District-Level Road Transport Emission Inventory for Punjab Province, Pakistan: A 2015–2023 Multi-Year Assessment

Mahad Naveed*

Pakistan Air Quality Initiative, Lahore, Pakistan

Abstract

This paper describes the construction of a district-level road transport emission inventory for Punjab, Pakistan, covering the period 2015–2023. Annual emissions of six road-transport air pollutants and precursor species (nitrogen oxides [NO_x], carbon monoxide [CO], volatile organic compounds [VOC], fine particulate matter [$PM_{2.5}$], sulphur dioxide [SO_2], and ammonia [NH_3]) are estimated for nine vehicle classes across 36 districts using Punjab Bureau of Statistics (PBS) vehicle registration data. The inventory extends the IPCC 2006 Tier 1 road transport framework with two Tier 2 refinements: (i) a Weibull survival function is applied to annual new-registration cohorts to estimate the *actively operating* fleet in each year, following vehicle-survival approaches established for South Asian fleets (Guttikunda, 2024); and (ii) emission factors are adjusted for technology-vintage effects (Euro II blend for post-2012 cohorts) and fuel quality improvement (diesel SO_2 and PM reductions from 2015, coinciding with adoption of Euro II-equivalent fuel specifications). Raw PBS data required systematic correction for a 2022 flat-copy artefact (the PBS 2024 Statistical Pocket Book publishes 2022 values as a direct repeat of 2021, denoted by the '(R)' revision marker), a 2018 flat-copy artefact affecting

*Corresponding author. E-mail: mahad@pakairquality.com. ORCID: 0009-0000-7513-7552.

multiple vehicle types, and further class-specific point anomalies; all corrections use linear interpolation between flanking reliable values. Vehicle kilometres travelled (VKT), which are unavailable from PBS, are estimated from IPCC 2006 default ranges; fuel type fractions are calibrated from Pakistan Automobile Manufacturers Association (PAMA) sales data. Parametric uncertainty is quantified through Weibull survival scenario comparison (medium versus high scenario, 8–20% range on provincial totals) and a ±50% VKT sensitivity analysis, which constitutes the dominant uncertainty source and propagates linearly to all emission totals. The resulting district-level dataset provides a baseline monitoring record for pollution-risk assessment and spatial prioritisation of vehicle emission control interventions across Punjab's 36 administrative districts.

Keywords: vehicle survival modelling · emission factors · air-pollution exposure · Punjab · spatial inventory · uncertainty analysis

1 Introduction

Road transport constitutes a principal source of air pollutants and precursor species in South Asian urban environments and is associated with substantial adverse health outcomes (World Health Organization (WHO), 2021, 2018). Punjab, Pakistan's most populous province with over 110 million inhabitants, has undergone rapid motorisation over the past two decades; motorcycle registrations alone increased several-fold since the early 2000s (Punjab Bureau of Statistics (PBS), 2023). Notwithstanding this growth, no spatially disaggregated, multi-year road transport emission inventory for Punjab at the district level has been published.

District-level emission inventories are essential inputs to air quality dispersion models, to the attribution of pollution burdens across administrative units, and to the prioritisation of vehicle emission control policies. National-level inventories, while informative, obscure the considerable spatial heterogeneity in fleet composition and travel activity between, for example, the Lahore metropolitan area and the rural districts of D.G. Khan or Rajanpur.

The present inventory is a baseline monitoring dataset for air-pollution exposure assessment and spatial risk prioritisation. District-level resolution across nine years supports pollution trend analysis, identification of high-burden districts where monitoring infrastructure and emission controls should be concentrated, and future air-quality management planning. Growth patterns that single-year snapshots cannot resolve are visible over this horizon.

This paper reports the methods, results, and uncertainty assessment for the Punjab Road Transport Emission Inventory 2015–2023.

2 Background and Knowledge Gap

The IPCC (2006) three-tier framework is the reference standard for road transport emission inventories (Intergovernmental Panel on Climate Change (IPCC), 2006). Tier 1 uses aggregate fleet size, assumed annual VKT, and class-average emission factors; Tier 2 substitutes country-specific emission factors; Tier 3 applies age- and technology-resolved models. For Pakistan, where vehicle-technology distributions and local emission factor measurements are unavailable at provincial scale, Tier 1 is the appropriate and methodologically defensible starting point (Singh et al., 2022).

