to be 93 Gg/year of $PM_{2.5}$ and 109 Gg/year of PM_{10}. Super-emitters (the remaining 23% of the national HCV fleet) are responsible for an additional 154 Gg/year of $PM_{2.5}$ emissions or 62% (Figure 2) of the total HCV fleet

$PM_{2.5}$ emissions. Hence, targeting super-emitter HCVs will be highly beneficial and more effective for emission reductions than simply regulating all HCVs.

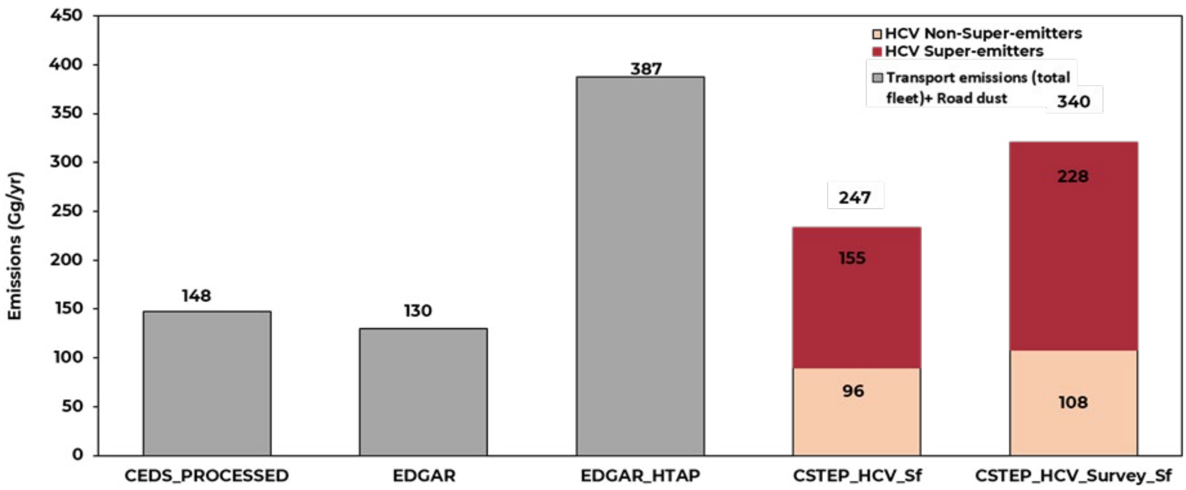
***Table 1**: Baseline emissions from HCVs*

SF type	Emission load (Gg/yr)*				
	PM_{10}	$PM_{2.5}$	Black carbon (BC)	Nitrogen oxides (NO_X)	Carbon monoxide (CO)
With the SF from literature (Pandey & Venkataraman, 2014a)	168 (274)	143 (233)	100 (163)	1,226 (2,261)	997 (1,821)
With the SF based on CSTEP's petrol pump survey	216 (378)	184 (321)	129 (225)	4,933 (9,199)	1,188 (2,170)

*Our default assumption, based on the literature, is that trucks are driven for 142 km/day. We also consider an alternative scenario where trucks are driven for 300 km/day based on stakeholder feedback (values in parentheses).

To better understand the impact of our methodology on transport emissions estimation, we compared our estimated emissions ($PM_{2.5}$) with transport emissions presented in global EIs such as the Emissions Database for Global Atmospheric Research (EDGAR), the Community Emissions Data System (CEDS), and EDGAR-HTAP (Hemispheric Transport of Air Pollution). Emission estimations in this study are 36% lower than those of EDGAR-HTAP but 40%–90% higher than CEDS- and EDGAR-reported emissions (Figure 2). This is because global emissions inventories rely on fuel sales data, which they apportion to the transport sector based on certain assumptions; differences in assumptions lead to variations in the final estimates. The apportioned fuel is further distributed among various vehicle categories. At present, discussing the reasons behind discrepancies in estimates is difficult because the exact assumptions followed by global EIs are not publicly known. Figure 2 shows estimated emission loads using the literature-based SF (CSTEP_HCV_Sf) and the SF derived from CSTEP's survey on tailpipe emissions of HCVs (CSTEP_HCV_Survey_Sf).

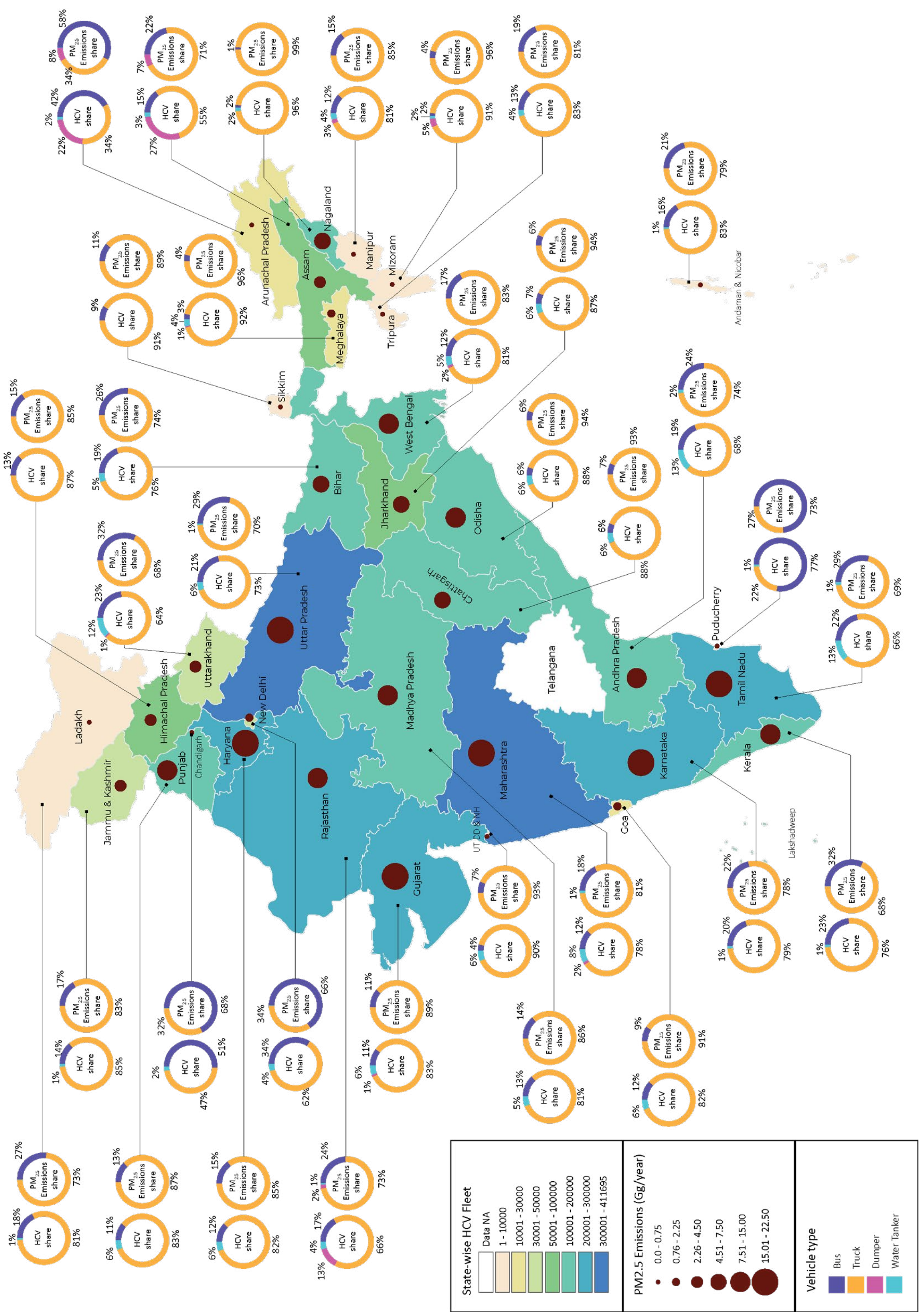
***Figure 2**: Comparison of India's transport emissions ($PM_{2.5}$) with the estimations of global EIs. The study estimate considers trucks' VKT as 300 km/day, which is the upper end for our emission estimate (The baseline VKT is 142 km/day.)*



Global EIs: Transport emissions (total fleet) + Road dust; CSTEP: Tailpipe emissions of HCVs

CSTEP also investigated state-wise bifurcation of emissions based on different HCV types (e.g. trucks, buses, water tankers, and dumpers), as seen in Figure 3. Except in a few states, such as Delhi, and union territories (UTs), such as Puducherry, the majority of $PM_{2.5}$ emissions are from trucks. High emissions from trucks are primarily due to their greater number, as evidenced by registration numbers, compared to other HCVs.

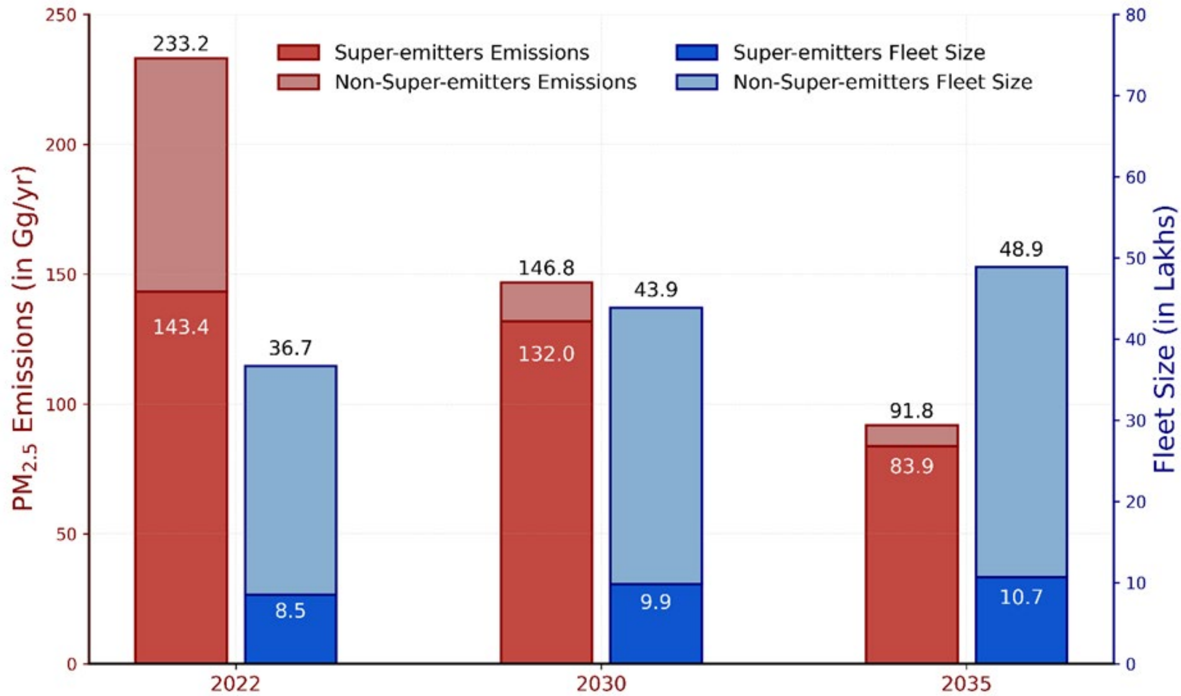
***Figure 3**: $PM_{2.5}$ emissions from HCVs (based on the VKT of 300 km/day)*



Future HCV emission projections: In a business-as-usual (BAU) scenario, the number of HCVs will continue to increase by 27% through 2035. However, total HCV emissions will decrease due to the growing number of Bharat Stage (BS) VI vehicles as a share of the on-road fleet and non-usage of older vehicles due to scrappage or other causes (Figure 4). Normatively, BS-VI $PM_{2.5}$ emissions are approximately 70% less than those of their BS-IV counterparts because of changes in engine technology and in-built diesel particulate filters (DPFs).

The emissions were estimated considering the current SF published in 2014 and may not be valid 10 years from now (assuming older vehicles stop plying on the road). However, this is an assumption; the ground reality is different. Stakeholder feedback indicates that trucks typically operate for around 20 years. In case there are restrictions in certain cities, older trucks make their way to smaller towns and other states. Studies measuring emissions from BS-VI super-emitters are scant; hence, the authors have assumed the same range of emissions for super-emitter BS-VI vehicles. Although the penetration of cleaner, non-super-emitter BS-VI HCVs will increase, eventually forming a larger fraction of the on-road fleet, emissions from super-emitters will become overwhelmingly dominant if they are not scrapped (Figure 4; details are in Appendix B). Hence, the regulation of super-emitters will become even more critical in the future.

***Figure 4**: $PM_{2.5}$ emissions projection (BAU) from HCVs (considering 300 km/day as truck VKT)*



Existing Policy Interventions

3. Existing Policy Interventions

Current policies that have a direct or indirect impact on overall HCV emissions are listed in Figure 5. A detailed analysis can be found in Appendix D (Tables A6–A8).

***Figure 5**: National policies that directly or indirectly affect HCV emissions*

2014

Auto Fuel Vision & Policy 2025

BS-VI norms were implemented in 2020, leapfrogging from BS-IV to reduce $PM_{2.5}$ emissions by nearly 60%–90%. Policy includes the incorporation of diesel particulate filters (DPFs) and selective catalyst reduction (SCR) systems in vehicles to improve air quality.

2015

Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles Scheme I (FAME-I)

Policy push for EV adoption, infrastructure development (charging stations), and provision of public subsidies.

2018

Biofuel promotion policy

National Policy on Biofuels (2018) aims for 20% ethanol blending in gasoline and 5% biodiesel blending by 2030 (later target date was decreased to 2026) to reduce dependency on conventional fuels.

2019

FAME-II

Policy push for EV adoption, infrastructure development (charging stations), and provision of public subsidies. FAME-II was extended till March 2024 with an INR 11,500 crore budget.

2021

Vehicle scrappage policy

- Voluntary scrappage of vehicles irrespective of age.
- Mandatory scrappage of commercial vehicles and passenger end-of-life vehicles.
- Mandatory scrappage of government vehicles older than 15 years (from April 2022).

2022

National Rail Plan Vision-2030 & Hydrogen fuel for commercial vehicles

- Aims to increase freight traffic share from 27% to 45% by 2030 through Dedicated Freight Corridors (DFCs) and the Trucks-on-Train service to reduce reliance on road transport and lower emissions.
- The National Green Hydrogen Mission supports hydrogen-based transportation technology with an INR 19,744 crore allocated.

2024

PM E-Drive Scheme

Replacing FAME-II, with an INR 10,900 crore budget focusing on EVs for public transport and fast charging stations. Allocates funds for e-trucks, e-buses, and charging infrastructure development.

Potential Mitigation Strategies

4. Potential Mitigation Strategies

To address tailpipe emissions from HCVs, a multifaceted approach is required, combining technological upgrades, regulatory reforms, and infrastructure development. Below are key strategies, their implementation challenges, and recommendations for the path forward. A stakeholder consultation was initiated (see Appendix E), and the feedback has been considered while proposing these mitigation strategies.

4.1. Removal of super-emitters

Super-emitters will continue to emit a large share of tailpipe emissions ($PM_{2.5}$); therefore, reducing their number will help decrease tailpipe emissions to a greater extent. Key strategies to mitigate tailpipe emissions from HCVs involve the identification and removal of super-emitters. Further, although traffic police are empowered to fine visibly polluting vehicles (i.e. emitting smoke), a more scientific approach needs to be followed for identifying and penalising polluting vehicles. Two solutions to address this issue are listed below.

Isolating super-emitters via remote sensing technology: Super-emitters can be identified using remote sensing technologies and high-resolution cameras (Narla et al., 2024). The vehicles need to be tested, isolated, issued challans (penalty tickets for traffic violations), and sent for maintenance checks. The penalties need to be progressively made more stringent until the issues are rectified or the vehicles are scrapped. Ideally, this will reduce the number of super-emitters on the road. For several years now, Kolkata has implemented these methods in addition to the prevalent Pollution Under Control (PUC) certification system.

Bringing super-emitter HCVs into compliance through repairs can reduce their emissions by 75% (considering super-emitters emit at least four times more than the non-super-emitter equivalent). Each remote sensing set-up will cost around INR two crores (INR 2,00,00,000). If the remote sensing technology can be set up in entry and exit points for a designated area, then the super-emitter problem can be brought under control.

However, there is currently a lack of strong policy support for addressing super-emitter HCVs in India. Apart from the Calcutta High Court's directive concerning Kolkata, there is a lack of regulatory backing for using remote sensing as an enforcement tool. To move forward, the Ministry of Road Transport and Highways (MoRTH) must formalise the use of remote sensing and enshrine it as a part of motor vehicle rules for identifying and penalising super-emitter vehicles.

Periodic testing: Another promising solution is the mandatory 6-monthly testing of HCVs at automated testing stations (ATSs; costing around INR 800 for testing and certification) using on-board diagnostics (OBDs) to monitor engine performance and maintenance status. Despite its potential, the current infrastructure is inadequate, with only 131 ATSs across India (as of June 2025) and no established protocol for using OBDs to monitor pollution (Ministry of Road Transport and Highways, n.d.). Moreover, many older HCVs lack OBD systems because this technology was introduced only in 2010. Scaling up this solution would require increasing the number of ATS facilities and developing standardised OBD protocols for pollution monitoring. The PUC certification system remains grossly inadequate to address on-road emissions from HCVs.

4.2. Removal of older HCVs and replacement with cleaner alternatives

Owing to older engine technology and engine degradation, older HCVs tend to have higher emissions. Therefore, it is particularly important to replace such HCVs with new, clean alternatives.

4.2.1. Mandatory Voluntary Vehicle-Fleet Modernisation Programme (VVMP) or Vehicle Scrappage Policy

Scrappage policy, if made mandatory and implemented well, will be pertinent in reducing vehicular emissions by removing super-emitters and end-of-life vehicles (ELVs). This will also add to the volume of vehicles that need to be scrapped.

Emissions-reduction potential

Reduction in emissions from the scrappage of vehicles depends upon the tailpipe emissions of the replacement vehicle. If the scrapped vehicle is replaced by EVs or not replaced at all, then the tailpipe emissions reduction potential is 100%. Even if the scrapped vehicle is replaced by BS-VI diesel vehicles, the PM emissions reduction is estimated to be 70% (at the minimum).

Current relevant policies and governance landscape

India implemented the VVMP or Vehicle Scrappage Policy in 2022. According to this policy, commercial vehicles older than 15 years and passenger vehicles older than 20 years are to be mandatorily scrapped if they do not pass the fitness and emission tests. To encourage vehicle owners to scrap ELVs under the Vehicle Scrappage Policy, a concession of up to 25% on Motor Vehicle Tax has been offered for non-transport vehicles and up to 15% for transport vehicles, provided they submit a 'Certificate of Deposit'. In accordance with the notification, GSR 29(E) dated 16. 01. 2023 (Non-Renewal of Certificate of Registration of Government Owned Vehicles after the Lapse of 15 Years, 2023), central- and state-government-owned vehicles that are over 15 years old will have to be phased out and scrapped.

Costs associated with the scrappage policy

Building the scrappage infrastructure is capital-intensive, and each centre requires around INR 14 crore for a registered vehicle scrapping facility (RVSF) with an annual capacity of 28,000 vehicles (Investment Opportunities under Voluntary Vehicle Fleet Modernisation Policy [VVMP], 2023). The estimated break-even period is after 7 years of operation. Further, industry stakeholders estimate that currently less than 5% of HCVs are formally scrapped, although the actual number may be slightly higher when accounting for grey-market activity. Usually, older HCVs are resold and reused in smaller towns.

If an HCV is scrapped under the current policy framework, it can be replaced with one of the available alternatives. However, many of the technological alternatives are in the process of getting introduced to the Indian market or are in trial phases. The corresponding unit costs are obtained from original equipment manufacturer (OEM) websites and through stakeholder consultations. The available incentives, along with unit costs, are detailed in Table 2.

***Table 2**: Cost associated with purchasing replacement vehicles*

HCV category	Replacement option	Range (in tonnes)	Unit cost in lakhs (INR)	Available additional incentives for users
Bus	BS-VI	10 T–16 T	33.2–90	No
	EV	10 T–16 T	70–200	Yes (PM E-DRIVE; Ministry of Heavy Industries, n.d.-b)
	Compressed natural gas (CNG) / liquefied natural gas (LNG)	14 T	30–41.8	No (production-linked incentives [PLIs] are proposed)
	Hydrogen	10 T	225	No (PLIs are available)
Truck	BS-VI	14 T–55 T	16–35	No
	EV	14 T–55 T	80–140	Yes (PM E-DRIVE)
	CNG/LNG	35 T	30–59.6	No (PLIs are proposed)
	Hydrogen	55 T	90 (H2-ICE [internal combustion engine) 100–200 (H2-FCEV [fuel cell electric vehicle)	No (PLIs are available; Ministry of Road Transport and Highways, 2023)

If HCVs older than 15 years are scrapped from the 2030 and 2035 fleet, the following alternative technologies are expected to replace them based on consultation with stakeholders (Table 3). These replacements will differ for public- and private-owned vehicles.

***Table 3**: Projected replacement vehicle share percentages for 2030 and 2035*

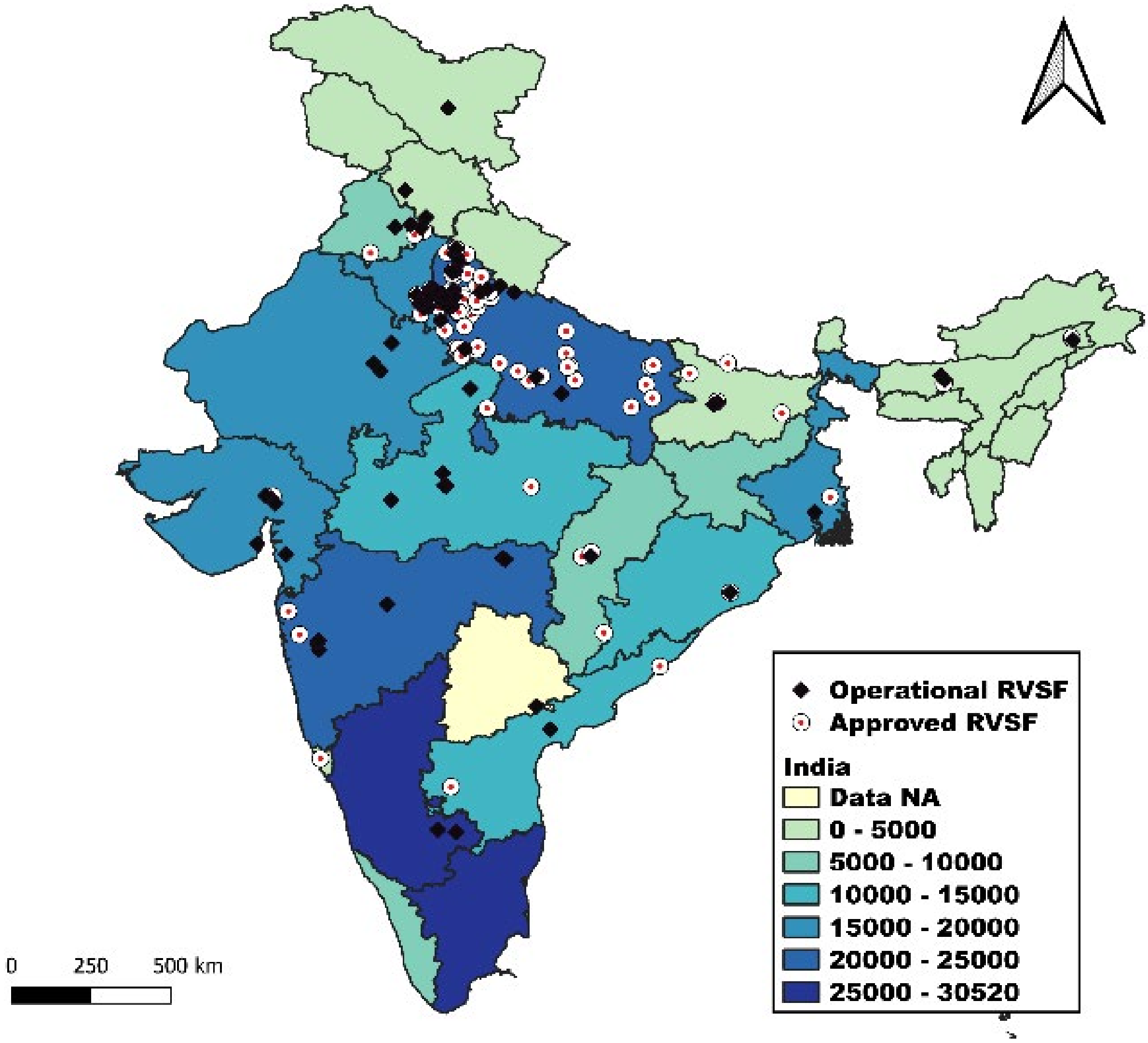
Category	Alternative for new vehicles	2030	2035
Govt	BS-VI	50%	20%
	EV	40%	70%
	LNG	10%	9%
	Hydrogen	0%	1%
Private	BS-VI+	90%	60%
	EV	2%	20%
	LNG	8%	20%
	Hydrogen	0%	0%

The total cost of ownership (TCO) is calculated for BS-VI diesel trucks, considering the truck's age as 10 years and 15 years, to understand the differences in costs of the truck at 10 and 15 years, primarily owing to increased maintenance and operation costs, as shown in Table 4.

***Table 4**: TCO per km for a BS-VI diesel truck over 10- and 15-year lifespans*

Particular	TCO (in INR/km)
BS-VI diesel truck, considering the lifespan of the vehicle as 10 years	25
BS-VI diesel truck, considering the lifespan of the vehicle as 15 years	33

Figure 6: Location of RVSFs



Barriers, entry points, and the way forward

The existing scrappage infrastructure (RVSFs) is inadequate to handle the growing number of ELVs. As of 15 April 2025, 152 RVSFs had been approved across India, but only 79 of these are presently operational (Figure 6). The presence of RVSFs is limited in many states, with only one or two facilities being operational. Each of these facilities has a processing capability of 10,000–20,000 vehicles (all categories) per year. In 2022, there were around 2,70,000 HCVs aged more than 15 years plying on the road. Considering around 3%–7% of scrappage vehicles are HCVs, around 300 operational RVSF centres are required just for HCV scrappage (Investment Opportunities under Voluntary Vehicle Fleet Modernisation Policy [VVMP], 2023).

Further, financial incentives against buying a new vehicle differ between states and range from 5% to 6% of the vehicle cost (ex-showroom price), and further tax benefits continue to be inadequate to make people willingly give up their vehicles. Finally, the informal scrapping industry provides greater financial incentives for scrapping vehicles by paying around INR 100/kg of truck weight (unladen) in comparison to around INR 25/kg from the authorised scrappage centres (Centre for Science and Environment, 2020). This segment has been completely ignored by the current policy. The stringency of norms also varies from state to state; hence, older vehicles are often sold and re-registered in other states.