Sub-national emission inventories for road transport in South Asia have demonstrated the feasibility of district-level disaggregation under data-limited conditions analogous to those in Punjab (Sahu et al., 2014; Pandey and Venkataraman, 2014). Published inventories for Pakistan are predominantly national in scope. Mir et al. (2026) provides the most recent GAINS Tier 2 multi-pollutant estimate for Pakistan's transport sector, showing road transport accounts for 97% of total transport-sector emissions and that the post-2012 CNG fleet contraction shifted activity toward liquid fuels, increasing NOx and $PM_{2.5}$ intensities. Mir et al. (2023) estimated total road-transport black carbon at 181 kt for 2021. Bajwa and Sheikh (2023) document that road transport contributes 20–35% of urban primary $PM_{2.5}$ in Pakistani cities.

Real-world emission rates for key classes may exceed IPCC Tier 1 defaults. Measurement campaigns for two-wheelers and auto-rickshaws in South Asia report real-world CO

rates 40–50% above chassis-dynamometer values (Mahesh et al., 2019; Grieshop et al., 2012; Adak et al., 2016). For heavy trucks under Pakistani road conditions, Shaikh et al. (2022) measured NO_x at 10.69 ± 1.34 g km^{-1}, substantially exceeding Tier 1 defaults; HDV estimates from this inventory are therefore likely conservative.

Annual VKT per vehicle is the dominant uncertainty source in Tier 1 inventories. No province-wide VKT survey has been published for Pakistan; class-specific values are adopted from comparable South Asian inventories (Sahu et al., 2014; Singh et al., 2022; Guttikunda, 2024), with uncertainty explicitly bounded in Sect. 5.

No prior study has disaggregated road transport emissions across all 36 Punjab districts over a multi-year period. This inventory fills that gap.

3 Materials and Methods

3.1 Study Area

Punjab contains 36 districts grouped into 9 administrative divisions. A small number of records in the raw PBS dataset assign a district to more than one division across different years (specifically Okara, Pakpattan, and Sahiwal). These inconsistencies were resolved by assigning each district to the division appearing most frequently across all years in the source data. The resulting division–district mapping is summarised in Table 1.

Division	**Districts**
Lahore	Lahore, Sheikhupura, Nankana Sahib
Gujranwala	Gujranwala, Gujrat, Hafizabad, Mandi Bahauddin, Narowal, Sialkot
Faisalabad	Faisalabad, Chiniot, Jhang, Toba Tek Singh
Rawalpindi	Rawalpindi, Attock, Chakwal, Jhelum
Sargodha	Sargodha, Bhakkar, Khushab, Mianwali
Multan	Multan, Khanewal, Lodhran, Vehari
Sahiwal	Sahiwal, Okara, Pakpattan
Bahawalpur	Bahawalpur, Bahawalnagar, Rahim Yar Khan
D.G. Khan	D.G. Khan, Layyah, Muzaffargarh, Rajanpur

Table 1. Administrative divisions of Punjab and their constituent districts.

3.2 Data Sources

3.2.1 Vehicle Registration Data

Vehicle registration data are drawn from the Punjab Bureau of Statistics (PBS) *Statistical Pocket Book*, which tabulates registered motor vehicles by type, district, and year (Punjab Bureau of Statistics (PBS), 2023). The series used covers the period 2015–2023. PBS compiles annual district-level counts of motor vehicles registered with provincial motor vehicle authorities. The categories utilised in this inventory comprise: Motor Cycles/Scooters, Auto Rickshaws, Motor Cars/Jeeps/Station Wagons, Taxis, Pickups/Delivery Vans, Mini Buses/Buses/Flying/Luxury Coaches, Trucks, Tractors, and Other Vehicles. Registration counts represent the *cumulative stock of registered vehicles* as of the reference year and are not adjusted for retirements or deregistrations (Sect. 5.1). Figure 1 shows the estimated fleet growth trajectory for each vehicle class over the study period. The raw data can be accessed at `https://www.pbs.gov.pk/content/statistical-pocket-book-punjab`.