4.2.2. Retrofitting HCVs with diesel oxidation catalyst (DOC), partial flow filters (PFFs), and selective catalytic reduction (SCR) systems for HCVs (BS-IV)

Retrofitting existing HCVs with PFFs and SCR systems, especially for BS-IV vehicles, can also curb emissions.

Emissions reduction potential

Expert consultations revealed that the DPF is not suitable for Indian city road conditions; however, by capturing soot particles in the exhaust stream, PFFs have the potential to reduce PM emissions by 55%–65%. SCR systems are effective in reducing NO_x by up to 90%, especially under high-temperature operating conditions typical of long-haul diesel engines (Mera et al., 2020). Because a significant portion of India's HCV fleet still operates on BS-IV standards, retrofitting presents an opportunity to rapidly reduce harmful emissions without waiting for a complete fleet turnover to newer, cleaner BS-VI vehicles or e-HCVs. This is particularly crucial in urban and industrial areas suffering from poor air quality, where HCVs contribute disproportionately to local pollution.

Cost associated with retrofitting

As per the stakeholder consultation, only BS-IV vehicles can be retrofitted with a combination of DOC and PFFs. Retrofitting older vehicles with PFFs and DOC will cost around INR 50,000 for each vehicle. Associated maintenance cost largely depends on the vehicles' running condition.

Barriers, entry points, and the way forward

The absence of regulatory requirements for retrofitting hinders adoption. In the absence of clear regulatory guidelines or mandates requiring retrofitting, there is little motivation for fleet owners to invest in emission control devices voluntarily. Retrofitting involves both upfront investment and recurring maintenance costs. PFFs need periodic replacement or cleaning, while SCR systems require regular urea (AdBlue) refills and component servicing. These costs deter small and independent fleet operators who work with thin profit margins. Additionally, the effectiveness of passive regeneration is limited in India owing to traffic conditions that prevent sustained speeds. The absence of a national certification scheme for retrofit kits and accredited installers has led to quality concerns, further reducing trust and uptake among vehicle owners.

Introducing a regulatory framework that mandates retrofitting for older HCVs in high-pollution zones can drive demand. Incentives such as subsidies, reduced tolls, or lower road taxes for retrofitted vehicles can enhance economic viability. Allowing the operation of HCVs that are successfully retrofitted with certified emission control systems within cities could provide a strong financial rationale for fleet owners to comply.

4.2.3. Low-emission zones (LEZs)

Low-emission zones are designated areas where the entry of high-polluting vehicles, typically older or non-compliant with current emission standards, is restricted or discouraged. These zones aim to improve local air quality by reducing tailpipe emissions.

Emissions reduction potential

Global evidence suggests that LEZs can reduce PM and NO_x levels by 15%–30% within designated zones and accelerate fleet modernisation, as vehicle owners are incentivised to upgrade to cleaner alternatives to maintain access (Santos et al., 2019; Shin et al., 2024). However, this solution is still in its pilot phase in India (in the Pimpri Chinchwad area in Pune).

Barriers, entry points, and the way forward

Key challenges include the inability to track vehicle pollution levels or enforce entry restrictions without toll gates or monitoring at every entrance. Without physical infrastructure such as automated toll barriers, cameras, or Automatic Number Plate Recognition (ANPR) systems at every entry point, enforcing vehicle restrictions in LEZs is practically unfeasible. There is no clear legislative authority for municipalities or transport departments to ban vehicle entry based on age or BS norms without a judicial order or central directive. This limits the ability to enforce differentiated access policies. Restricting HCV access to key commercial areas may face pushback from logistics and supply chain operators, especially in the absence of alternative routes or timing-based exemptions.

For LEZs to be effective in the Indian context, establishing a clear national regulatory framework enabling states and municipalities to define, implement, and enforce LEZs is important. Deploying smart infrastructure, including ANPR cameras, Global Positioning System (GPS)–based monitoring, and digital tolling systems to detect and restrict high-emission vehicles, is needed. Linking LEZ access to BS compliance, retrofitting, or scrappage will provide strong incentives for clean vehicle adoption.

With the right legal, technological, and infrastructural support, LEZs can play a critical role in India's clean transportation roadmap and help cities achieve meaningful air quality improvement.

4.2.4. Widespread adoption of EVs

Electric vehicles also have a strong potential to cut emissions from HCVs as they can mitigate 100% of tailpipe emissions. However, at present, although EVs have penetrated the passenger vehicle market well, and e-bus adoption is increasing thanks to FAME and PM E-DRIVE schemes, there are very few e-trucks.

Cost associated with the adoption of e-HCVs

As per the literature and stakeholder consultation, EV adoption is showing significant growth in the bus segment; regarding other categories, EV models of HCVs have recently been introduced to the market. To evaluate economic viability, the TCO is calculated in comparison with a diesel bus, considering both the lower and upper range of cost estimates. Based on stakeholder consultation, the upper-range e-bus is assumed to operate using fast-charging infrastructure (12m_FC), while the lower-range e-bus is considered to operate on slow-charging infrastructure (12m_SC).

Table 5 provides TCO in INR/km by accounting for scenarios with and without PM E-DRIVE incentives to analyse the impact of policy support and cost differences between these two variants; the detailed calculation is given in Appendix F. The TCO of an e-truck is typically 14%–22% higher than that of its ICE counterpart (RMI, 2025). As per OEM websites, direct current (DC) fast chargers of 50 KW to 150 KW will cost around INR 5 lakh to INR 15 lakh. An ultra-fast charger of 350 KW will cost more than INR 20 lakhs. Installation and land cost will add INR 5–10 lakh, depending on various factors such as the number of chargers, types of commercial spaces, and location.

Table 5: *Comparative analysis of TCO (e-bus vs diesel bus)*

TCO (in INR/km)	E-bus (12m_FC)	E-bus (12m_SC)	Diesel bus (high-end)	Diesel bus (low-end)
Without incentive	55	43	51	44
With incentive	53	42	51	44

Barriers, entry points, and the way forward

The FAME scheme was launched by the Indian government to promote the adoption of electric and hybrid vehicles with a budget of INR 895 crores. To continue the momentum of FAME-I and further boost the adoption of EVs, FAME-II was launched with a total budget of INR 11,500 crores. The objectives of FAME-I and FAME-II include a 40% EV penetration for buses. Although e-buses are being widely adopted (specifically by city governments), e-trucks are still being evaluated by manufacturers.

In 2024, PM E-DRIVE was introduced with a budget allocation of INR 10,900 crores for 2 years. Out of the total budget, INR 500 crores are allocated to incentivise e-trucks and INR 4,391 crores for 14,028 e-buses by state transport agencies. Impacts of electrification policies are listed in Table 6. While this is encouraging, a budget of INR 500 crores for trucks is still inadequate.

Table 6: *Impact of electrification policies for e-trucks*

Policy	Unit cost	Barrier	Impact
FAME-I & -II	2–3.5 times the ICE equivalent	High battery cost, limited EV models for commercial use, lack of sufficient charging infrastructure, and commercial unavailability of e-trucks	Accelerated reduction in emissions through increased EV adoption, decreased reliance on fossil fuels, and mitigation of urban air pollution through widespread EV use. However, regions without charging infrastructure might see a slower transition, potentially widening urban–rural technological divides.
PM E-DRIVE			

Currently, e-trucks face high initial costs—two to three times that of their ICE counterparts—and a limited range of commercial models. Additional concerns include long charging times and a lack of charging stations, particularly outside city limits. Solutions include enhancing financial incentives for single-owner EV trucks, increasing the availability of fast-charging infrastructure along major routes, and supporting battery subscription models. Establishing automated or manual battery swapping stations would reduce downtime, ease range anxiety, and lower the upfront cost of ownership. However, battery interoperability poses a challenge among different OEMs.

4.3. Promotion of alternative-fuel-based HCVs (LNG/CNG/hydrogen)

Promoting alternative fuels such as CNG, LNG, and hydrogen offers a promising route to reduce tailpipe emissions from HCVs.

Compressed natural gas, widely used in urban public transport, has helped lower $PM_{2.5}$ emissions, especially through CNG-powered buses. With its longer range, LNG is better suited for long-haul freight but remains in early stages of adoption due to limited infrastructure. The expansion of both fuels is hindered by inadequate refuelling stations, especially on highways and rural routes. Further, LNG vehicles are few, with infrastructure and awareness still lacking. High upfront costs also limit fleet adoption.

Hydrogen, with zero tailpipe emissions and quick refuelling, is promising for long-distance heavy-duty transport, where battery EVs fall short. However, hydrogen deployment is almost non-existent in India, with only a few test trucks on the road. Challenges include high production costs, complex storage needs, a lack of refuelling infrastructure, and technical limitations under Indian conditions.

For hydrogen, pilot programmes and infrastructure investments are essential, along with international collaboration to accelerate development and adoption.

Unit costs of the vehicles with alternative technologies are discussed in Table 3.

4.4. Modal share shift

A critical long-term solution for reducing tailpipe emissions from HCVs lies in shifting a significant portion of freight movement from road to rail. Rail transport is inherently more energy-efficient and produces far fewer emissions per tonne-kilometre (km) than road-based alternatives, especially when powered by electrified networks. For medium to long distances, rail freight is significantly more cost-effective, averaging around INR 1.6 per tonne-km compared with INR 3.6 per tonne-km by road transport (NITI Aayog and RMI & India, 2021). By decreasing the dependency on diesel-powered trucks for long-distance cargo movement, the overall environmental footprint of the transport sector can be significantly reduced.

There are several structural and operational hurdles to shifting freight from trucks to rail. Key issues include inefficient and congested freight terminals, outdated infrastructure, and the prioritisation of passenger trains over freight on shared lines—all of which reduce rail's appeal for time-sensitive logistics. Additionally, developing dedicated freight corridors demands substantial capital investment for land acquisition, new tracks, and multimodal hubs, requiring strong policy backing and public–private partnerships. Notably, infrastructure spending on road freight and rail freight has shrunk in the last decade.

To address these challenges, a coordinated strategy is vital. Priority should be given to accelerating dedicated freight corridors along high-traffic routes, supported by modern terminals, efficient port linkages, and integrated logistics infrastructure.

Further, innovative solutions such as the Trucks-on-Train service should be actively promoted. This model involves loading entire trucks or trailers onto specially designed flatbed rail wagons for part of their journey, combining the flexibility of road transport with the efficiency of rail over longer distances. This approach not only reduces fuel consumption and emissions but also helps ease highway congestion and road maintenance burdens.

Ultimately, policy reforms, infrastructure investments, and stakeholder engagement are crucial to facilitate this transition. Incentives for logistics companies to adopt rail-based solutions, digital integration of freight booking systems, and synchronised operations between road and rail networks can further enhance the viability of this shift. With a clear vision and sustained commitment, modal shift from road to rail can become a cornerstone strategy in India's effort to curb emissions from the heavy-duty transport sector.

4.5. Scenarios for emissions reduction

To better understand the possible adoption of present and upcoming emission-reduction technologies, we conducted a stakeholder roundtable. Experts from various backgrounds, including think tanks, research organisations, government stakeholders, and regulatory bodies, were present and shared their opinions. A detailed summary of the roundtable discussions is provided in Appendix E. We have developed three scenarios based on existing and potential policies for emissions reduction. The high emissions reduction scenarios are presented in Tables 7 and 8. For the existing scenarios and lower and medium targets, please refer to Appendix F. Other than the above-mentioned mitigation measures, we have assessed the possibility of increasing the efficiency of freight movement by reducing the empty running of trucks.

***Table 7**: Emissions reduction potential of VVMP*

Category	Control measure		High adoption (%)		Reduction in $PM_{2.5}$ emissions (tonnes/yr)		Marginal abatement cost (unit cost [in crores] per $PM_{2.5}$ [tonnes/yr])	
			2030	2035	2030	2035	2030	2035
Scrappage	Mandatory scrappage	Govt	100	100	6,144 (8,094)	4,068 (5,404)	2.7 (2.0)	5.3 (4)
		Private	30	50	17,376 (32,036)	18,988 (35,107)	1.6 (0.9)	3.4 (1.9)

*The unit cost per $PM_{2.5}$ reduction includes the cost of replaced vehicles, but the cost of scrappage infrastructure is not included.

***Table 8**: Emissions reduction potential for the high adoption scenario*

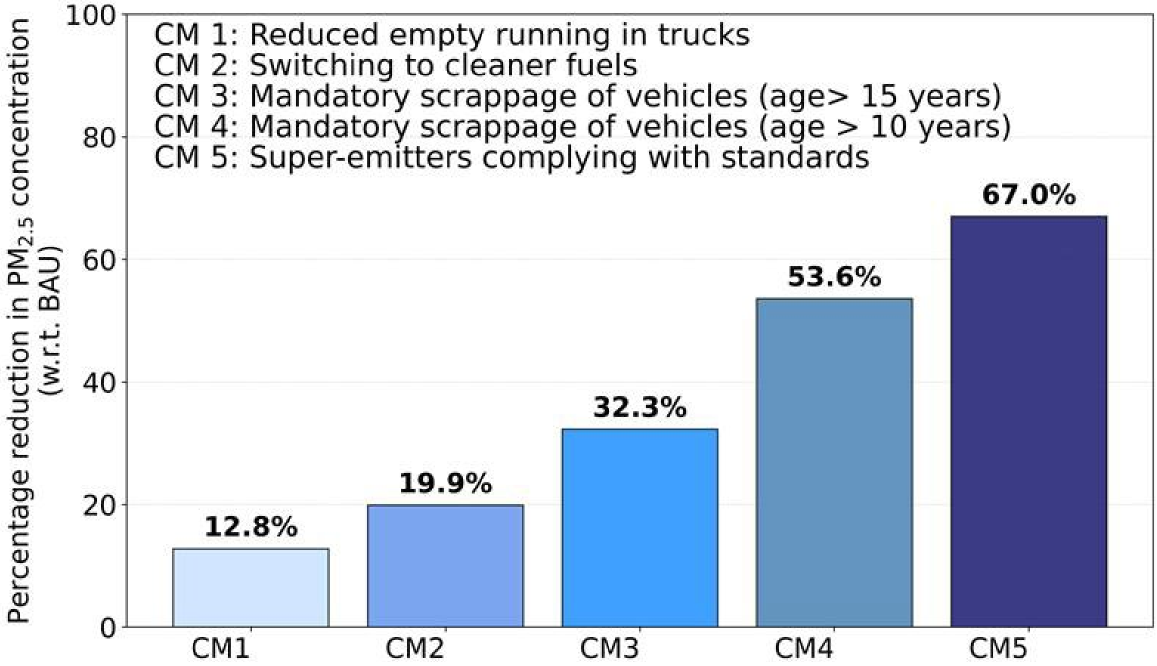
Category	Control measure	Baseline scenario	Target (%)		Reduction in $PM_{2.5}$ emissions (tonnes/year)		Marginal abatement cost (in crores)	
			2030	2035	2030	2035	2030	2035
Efficiency improvement	Reduce empty running	Empty running: 40%	30	25	6,206 (12,411)	5,577 (11,745)	-	-
Retrofitting	Installation of DOC and PFFs for BS-IV vehicles	0% adoption	50	-	2,000 (4,000)	-	0.67	-

Category	Control measure		Baseline scenario	Target (%)		Reduction in $PM_{2.5}$ emissions (tonnes/year)		Marginal abatement cost (in crores)	
				2030	2035	2030	2035	2030	2035
Switching to cleaner fuels	Increasing share of buses	Govt (25%)	EV: >1%–2%	80	90	176 (176)	399 (400)	510 (510)	372 (372)
			LNG: 1%	1	1				
			H_2: 0%	0	1				
		Private (75%)	EV: >1%	30	40	285 (285)	716 (716)	401 (401)	322 (322)
			LNG: >1%	10	15				
			H_2: 0%	0	0				
	Increasing share of trucks		EV: 0%	4	19	478 (992)	3,404 (7,070)	338 (163)	47 (23)
			LNG: >1%	7	30				
			H_2: 0%	0	0				

4.6. Air quality modelling simulation

To analyse the impact of different emission control measures on air quality in India, the study used the Rapid Estimation of Air Concentrations for Health (REACH) air quality model. Details of the REACH model can be found in Appendix I. For this study, 2022 was chosen as the baseline year and meteorological inputs from a global reanalysis data product for the same were used. The model-ready emissions were developed using national and state highway road lengths as proxies to apportion HCV emissions to each 0.25° × 0.25° grid cell for 2022. Emissions from HCVs for 2035 were projected based on registration data and SF. The 2035 model results were compared with those of the baseline year to estimate percentage reductions in HCV-linked $PM_{2.5}$ concentrations (i.e. the reduction in the ambient $PM_{2.5}$ attributed to HCV emissions, not total $PM_{2.5}$) in response to five different control measures. The emission reduction potentials for each scenario are listed in Tables 7 and 8; the resulting changes in $PM_{2.5}$ concentrations are shown in Figure 7. The maximum reduction in $PM_{2.5}$ concentrations (67%) was observed when super-emitters were identified and adequately repaired to comply with emissions standards. This would mean truck drivers would not need to invest in new trucks, and it could be the most effective policy if implemented properly. The scrapping of older vehicles was the next best option. The mandatory scrapping of more than 15-year-old HCVs resulted in a reduction in $PM_{2.5}$ concentrations by nearly one-third; further, more than half of $PM_{2.5}$ concentrations will be reduced if HCVs over 10 years old are scrapped. The other control measures that could be effective in reducing $PM_{2.5}$ concentrations are switching to cleaner fuels and reducing the empty running of trucks. These control measures resulted in about one-fifth and one-eighth reductions in $PM_{2.5}$ concentrations, respectively.

***Figure 7**: Reduction in HCV-linked $PM_{2.5}$ concentration (population-weighted national annual averages) in response to five different control measures (CMs)*

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Summary

5. Summary

Heavy commercial vehicles are significant contributors to air pollutant emissions in many non-attainment cities across India. Reducing emissions from HCVs is crucial for lowering the transport sector's overall contribution to air pollution. Achieving this will require enhancing initiatives such as PM E-DRIVE from the central government, improving enforcement by state authorities, technological advancements by OEMs, and active participation from the private sector.

Recommendations for the central and state governments are the following:

1. Super-emitters will continue to account for more than 50% of the total emissions from HCVs. India currently lacks a policy focused on the targeted removal of these super-emitters. We recommend the use of remote-sensing techniques and cameras to identify vehicles with excessive emissions. Violators should be encouraged or required to repair their vehicles to ensure they meet the applicable emission standards. Each successive violation by such vehicles should attract stricter penalties, ultimately leading to removal from the fleet through scrappage.
2. The scrappage policy remains an effective tool for fleet modernisation and reducing emissions. Although scrappage is already mandatory for government vehicles, we recommend making scrappage mandatory for private HCVs, as well. We also recommend enforcing mandatory scrappage based on engine emissions (e.g. persistent super-emitter status).
3. The study team recommends increasing HCV scrappage infrastructure significantly in all the states, along with simplification of the scrapping process (from an ownership point of view). This will help in faster fleet modernisation.
4. For maximum benefits towards emission reduction, a scrapped vehicle must be replaced by an EV. However, e-trucks are generally two to three times more costly than their diesel engine equivalents, though there is considerable TCO parity for e-buses. This study recommends increasing government incentives for EV adoption in the HCV segment.
5. Stopping the entry of HCVs older than 10 years, as a part of LEZs in all the major cities in India, will encourage private HCV owners to shift to new and low-emitting vehicles.
6. The government can push extended producer responsibility (EPR) to OEMs in cases where the latter are willing to buy back HCVs with added incentives after certain years in exchange for selling newer variants.
7. Emissions from BS-IV super-emitters and normal vehicles can be reduced through retrofitting, and we recommend that mandates be set for the same.

Total financial outlay for the scenarios is mentioned in Table 9.

***Table 9**: Estimated financial outlay for three scenarios (capital cost)*

Control measures			Total number of vehicles affected		Total capital cost (in thousand crores; INR)		$PM_{2.5}$ emissions reduction from HCVs (%)	
			2030	2035	2030	2035	2030	2035
Retrofitting vehicles			2,69,584	-	1.3	-	2.70%	-
Switching to cleaner fuels	Bus	Govt	66,739	1,15,241	90	149	1.30%	8.90%
		Private	74,159	1,52,024	111	223		
	Other HCVs		2,64,919	18,49,465	162	162		
Replacement of vehicles due to scrappage	Govt		22,754	22,036	16.5	21.4	27.5	44%
	Private		84,301	1,39,331	28	65		

Note: Costs for the repair of super-emitters are currently not available and should be investigated further.

India should focus on moving towards clean transport, but with a different timeline: buses can go electric early, whereas freight needs to go through intermediate fuels, including the much cleaner BS-VI (and potentially BS-VII) variants. Alternative fuels have the potential to reduce emissions from India's heavy vehicle sector, allowing for interim solutions till EV infrastructure picks up. Realising this vision requires targeted infrastructure development, supportive policy measures, industry collaboration, and a strong commitment to research and innovation. A comprehensive transformation of the transport sector is largely unattainable without private ownership embracing clean transportation. While the capital expenditure for acquiring a new vehicle may be high, government incentives, benefiting from lower running costs (especially in the case of e-buses), and avoiding penalties for operating polluting vehicles can yield significant economic benefits—even without factoring in the environmental gains.

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7. Appendices

7.1. Appendix A: Methodology

7.1.1. Emissions estimation methodology

The following equation was used to estimate HCV emissions for the base year 2022. The methodology used for emission estimation development is based on the vehicle fleet for each year; annual kilometres run for each category of HCV; and the deterioration factor, which takes care of the emissions rate due to the degradation of engines with an increase in vehicle age and respective emission factors based on the vehicle's BS category.

$$E_h = \sum \left(Veh_j \times D_j\right) \times EF_{i,j,km} \times DF_j$$

Here, Veh_j is the on-road vehicle count after multiplying the registered vehicles with the SF rate for each year, considering 2022 as the base year; Dj is distance travelled annually in kilometres; EF is the emission factor for vehicle type 'i' and fuel 'j' per kilometre; and DF is the deterioration factor for each category of the vehicle. To estimate national emissions from diesel-fuelled HCVs for the base year 2022, the activity data were obtained from the Vahan portal (Dashboard, Vahan Sewa) and emission factors from the Automotive Research Association of India (ARAI). From the Vahan portal, the annual registered HCV count for each state, except Telangana, was downloaded for 2000–2022. HCVs were divided into four categories: buses, trucks, dumpers, and water tankers. The state-wise usage data of dumpers and water tankers were obtained from state-wise regional transport offices and national survey data.

The SF was used to calculate the age-wise distribution of the HCV fleet (Pandey & Venkataraman, 2014b) .

The category-wise annual VKT was taken from the stakeholder consultations (Table A1). Emission factors for diesel-fuelled vehicles for pollutants, including PM, NO_x, CO, hydrocarbons (HCs), and BC, conforming to Indian standards from BS-I to BS-III, were derived from laboratory tests and values prescribed by ARAI. For BS-IV and BS-VI vehicles, laboratory-tested emission factors are not available. Based on stakeholder consultations, the emission norms have been used as a substitute. These norms specify the maximum allowable emissions from a vehicle and are outlined in the Indian Emission Regulation, released in 2021 by ARAI. The state-wise emission estimates were estimated using the above equations for the base year 2022.

Table A1: VKT considered for the HCV category (from stakeholder consultations)

HCV category	VKT (km/year)
Buses	1,00,000
Dumpers	65,700
Water tankers	10,920
Trucks	52,000
	1,09,500

7.1.2. Vehicular emission factors: Data sources and assumptions

Vehicular emission factors are critical for estimating emissions from diverse vehicle categories. These factors are typically categorised by the vehicle type, fuel type, and applicable emission standards, such as BS norms. In India, the ARAI—an autonomous institution under the Ministry of Heavy Industries—provides standard emission factors. These are derived from laboratory tests conducted using standardised drive cycles and account for pollutants such as CO, HC, NO_X, and PM, reported in grams per kilometre (g/km).

7.1.3. Data availability and limitations

Emission factors provided by ARAI cover BS-I to BS-III vehicles and certain categories under BS-IV. The Indian Emission Regulation also includes emission norms for BS-IV and BS-VI vehicles (ARAI, 2021). However, these norms, representing permissible emission limits rather than empirically derived emission factors, were not uniformly available for all vehicle–fuel combinations. To address such data gaps, expert consultations were conducted to establish a methodology for filling in the missing emission factors based on logical assumptions and regulatory guidance.

7.1.4. Colour-coded legend for emission factors tables

To enhance interpretability, the following colour coding scheme was used in the emission factors tables:

Green cells: Laboratory-tested emission factors from ARAI (2007, 2018)
Blue cells: Assumptions as per ARAI 2021 guidelines—for gross vehicle weight (GVW) >3.5 tonnes, CNG assumed to be equivalent to diesel; for GVW <3.5 tonnes, CNG to be assumed equivalent to petrol
Pink cells: Emission norms as per the Indian Emission Regulation (ARAI, 2021)

***Table A2**: BS-wise emission factors*

Vehicle categories	BS	NO_x (g/km)		CO (g/km)		PM_{10} (g/km)		$PM_{2.5}$ (g/km)	
		Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG
Buses	BS-I	6.77	6.21	3.97	3.72	1.075	0.044	0.914	0.037
	BS-II	6.53	6.21	3.92	3.72	0.3	0.044	0.255	0.037
	BS-III	5.172	15.156	4.735	9.221	0.482	0.023	0.41	0.019
	BS-IV	5.81	1.558	2.49	1.781	0.033	0.013	0.028	0.011
	BS-VI	0.664	0.664	2.49	2.49	0.017	0.017	0.014	0.014
Trucks	BS-I	9.3	9.3	6	6	1.24	1.24	1.054	1.054
	BS-II	8.63	8.63	4.13	4.13	0.42	0.42	0.357	0.357
	BS-III	8.353	8.353	4.857	4.857	0.399	0.399	0.339	0.339
	BS-IV	5.81	1.558	2.49	1.781	0.033	0.013	0.028	0.011
	BS-VI	0.664	0.664	2.49	2.49	0.017	0.017	0.014	0.014

7.1.5. BS-wise methodological notes

BS-I: Emission factors were primarily derived from ARAI's 2007 laboratory tests (The Automotive Research Association of India & CPCB and MOEF, 2007). For CNG-fuelled trucks, where data was lacking, diesel vehicle emission factors were used as per ARAI's 2021 guidelines for vehicles above 3.5 tonnes.

BS-II: As with BS-I, emission factors are largely based on ARAI's 2007 data. CNG truck emission factors were assumed to be equivalent to diesel counterparts, as per regulatory guidelines.

BS-III: Laboratory-tested emission factors from ARAI (2007, 2018) were utilised. Emission equivalence guidelines from the Indian Emission Regulation were applied to CNG trucks (ARAI, 2021).

BS-IV: Tested emission factors were available for select categories only (e.g., diesel 4-wheelers and light commercial vehicles, tested in 2018). For other categories, emission norms from the Indian Emission Regulation were used as proxy emission factors (ARAI, 2021).