3.2.2 Emission Factors

Tier 1 default emission factors (g km^{-1}) are drawn from the IPCC (2006) Guidelines for National Greenhouse Gas Inventories, Volume 2, Chapter 3, Tables 3.2.2, 3.3.2, and Annex 3A.2 (Intergovernmental Panel on Climate Change (IPCC), 2006). Where IPCC tables provide a range, the mid-range value is selected, consistent with pre-Euro II technology conditions applicable to Pakistan's road fleet over the study period. Pakistan adopted Euro II equivalent tailpipe standards in 2009 under SRO 72(KE)/2009 (Government of Pakistan, Ministry of Environment, 2009); no binding national emission standard was in force prior to that date. Emission factors are therefore held constant across all study years as a conservative approximation (Sect. 5.2).

3.3 Vehicle Classification

PBS vehicle categories were mapped to nine vehicle classes uniformly across all districts. For all categories except "Motor Cars/Jeeps/Station Wagons", the mapping fraction is

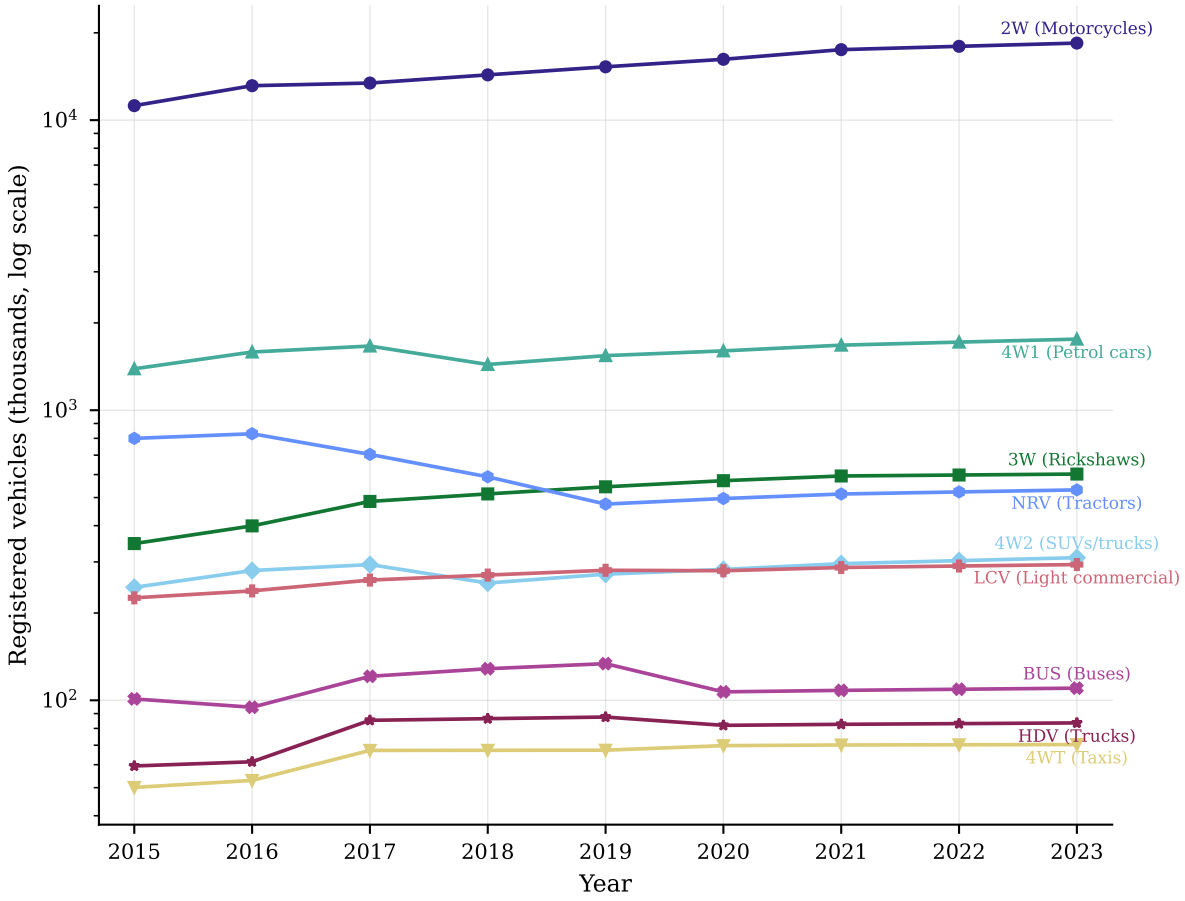


Figure 1. Registered vehicle fleet by vehicle class, Punjab, 2015–2023 (log scale). Data from PBS cumulative registration records (Punjab Bureau of Statistics (PBS), 2023) after cleaning (Sect. 3.4). The actively operating subset is estimated via Weibull survival correction (Sect. 3.7.3).

fixed across years. For Motor Cars, the 4W1/4W2 allocation is time-varying as described below. The PBS category "Other Vehicles" is excluded on account of its heterogeneous composition and the absence of a representative IPCC Tier 1 emission factor for this category.