BS-VI: Emission norms from the Indian Emission Regulation were uniformly adopted as proxy emission factors (ARAI, 2021).

The data used in emissions estimation, along with their respective sources, are detailed in Table A3.

Table A3: Data type used for the emission estimation

Parameter	Data type	Source
Activity data	Number of HCVs registered category-wise	Vahan Dashboard, MoRTH
	On-road fleet HCV numbers based on SF	Pandey et al. (2014)
	VKT travelled	Stakeholder consultation
Emission factors	Pollutant-specific emission factors	ARAI
Spatial allocation	State boundary	ArcGIS India basemap
Spatial proxy	For the REACH model run (0.25° × 0.25°)	OpenStreetMap road network

7.2. Appendix B: Super-emitters

7.2.1. What are super-emitters?

Super-emitters emit significantly higher levels of pollutants than other vehicles in the fleet. Abnormally high emissions can occur because of any of the following factors (or a combination thereof): old age / excessive vehicle use; overloading; and poor maintenance (Debbarma et al., 2024).

7.2.2. State-wise super-emitters' fractions

A previous study estimated the number of super-emitters for states (other than Telangana) and union territories (Table A4; Prakash et al., 2020).

Table A4: Number of super-emitters in the HCV fleet for the base year 2022

State/UT	<5 yrs (17% fleet)	5–10 yrs (17% fleet)	10–15 yrs (17% fleet)	>15 yrs (100% fleet)	Total super-emitters for 2022 fleet
Andaman Nicobar	85	64	37	95	280
Andhra Pradesh	9,120	8,306	7,361	14,343	39,131
Arunachal Pradesh	903	730	141	76	1,850
Assam	4,646	3,607	2,578	3,060	13,891
Bihar	6,592	6,789	3,980	4,386	21,747
Chandigarh	209	264	127	168	768
Chhattisgarh	6,917	6,306	3,797	9,205	26,226
Delhi	3,075	1,630	0	0	4,705
Goa	347	333	878	1,574	3,131
Gujarat	17,373	16,554	11,589	17,035	62,552
Haryana	18,328	14,993	9,892	19,816	63,029

Himachal Pradesh	2,769	2,818	2,234	4,112	11,933
Jammu & Kashmir	2,952	1,816	1,484	2,492	8,744
Jharkhand	4,845	5,555	3,412	5,322	19,134
Karnataka	15,035	14,793	10,699	30,517	71,044
Kerala	5,489	5,461	4,681	8,278	23,908
Ladakh	159	84	78	55	376
Madhya Pradesh	5,187	7,420	6,789	12,879	32,275
Maharashtra	28,543	22,308	15,604	20,775	87,230
Manipur	424	411	199	122	1,156
Meghalaya	935	595	958	1,122	3,610
Mizoram	497	245	159	291	1,193
Nagaland	8,046	7,367	4,383	4,994	24,790
Odisha	10,660	7,515	5,810	12,963	36,948
Puducherry	120	229	132	385	865
Punjab	5,880	7,334	5,528	8,393	27,136
Rajasthan	13,201	12,884	8,944	16,377	51,406
Sikkim	266	207	133	71	677
Tamil Nadu	14,506	13,017	12,517	28,487	68,527
Tripura	376	414	248	420	1,457
UT_DNH_DD (Dadra and Nagar Haveli)	1,479	483	328	659	2,950
Uttarakhand	1,920	21,86	1,770	3,614	9,490
Uttar Pradesh	21,990	21,631	12,203	20,248	76,072
West Bengal	10,518	11,312	8,270	16,125	46,225

Calculated based on Prakash et al.'s (2020) findings

7.2.3. How were the calculations done?

All vehicles older than 15 years and 17% of the fleet from each newer age group were considered super-emitters. This resulted in an estimated 23% of the on-road fleet in 2022 being super-emitters, compared with 25% in Prakash et al. and 43% in Debbarma et al. $PM_{2.5}$ emissions of super-emitters were estimated using the emission factor multipliers compiled by Prakash et al. and are reported for the base year (2022) in Figure 3. Emissions were estimated for the years 2030 and 2035 by including super-emitters.

7.3. Appendix C: State-wise $PM_{2.5}$ emissions

State-wise emission estimations based on the vehicle registration data for the base year 2022 are presented in Table A5, which shows Uttar Pradesh being the dominant state, contributing 14.92 Gg/yr to the total $PM_{2.5}$ emissions.

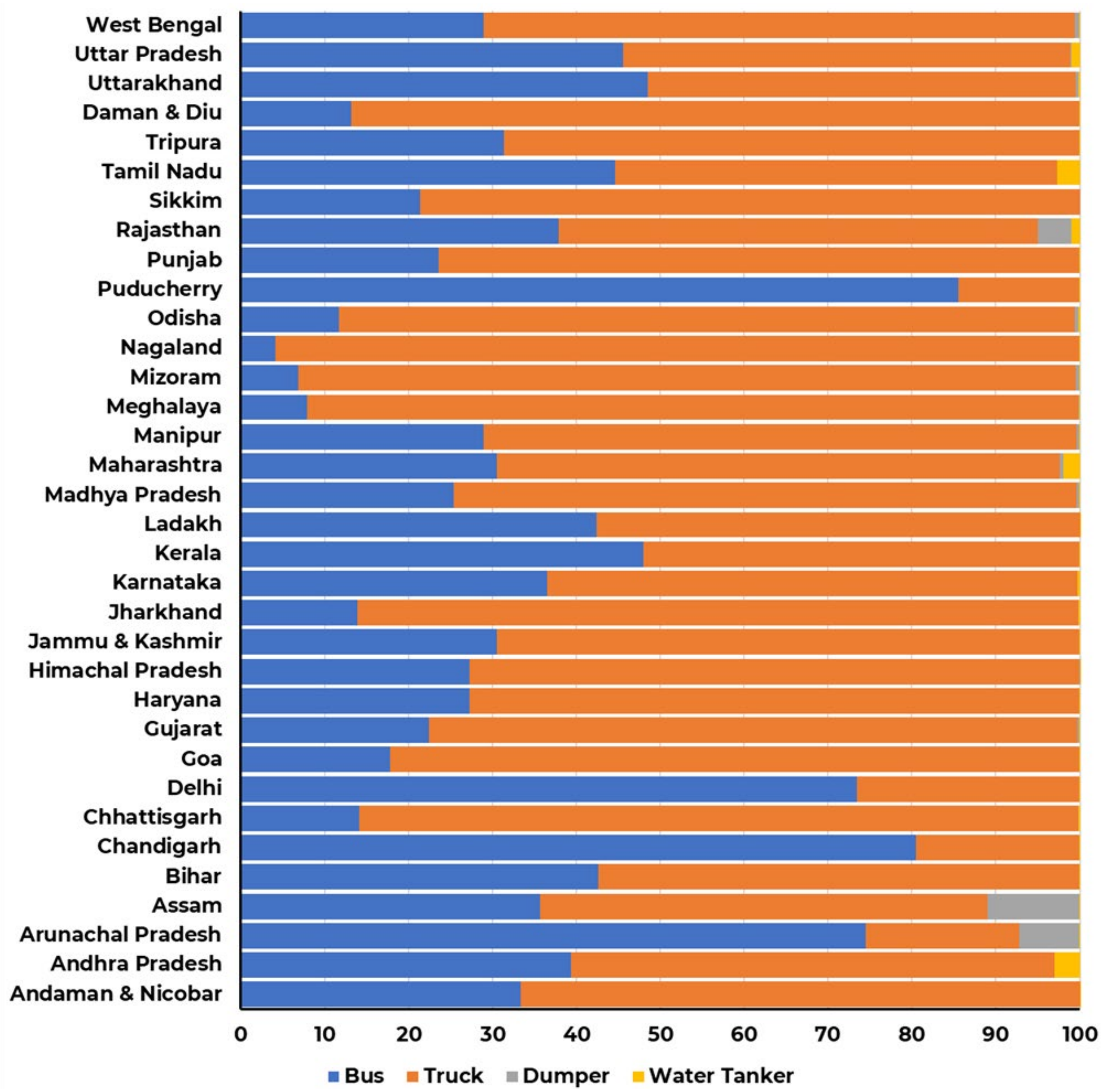
***Table A5**: State-level BS-wise HCV fleet and $PM_{2.5}$ emissions for 2022*

State	BS-I	BS-II	BS-III	BS-IV	BS-VI	$PM_{2.5}$ emissions (Gg/yr)
Andaman and Nicobar Islands	11	158	436	286	294	0.05 (0.07)
Andhra Pradesh	3,203	22,939	67,652	45,883	20,484	6.9 (10.8)
Arunachal Pradesh	15	166	3,841	4,101	2,399	0.2 (0.35)
Assam	849	5,242	28,049	18,099	14,549	2.1 (3.2)
Bihar	819	10,164	47,974	34,633	12,923	3.7 (5.7)
Chandigarh	30	282	1,912	752	720	0.19 (0.23)
Chhattisgarh	1,669	13,924	43,204	30,443	20,090	3.9 (7.1)
Delhi	0	0	2,108	1,284	2,104	0.8 (1.6)
Goa	287	2,609	5,424	1,302	1,112	0.6 (1.1)
Gujarat	3,010	26,712	1,33,357	69,913	51,800	9.5 (16.6)
Haryana	4,836	27,090	1,12,757	67,449	61,878	9.7 (16.6)
Himachal Pradesh	1,168	5,826	23,330	11,278	8,521	2.1 (3.6)
Jammu and Kashmir	580	4,327	13,875	11,089	9,402	1.4 (2.3)
Jharkhand	1,180	9,885	39,245	25,146	11,113	2.8 (5.2)
Karnataka	8,133	40,582	1,12,721	62,918	44,566	13.6 (22.2)
Kerala	2,051	12,934	47,478	21,374	16,383	5.0 (7.5)
Ladakh	33	119	728	398	669	0.06 (0.08)
Madhya Pradesh	3,444	18,757	65,186	28,102	11,491	5.9 (10.2)
Maharashtra	3,661	35,580	1,71,484	1,16,338	84,632	13.1 (21.4)
Manipur	33	351	2,500	2,070	1,257	0.15 (0.2)
Meghalaya	296	2,172	7,113	2,922	3,260	0.5 (1.0)
Mizoram	121	376	1,741	1,407	1,951	0.14 (0.25)
Nagaland	786	9,838	50,494	40,358	19,969	3.2 (6.0)
Odisha	2,946	22,347	53,144	46,296	29,332	5.3 (9.8)
Puducherry	156	445	1,631	757	220	0.28 (0.3)
Punjab	1,708	13,463	59,164	27,306	17,002	4.5 (7.8)
Rajasthan	4,026	24,837	97,278	55,190	41,105	9.1 (14.1)

State	BS-I	BS-II	BS-III	BS-IV	BS-VI	$PM_{2.5}$ emissions (Gg/yr)
Sikkim	10	218	1,601	709	1,096	0.09 (0.15)
Tamil Nadu	6,808	40,443	1,16,450	55,449	44,875	13 (19.6)
Tripura	109	754	2,919	1,261	1,479	0.25 (0.4)
UT_DNH_DD (Dadra and Nagar Haveli)	177	940	3,638	3,237	6,141	0.3 (0.5)
Uttarakhand	909	5,435	17,872	8,366	5,606	1.9 (2.7)
Uttar Pradesh	4,892	33,206	1,42,377	1,14,545	53,616	13.4 (20.4)
West Bengal	4,489	25,155	87,201	47,495	28,847	8 (13.4)

For the base year 2022, trucks account for the majority of $PM_{2.5}$ emissions across most of the states (Figure A1).

Figure A1: *Category-wise percentage share of $PM_{2.5}$ emissions in Indian states and UTs for 2022*



For the base year 2022, in most of the states, the percentage share of BS-I and BS-II category vehicles on the road was only 2% to 10%, respectively. However, these vehicles are responsible for 10%–35% of the $PM_{2.5}$ emissions. The on-road BS-III category vehicles were around 40%; these are responsible for up to 45% of emissions. In contrast, BS-IV and BS-VI category vehicles account for 15%–28% of the fleet but are responsible for only 10% of emissions. The state-wise share of $PM_{2.5}$ emissions by BS categories is presented in Figure A2, and the state-wise HCV fleet share by BS category is given in Figure A3. State-wise number of HCVs according to age is presented in Figure A4.

Figure A2: BS-wise $PM_{2.5}$ emissions in Indian states and UTs for 2022

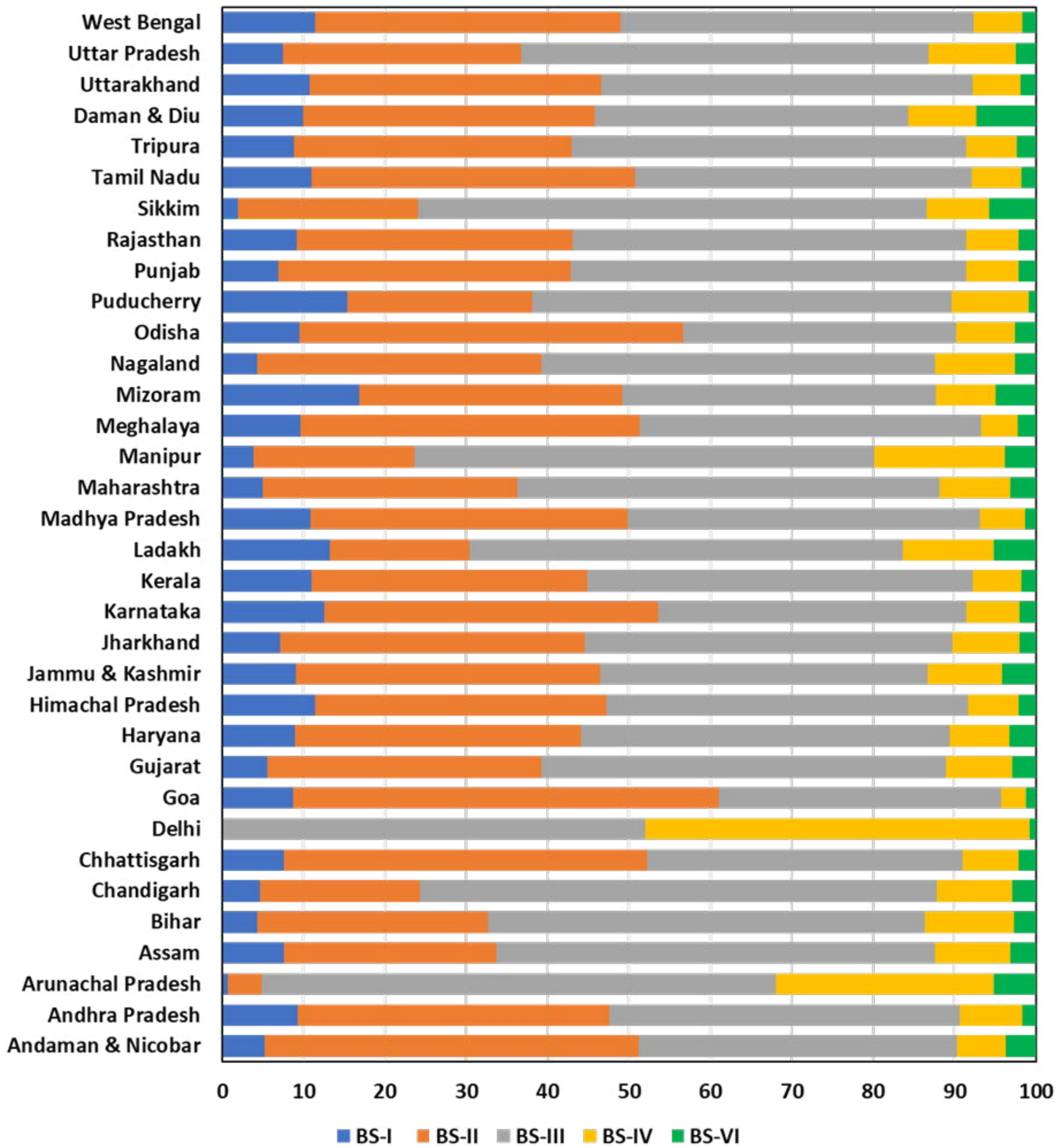


Figure A3: *Percentage share of HCVs based on BS-wise categories in Indian states and UTs for 2022*

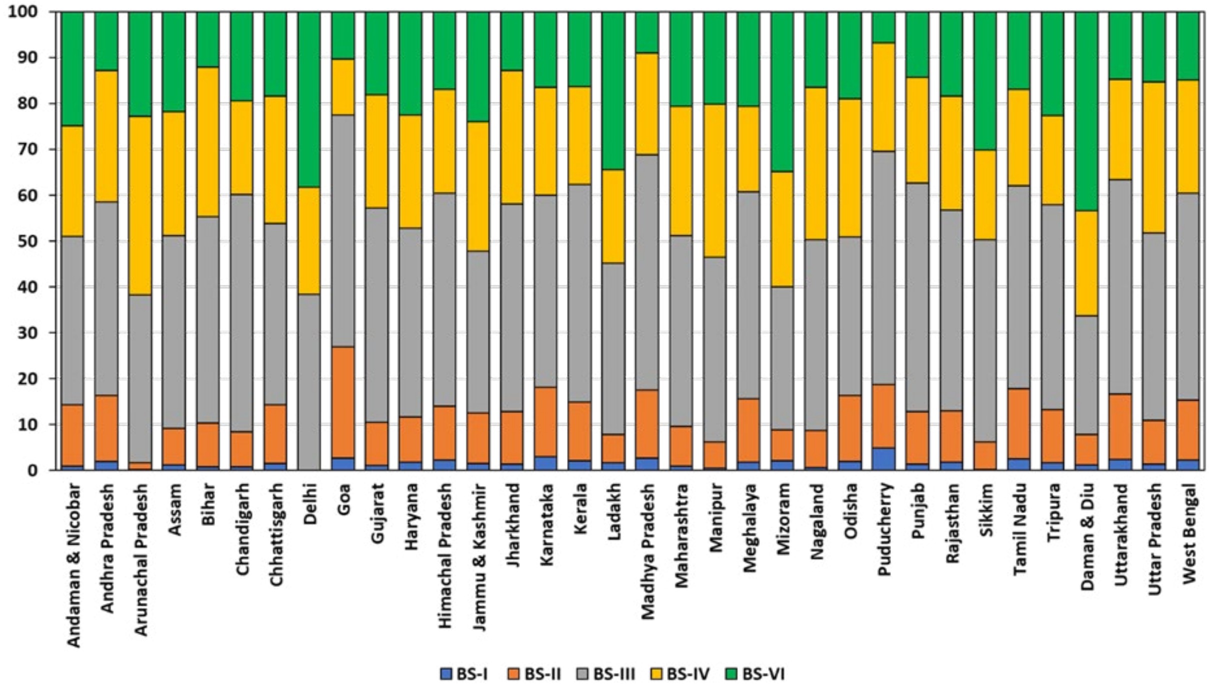
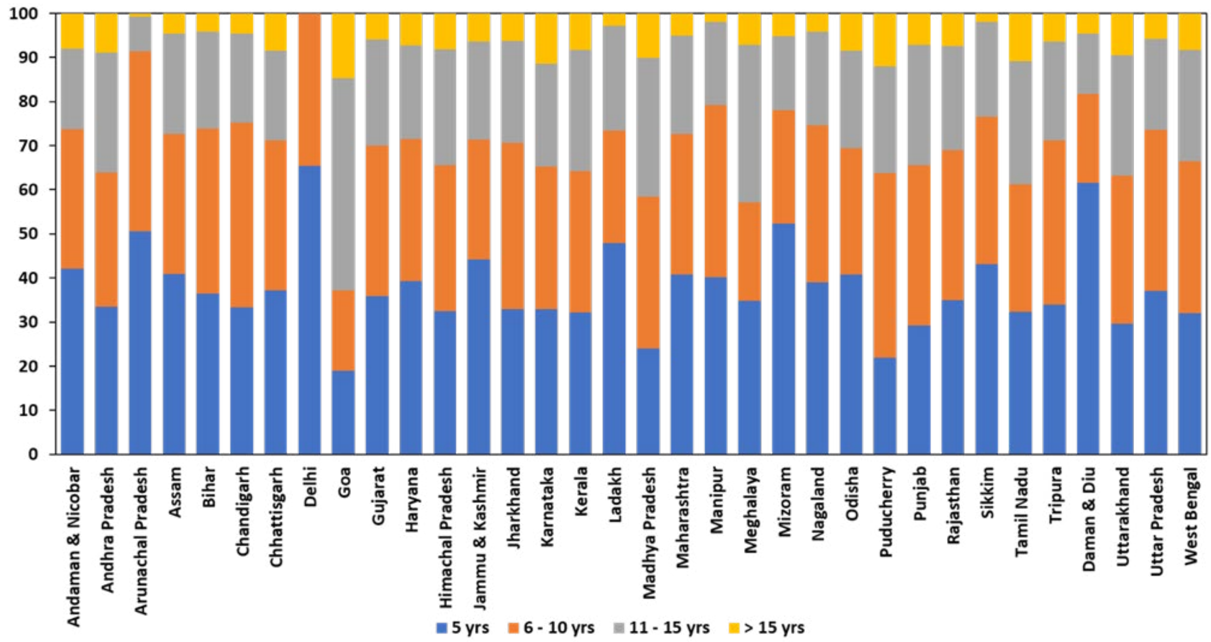


Figure A4: *Percentage share of HCVs according to age in Indian states and UTs for 2022*



7.4. Appendix D: Policies for mitigation of air pollution caused by HCVs

***Table A6**: National-level policies for mitigating air pollution caused by HCVs (notified)*

Policy name	Vehicle Scrappage Policy (GSR 720 [E] dated 5 October 2021)
Description	Voluntary scrappage of vehicles irrespective of age Mandatory scrappage of commercial vehicles and passenger ELVs Mandatory scrappage of government vehicles older than 15 years (from April 2022) Offers incentives (up to 25% tax concession) for scrapping
Benefit	Modernisation of fleet, increased share of clean-fuel vehicles on the road, and reduced pollution
Barrier	Inadequate infrastructure, high scrapping cost, compliance complexity, and environmental impact of scrapping
Recommendation	Ensure clear targets for OEMs' EPR, phased implementation, support for land acquisition for RVSFs, and increase public awareness
Detail (current progress)	128 RVSFs across India. A total of 40,590 private scrap applications have been submitted, with 38,601 having been approved and 1,989 still pending. Additionally, there are 9,631 government scrap applications and 28,813 defence/impound scrap applications (The number of HCVs is not specified.).

Policy name	FAME Scheme (FAME-I & -II; Department of Heavy Industry [DHI], n.d.; Ministry of Heavy Industries, n.d.-a)
Description	Policy push for EV adoption, infrastructure development (charging stations), and the provision of public subsidies. FAME-II extended to March 2024 with an INR 11,500 crore budget
Benefit	Accelerated EV adoption and reduced emissions
Barrier	High battery cost, limited EV models for commercial use, lack of sufficient charging infrastructure, and commercial unavailability of EV trucks (ongoing testing)
Recommendation	Incentives for e-trucks and e-buses, modernise testing facilities for EV technology, support installation of fast chargers, and provide financial support for charging stations
Detail (current progress)	6,862 e-buses were sanctioned to various cities, state transport undertakings, and state government entities for intra-city operations under the FAME-II Scheme. Out of 6,862 e-buses, 4,853 have been supplied till 31 July 2024.

Policy name	PM E-DRIVE Scheme (S.O. 4259 [E] on 29 September 2024; PM Electric Drive Revolution in Innovative Vehicle Enhancement [PM E-DRIVE] Scheme, 2024)
Description	Replaced FAME-II; INR 10,900 crore budget focusing on public transport EVs and fast chargers. Allocates funds for e-trucks, e-buses, and charging infrastructure development
Benefit	Enhanced electric mobility infrastructure and expansion of the EV market for public transport
Barrier	High cost of battery and EV trucks, need for extensive charging infrastructure, and lack of EV truck models
Recommendation	Provide direct financing for buyers, incentivise infrastructure development, arrange awareness campaigns targeting freight ecosystem stakeholders, and develop comprehensive charging infrastructure plans
Detail (current progress)	The scheme aims to enhance public charging infrastructure with over 22,000 EV chargers for electric four-wheelers and 1,800 chargers for e-buses, boosting EV user confidence. A total of INR 4,391 crores has been allocated for the procurement of 14,028 e-buses by public transport agencies. Additionally, INR 500 crore is set aside to incentivise e-truck deployment, with incentives for vehicles scrapped at the Ministry of Road Transport–approved RVSF centres.

Policy name	Auto Fuel Vision & Policy 2025 (2022; further stricter emission norms [BS-VI+]; Ministry of Petroleum & Natural Gas, 2022)
Description	B-VI norms implemented in 2020, skipping BS-V, to reduce $PM_{2.5}$ emissions by nearly 60%–90%. The policy includes DPFs and SCR systems in vehicles to improve air quality
Benefit	Mitigation of pollution caused by diesel emissions
Barrier	Costs of upgrading vehicles, infrastructure readiness for fuel transition, and market compliance challenges
Recommendation	Increased public–private partnerships to spread adoption, financial incentives for upgrading vehicles, and increased accessibility to BS-VI+-compliant fuels across the nation
Detail (current progress)	-

Policy name	National Rail Plan Vision – 2030 (2022) (Ministry of Railways, 2022)
Description	Aims to increase freight traffic share from 27% to 45% by 2030 through DFCs and the Trucks-on-Train service to reduce reliance on road transport and lower emissions
Benefit	Shifting of freight from road to rail reduces emissions, improves energy efficiency, and reduces logistics costs
Barrier	Inefficient freight terminals, long turnaround times owing to passenger train preference, and capital costs for infrastructure
Recommendation	Shared capital costs for private freight terminals, redesign junction stations to reduce detentions, and improve private sector incentives for terminal development

Detail (current progress)	A total of 657 km of the Eastern and Western DFC has been commissioned. The average freight train speed has doubled from 23 km/h to 46 km/h. Key corridors include East Coast (Kharagpur to Vijayawada), East–West (Bhusawal to Dankuni), and North–South (Itarsi to Vijayawada).

Policy name	Hydrogen Fuel for Commercial vehicles (2022) (Ministry of New and Renewable Energy, 2023)
Description	The National Green Hydrogen Mission supports hydrogen-based transportation technology with INR 19,744 crore allocated. Pilot projects are underway to establish hydrogen refuelling stations and support hydrogen vehicle technology.
Benefit	Promotes hydrogen as a zero-emission fuel
Barrier	High hydrogen production/storage cost, lack of refuelling infrastructure, and technical challenges in hydrogen fuel cell vehicles
Recommendation	Develop hydrogen infrastructure via public–private collaboration, introduce tax credits for hydrogen adoption, and increase research in hydrogen technology
Detail (current progress)	-

Policy name	Biofuel Promotion Policy (S.O. No.2492 [E] dated the 4th August, 2017; National Policy on Biofuels-2018 Amendment, 2022, 2022)
Description	National Policy on Biofuels (2018) aims for 20% ethanol blending in gasoline and 5% biodiesel blending by 2030 (later, the target date was reduced to 2026) to reduce dependency on conventional fuels.
Benefit	Reduces oil dependency and lowers emissions from conventional fuels
Barrier	Scaling biofuel production, supply chain issues, and economic feasibility for widespread biofuel use
Recommendation	Develop incentives for biofuel producers, build production infrastructure, support research into efficient biofuel crops, and promote cross-sector biofuel collaboration
Detail (current progress)	-

Table A7: Policies proposed for the reduction of emissions from HCVs

Policy name	Retrofitting HCVs with DPFs and SCR systems
Description	Reduces PM and NO_x emissions by 40%–95%. Conversion to CNG or LNG is proposed as an alternative to diesel.
Benefit	Improves air quality and supports cleaner fuel adoption
Barrier	High retrofit costs, integration constraints, availability of unadulterated fuel, and limited financing for LNG retrofits
Recommendation	Provide fiscal incentives, mandate cleaner fuel for HCVs, establish shared LNG stations along major routes, and pilot LNG adoption projects

Policy name	LEZs (possible)
Description	Designated areas restricting high-polluting vehicles and encouraging public transport and EVs; inspired by successful examples such as London's LEZ
Benefit	Improves urban air quality and reduces traffic emissions
Barrier	Limited awareness of the benefits of LEZs, enforcement challenges, and upfront costs for monitoring systems
Recommendation	Raise awareness on the benefits of LEZs, establish gradual LEZ standards to build compliance, and integrate with city planning to maximise public transport use

Table A8: Potential impacts (technical feasibility is not considered in this table)

Policy name	Vehicle Scrappage Policy
Environmental impact	Significant reduction in air pollution due to fewer high-emission vehicles on the road. Proper implementation could improve urban air quality and reduce vehicular emissions drastically, especially in congested cities.
Economic impact	Boost in automotive industry demand due to increased purchases of new vehicles; growth in the recycling and scrappage industry. However, infrastructure development costs for scrappage facilities may be a challenge without public support.
Social impact	A financial burden for owners of older vehicles who may struggle with the costs of new vehicles despite incentives.

Policy name	FAME Scheme (FAME-I & -II)
Environmental impact	Accelerated reduction in emissions through increased EV adoption, decreased reliance on fossil fuels, and mitigation of urban air pollution through widespread EV use.
Economic impact	Expansion of EV manufacturing could boost job creation in the green technology sector. However, investment in charging infrastructure and research in battery technology is needed to sustain growth.

Social impact	Wider EV adoption could improve the quality of life through better air quality and reduce fuel costs for EV owners. However, regions without charging infrastructure might see a slower transition, potentially widening urban–rural technological divides.

Policy name	PM E-DRIVE Scheme
Environmental impact	Expected to significantly reduce PM and NO_x emissions through large-scale deployment of e-trucks and e-buses and extensive charging infrastructure.
Economic impact	High initial costs for infrastructure. The scheme could attract private investment in EV infrastructure and foster competition among EV manufacturers, possibly reducing EV costs.
Social impact	The upfront costs of EVs may still be a barrier for some individuals.

Policy name	Stricter emissions norms (BS-VI+)
Environmental impact	The BS-VI+ norms can lead to a sharp reduction in $PM_{2.5}$, NO_x, and other toxic emissions from vehicles, improving public health, especially in urban areas.
Economic impact	Potential costs for compliance are higher in the automotive sector. It may indirectly encourage automakers to invest in cleaner technologies, benefiting the industry in the long term.
Social impact	Health benefits for populations and reduced healthcare costs related to pollution exposure. However, compliance costs may trickle down to consumers through higher vehicle prices, especially for diesel vehicle users.

Policy name	National Rail Plan (2030)
Environmental impact	Large reduction in PM emissions from trucks, if a substantial share of freight shifts to rail. Reduced environmental footprint of India's logistics sector.
Economic impact	Initial costs for rail infrastructure development, but long-term savings on logistics costs and enhanced efficiency in the freight sector. Competitive rail tariffs could support small and medium businesses in logistics.
Social impact	Creation of jobs in railway infrastructure and logistics. Potential to reduce road congestion, improving commuting conditions for general traffic. Some regions may benefit more than others based on rail infrastructure distribution.

Policy name	Retrofitting HCVs with DPFs and SCR
Environmental impact	Substantial reduction in PM and NO_x emissions from older diesel vehicles, extending vehicle life while lowering environmental impact.
Economic impact	Vehicle owners and retrofitting firms have to bear significant retrofit costs. Financial support could encourage faster adoption.
Social impact	Improved air quality benefits public health, but high retrofit costs may be a barrier for smaller businesses reliant on HCVs. Incentives may be necessary to prevent financial strain on small transport operators.

7.5. Appendix E: Stakeholder consultation

A stakeholder consultation meeting was conducted to understand the methodology and assumptions of this study and to discuss the technological interventions and available sustainable alternatives, best practices, and future opportunities in the transport sector for HCVs. Table A9 summarises the discussion on scenarios suggested for HCVs with reviews by the stakeholders based on the themes.

***Table A9**: Summary of stakeholder consultation conducted on 3 October 2024*

Serial No.	Proposed control measures by CSTEP	Review by the stakeholders
1	Installation of pollution control devices (PCDs) in trucks older than 10 years	Retrofitting technologies, such as DOCs and particulate flow filters (PFFs), show potential for reducing emissions in older vehicles, but a one-size-fits-all approach will not work as each vehicle's condition is different. If BS-IV vehicles have a remaining lifespan of 5–10 years, retrofits could be a viable option. However, pilot studies are needed for heavy-duty vehicles to assess the 1) efficiency and 2) durability of devices, as well as 3) low fuel penalty (<4%), before making any recommendations. Retrofitting BS-I, BS-II, and BS-III vehicles has technical limitations owing to the lack of electronic systems in older engines. It is challenging to integrate modern emission control technologies. Tampering issues pose additional challenges, as only BS-VI vehicles have anti-tampering techniques integrated. There are concerns regarding DPF regeneration and associated costs; thus, a combination of DOC and PFF was recommended. Both laboratory and real-world driving tests showed a PM reduction of approximately 55%–60% for the DOC and PFF combination. For retrofitting to be successful, it is crucial to ensure long-term system durability, establish reliable performance checks, and address implementation challenges such as costs and regulatory oversight.

Serial No.	Proposed control measures by CSTEP	Review by the stakeholders
2	Retrofitting older trucks with CNG / electric systems will not be a viable option, considering the initial cost	Retrofitting diesel trucks into CNG / hybrid models is not a viable solution for long-distance transportation, as the initial cost will be high. Retrofitting with CNG poses limitations for heavy-duty trucks due to the added weight of CNG systems, which reduces loading capacity and affects earnings per trip. Converting lighter trucks to CNG is feasible. However, for light commercial vehicles, electrification is a better option for vehicles running within cities.
3	Mandatory scrapping of commercial vehicles older than 15 years	A mandatory scrappage policy for older vehicles is essential to effectively clean up the older vehicular fleet. Without removing older vehicles from the roads, the impacts of new regulations and improvements, including the electrification of newer models, will be diminished. Recently, OEMs have agreed to offer a 6% discount on ex-showroom prices to individuals who scrap their vehicles and purchase new ones. However, this might not be enough to motivate consumers to scrap vehicles, as it is currently voluntary and not mandatory. The government should implement a supportive scheme for the scrappage policy, with contributions from OEMs, as well, since they stand to benefit from increased business. The focus should shift from capital expenditure (CapEx) to TCO when discussing incentives for scrapping commercial vehicles. While discounts on vehicle purchases are beneficial, they may not significantly impact decision-making, as operational expenses (OpEx) are more critical for fleet owners. Ultimately, if the TCO improves significantly, fleet owners will be more inclined to participate in the scrappage programme, as they see greater long-term benefits. Strengthening of regulatory frameworks, such as EPR and enforcing environmental compliance, will improve scrappage participation and accelerate the retirement of older, polluting vehicles. It is necessary to monitor older vehicles through remote sensing to identify super-emitters. These vehicles could then be sent for fitness checks and ultimately be scrapped. Stricter fuel economy regulations, such as Corporate Average Fuel Economy or Efficiency standards for HCVs, could also push manufacturers to produce cleaner vehicles. Propose to implement enforcement measures through annual insurance policies. There could be differential insurance premiums based on vehicle performance.

Serial No.	Proposed control measures by CSTEP	Review by the stakeholders
4	Transitioning of freight transport from road to rail	Expanding initiatives such as Roll-on/Roll-off (RORO) services, fostering private terminal development, and leveraging waterways for freight transport could help shift cargo from road to rail, reducing emissions and improving overall logistics efficiency. The railways have experienced an increase in absolute volume, which includes the total quantity of goods and passengers transported over a specific period, but operational challenges persist owing to prioritising passenger services over freight, unlike many European systems. In this context, a corridor approach could improve operations, but it needs an interconnected system rather than fragmented corridors. Regulatory reforms, such as a communal rating system for freight terminals and a shift to marginal cost pricing, are needed to improve efficiency, reduce costs, and encourage private sector involvement in rail freight. The decline in rail freight transport is largely because of the pressure of cross-subsidising passenger services, which distorts market dynamics and pricing. It is suggested that other ministries, such as Social Justice and Welfare, should manage this subsidisation to relieve the railways of this burden.
5	Switching to cleaner fuels (electric/hydrogen/LNG)	The government's vision of reducing fossil fuel imports aligns with the push for electrification, but it will take time to achieve substantial electrification across all segments, especially for HCVs, considering challenges such as battery size and charging infrastructure on highways. Cleaner fuels such as LNG, CNG, and hydrogen need to be considered as interim solutions for reducing emissions. There are investment gaps in EV adoption and insufficient government subsidies for the trucking sector. There is a need for increased funding, a phased incentive approach, and enabling policies. Technological innovations, stricter fuel economy regulations, and real-world testing are essential for accelerating the adoption of cleaner trucks, with tailored solutions for heavy-duty vehicles and sector-specific approaches to EV implementation. To significantly mitigate emissions, clear policies for the electrification of different vehicle classes are needed. Light-duty vehicles should target 100% electrification within the next 20 years, while medium-duty and heavy-duty vehicles can adopt partial electrification using alternative fuels such as LNG. Current subsidies under the PM E-DRIVE Scheme, though a step in the right direction, are deemed insufficient to stimulate the markets. We need increased funding and a broader support framework for the industry.

7.6. Appendix F: Scenario development

Three scenarios were developed based on the existing and potential policies for emission reduction. The existing scenario per the base year and targets considered for lower and medium scenarios are given in Table A10.

Table A10: *Existing baseline scenario and lower and medium targets for 2030 and 2035*

Category	Control measure		Baseline scenario (current adoption) 2030	Target percentage			
				Medium		Lower	
				2030	2035	2030	2035
Efficiency improvement	Reduce empty running in trucks		40% (empty running)	35%	30%	38%	35%
	Transitioning freight transport from road to rail		Truck: 73%	70%	63%	71%	68%
			Rail: 27%	30%	37%	29%	32%
Retrofitting	Installation of PCDs (i.e. DOCs and PFFs) in trucks for BS-IV category vehicles		0%	30%	-	10%	-
Switching to cleaner fuels	Increasing the share of buses that run on clean fuel	Govt (25%)	EV: >1%–2%	50%	70%	35%	55%
			LNG: 1%	1%	1%	1%	1%
			Hydrogen	0%	0%	0%	0%
		Private (75%)	EV: >1%	20%	25%	10%	15%
			LNG: >1%	8%	12%	3%	8%
			Hydrogen	0%	1%	0%	0%
	Increasing the share of trucks that run on clean fuel		EV:	3%	15%	2%	10%
			LNG: >1%	5%	20%	3%	15%
			Hydrogen	0%	1%	0%	0%

The estimated total number of HCVs for 2030 and 2035 is 43.9 and 81.3 lakhs, respectively, out of which the expected number of HCVs retrofitted by PFFs or replaced by electric/CNG/LNG/hydrogen vehicles are listed in Table A11.

***Table A11**: Number of HCVs affected (replaced/retrofitted) for the scenarios*

Control measure				2030			2035		
				Lower	Medium	Higher	Lower	Medium	Higher
Retrofitting in trucks, dumpers, and water tankers (i.e. DOCs and PFFs)				53,917	1,61,750	2,69,584	-	-	-
Switching to cleaner fuels	Increasing share of buses	Govt buses (25%)	EV	28,808	41,208	66,012	69,657	88,712	1,14,133
			LNG	727	727	727	1,108	1,108	1,108
			Hydrogen	0	0	0	0	0	0
		Private buses (75%)	EV	24,678	49,481	74,288	26,377	56,955	95,069
			LNG	7,320	19,717	24,678	30,280	45,528	56,955
			Hydrogen	0	0	0	0	3,614	3,614
	Increasing share of trucks		EV	47,970	72,115	96,253	3,77,120	5,65,955	7,17,023
			LNG	72,115	1,20,386	1,68,666	5,65,955	7,54,775	11,32,442
			Hydrogen	0	0	0	0	0	0

The unit cost per $PM_{2.5}$ emission reduction associated with lower and medium targets is listed in Table A12.

***Table A12**: Scenario table for lower and medium targets*

Sl. no	Category	Control measure	Baseline scenario (current adoption)	Reduction of $PM_{2.5}$ (tonne/yr)		Reduction of $PM_{2.5}$ (tonne/yr)		Marginal abatment cost (in crores)		Marginal abatment cost (in crores)	
				Medium		Lower		Medium		Lower	
				2030	2035	2030	2035	2030	2035	2030	2035
1	Efficiency improvement	Reduce empty running in trucks	40%	3,334 (6,206)	3,718 (7,830)	1,179 (2,482)	1,859 (3,916)	-	-	-	-
		Transitioning freight transport from road to rail	Truck: 73%	-	-	-	-	-	-	-	-
			Rail: 27%								

Sl. no	Category	Control measure		Baseline scenario (current adoption)	Reduction of $PM_{2.5}$ (tonne/yr) Medium 2030	Reduction of $PM_{2.5}$ (tonne/yr) Medium 2035	Reduction of $PM_{2.5}$ (tonne/yr) Lower 2030	Reduction of $PM_{2.5}$ (tonne/yr) Lower 2035	Marginal abatment cost (in crores) Medium 2030	Marginal abatment cost (in crores) Medium 2035	Marginal abatment cost (in crores) Lower 2030	Marginal abatment cost (in crores) Lower 2035
2	Retrofitting	Installation of PCDs (i.e. DOCs and PFFs) in trucks for BS-IV-category vehicles		Current adoption: 0%	1,400 (2,800)	-	700 (1,400)	-	0.6 (0.3)	-	0.4 (0.2)	-
3	Switching to cleaner fuels	Increasing the share of buses that run on clean fuel	Govt (25%)	EV: >1%–2% LNG: 1% Hydrogen: 0%	92	308	50	243	607	375	777	373
			Private (75%)	EV: >1% LNG: >1% Hydrogen: 0%	184	482	58	299	410	298	623	289
		Increasing the share of trucks that run on clean fuel		EV: 0% LNG: >1% Hydrogen: 0%	347 (721)	2,431 (5,050)	217 (451)	2,058 (3,607)	341 (164)	49 (23)	347 (167)	37 (21)

7.7. Appendix G: Techno-economic analysis

The TCO for the bus segment was calculated by comparing 50-seater interstate e-buses with diesel buses. Both the lower and upper cost ranges were considered following the methodology provided in the literature (WRI, n.d.).

Based on the stakeholder consultation, the upper-range e-bus was assumed to utilise fast charging (12m_FC), with a commercial electricity tariff of INR 25/kWh. The lower-range AC e-bus was considered to utilise slow charging (12m_SC), with an electricity tariff of INR 15/kWh.

The vehicle cost was considered an average of prices from multiple models reported by automotive websites. To estimate the total capital cost, the analysis included the vehicle cost along with road tax, vehicle insurance, and the vehicle resale values with a discount rate of 10% over the evaluation years. For the e-bus, the capital cost estimation also includes the PM E-DRIVE scheme incentives.

Maintenance cost for e-buses and diesel buses was considered as INR 7/km and INR 13.36/km, respectively. For EVs, the battery lifespan was considered as 6 years, and the battery replacement costs were considered based on the projections by BloombergNEF (2023), which estimates that the lithium-ion battery price would reach USD 65/kWh by 2030 (NITI Aayog, 2020). We assumed that the price remains constant after 2030. Table A13 provides the detailed costs considered for estimating the TCO analysis for both fuel types.

***Table A13**: Comparative analysis of capital and operational costs: e- vs diesel buses*

General detail				
Age of the vehicle	15 years	Discount rate	10%	
Daily VKT (km)	273	Resale rate for e-buses	10%	
Annual VKT (km)	1,00,000	Resale rate for diesel buses	15%	
Vehicle category	**E-bus (12m_ FC)**	**E-bus (12m_FC)**	**Diesel bus (high-end)**	**Diesel bus (low-end)**
Vehicle cost (INR)	2,00,00,000	1,00,00,000	90,00,000	43,00,000
Battery capacity (kWh)	320	125	-	-
PM E-DRIVE incentive (INR)	32,00,000	12,50,000	-	-
Total capital cost (INR)	1,60,94,886	83,51,426	96,17,278	45,94,921
Staff cost per month (INR)	1,50,000	1,50,000	1,50,000	1,50,000
Average fuel cost (INR/year)	27,45,597	22,46,397	27,45,597	22,46,397
Maintenance cost (INR/year)	7,00,000	7,00,000	13,36,000	13,36,000
Battery replacement cost (INR)	47,74,432	1,86,50,12.5	-	-

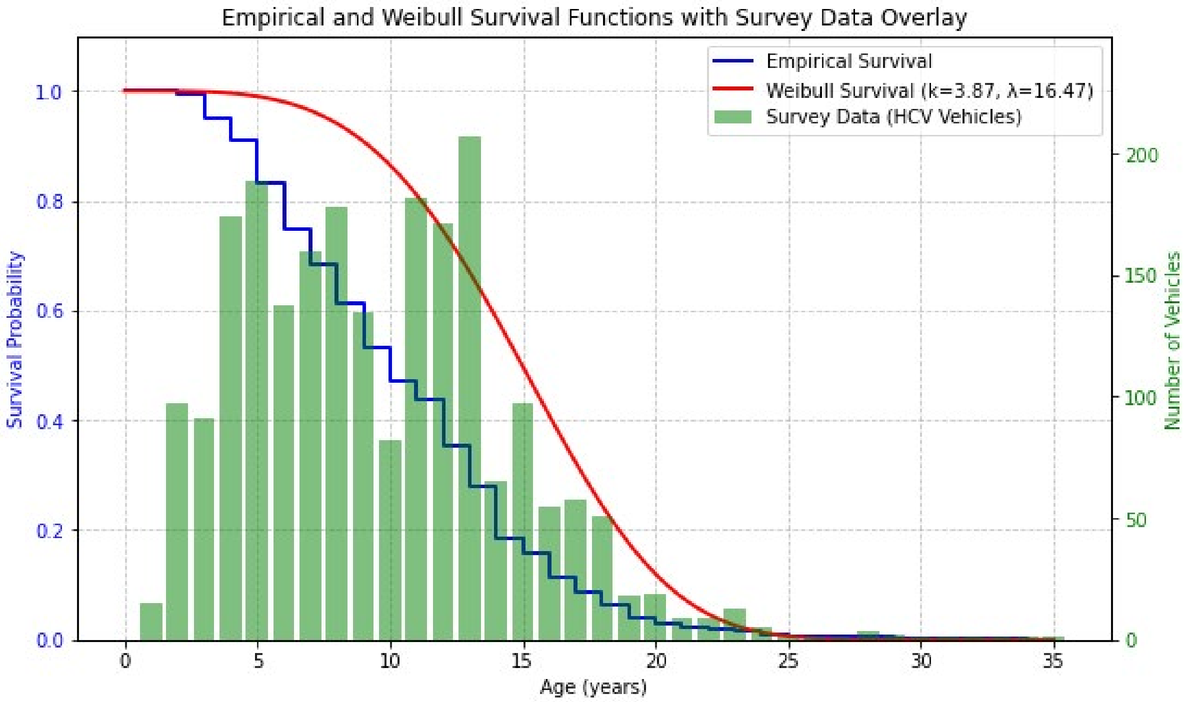
Total cost (capital + operational + maintenance; in INR)	7,95,74,004	6,39,22,191	7,67,21,126	6,60,03,342
TCO (INR/km)	**53**	**43**	**51**	**44**

7.8. Appendix H: Sensitivity analysis

Sensitivity analysis was performed for the estimated emissions inventory to assess the impact of emissions with changes in parameters, such as activity data and emission factors, which help in identifying uncertainty associated with the estimated emission values and focusing on data improvement methods.

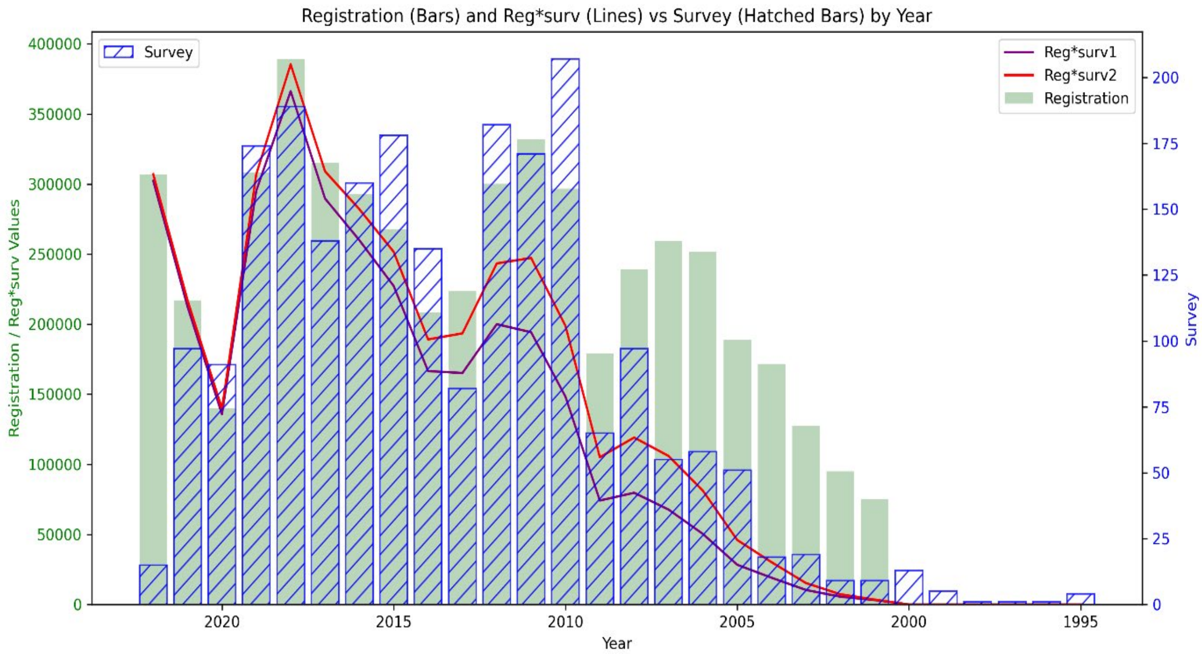
In the main study, the SF derived from the literature was used to determine the on-road fleet composition of HCVs and estimate emissions (Pandey & Venkataraman, 2014a). However, as per the petrol-pump survey conducted by CSTEP in 76 cities, there is a larger fraction of vehicles older than 10–15 years on the roads. Authors derived the SF using the survey data and the Weibull function, as shown in Figure A5 (Li et al., 2024; Li et al., 2024b).

Figure A5: *SF derived by using the Weibull function*



A comparison of the number of vehicles plying on the road using literature-based (surv1) and survey-based (surv2) SFs is presented in Figure A6.

Figure A6: Comparison of SFs based on the literature and survey data



The age-wise HCV fleet based on the estimated SF (SF-2) and literature-based SF (SF-1) is given in Table A14.

***Table A14**: Change in HCV fleet size based on SFs*

Year	HCV fleet size	
	SF-1	SF-2
<5 years	13,14,109	13,47,552
5–10 years	12,09,812	13,12,332
10–15 years	8,71,092	10,94,500
>15 years	2,70,654	4,16,976

Based on the SF selection, there is a difference of around 5 lakh vehicles plying on the road. Further, 73% of the difference is in the more-than-10 years-old category. This can result in a change in tailpipe emissions.

By using the estimated SF, the emissions are estimated for the base year 2022 (referred to as SF-2), as given in Table A15, along with the emissions estimated based on the SFs derived from the literature, referred to as SF-1 in Table A15.

***Table A15**: HCV fleet and category-wise emissions for the base year 2022 based on different SFs*

Vehicle type	Vehicle fleet as per SF		Emissions (Gg/yr)							
			PM_{10}		$PM_{2.5}$		NO_X		BC	
	SF-1	SF-2	SF-1	SF-2	SF-1	SF-2	SF-1	SF-2	SF-1	SF-2
Bus	10,87,174	12,47,067	52.2	74.5	44.4	63.3	272.4	311.7	31.1	44.3
Dumper	1,31,916	1,41,103	0.9	1.2	0.8	1	9.2	8.1	0.5	0.7
Water tanker	4,26,879	4,86,498	1.4	1.8	1.2	1.5	8.6	9.2	0.8	1.1
Truck VKT: 142 km/day	56,84,514	64,69,448	112.7	153.4	95.8	130.4	936.1	1,001.8	67.1	91.3
Truck VKT: 300 km/day			218.4	323.1	185.6	274.6	1,971.2	2,109.6	129.9	192.2

Appendix I: Air quality modelling

Rapid Estimation of Air Concentrations for Health (REACH) is a reduced complexity model (RCM). RCMs can estimate policy-relevant air pollution exposure at high spatial resolution significantly faster than traditional chemical transport models (CTMs) by simplifications such as using hourly data to predict annual-average $PM_{2.5}$ concentrations, which are more relevant for chronic health impacts and long-term policymaking. The REACH model is based on a non-steady-state Gaussian plume dispersion framework with simple representations of atmospheric processes such as dry/wet deposition and chemistry. The spatial resolution of REACH is defined by a set of centroids representing either regularly shaped grid cells or irregularly shaped administrative boundaries, and the domain extent could be defined over any spatial resolution and the region of interest. The input data to run the model are population, emissions, and meteorology. These inputs are used to calculate the source (emissions)–receptor (concentration) relationship (SR-Matrix) at each grid cell. Once developed, the SR-Matrix can be used with input emissions of primary $PM_{2.5}$ (including BC, organic carbon), NO_X, sulphur dioxide (SO_2), ammonia (NH_3), and non-methane volatile organic compounds (NMVOCs) to estimate $PM_{2.5}$ exposure differences for policy interventions (e.g. EVs replacing diesel trucks or biofuels replacing fossil fuels) in less time than traditional CTMs.

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