4W1/4W2 split. The PBS category "Motor Cars/Jeeps/Station Wagons" aggregates vehicles without fuel-type sub-classification. Two sub-classes are distinguished: 4W1 covers all regular saloons and hatchbacks (petrol-fuelled), while 4W2 covers SUVs and passenger trucks (diesel-dominant, e.g. Land Cruiser Prado, Hyundai Tucson, Haval).

Analysis of Pakistan Automotive Manufacturers Association (PAMA) sales records for 2008–2023 reveals that the SUV/passenger-truck segment was negligible in the formal market before 2016 but grew to 20% of formal passenger-vehicle sales by 2023. Adding a

baseline offset of approximately 5 percentage points to account for grey-market used-SUV imports (Toyota Surf, Land Cruiser variants) and legacy diesel jeep registrations that do not appear in PAMA data, a time-varying share $s(y)$ is applied to the 4W2 allocation:

$$s(y) = \begin{cases} 0.05 & y \leq 2008 \\ 0.07 & y = 2015 \\ 0.10 & y = 2018 \\ 0.13 & y = 2021 \\ 0.20 & y \geq 2023 \end{cases} \tag{1}$$

with linear interpolation between anchor years. The 4W1 fraction is $1 - s(y)$, ranging from 95% in 2003 to 80% in 2023. No district-level fuel-type breakdown is available from PBS data; the split is therefore applied uniformly across all 36 districts.

3.4 Data Cleaning

3.4.1 Overview

The raw PBS dataset contains systematic errors identified through visual inspection of time-series plots and cross-district consistency checks. Three categories of anomaly are present: (i) a universal 2022 flat-copy artefact, in which PBS published 2022 vehicle counts as a direct repetition of 2021 values (denoted by the '(R)' revision marker in the PBS 2024 Statistical Pocket Book); (ii) a 2018 flat-copy artefact affecting multiple vehicle types; and (iii) class-specific point anomalies in isolated years. All corrections are implemented via linear interpolation between the nearest reliable values.

3.4.2 Interpolation Formula

For a corrupted value at year t bracketed by reliable values at years t_0 and t_1:

$$\widehat{v}(t) = v(t_0) + \big[v(t_1) - v(t_0)\big] \cdot \frac{t - t_0}{t_1 - t_0} \tag{2}$$

This formula assumes monotonic growth between anchor years, which approximates cumulative vehicle stock accumulation.

3.4.3 Correction Rules

Correction rules (Fix 1–Fix 7) were applied programmatically to each district–vehicle-type time series. Table 2 summarises all rules; complete specifications are provided in Appendix A.

Rule	Trigger Condition	Year(s)	Vehicle Types Affected
Fix 1	$v(2018) = v(2017)$ and $v(2017) > 0$	2018	Rickshaws, Motorcycles, Pickups, Taxis, Tractors, Trucks
Fix 2	$v(2022) = v(2021)$, PBS 2022(R) flat copy	2022	All
Fix 3	$v(2015) > 1.5 \times \bar{v}(2014, 2016)$	2015	Trucks
Fix 4	$v(2017) > 1.5 \times \bar{v}(2016, 2018)$	2017	Buses
Fix 5	$v(2017)/v(2016) < 0.75$ and $v(2018) = v(2017)$	2017–18	Tractors
Fix 6	$v(2017) < 0.5 \times v(2016)$	2017	Other Vehicles
Fix 7	$v(2015) < 0.8 \times \bar{v}(2014, 2016)$	2015	Pickups

Table 2. Summary of data cleaning rules applied to raw PBS district-level vehicle registration data. $\bar{v}(a, b) = [v(a) + v(b)]/2$; all corrections are implemented via Eq. (2).

3.5 Fuel Split Assumptions

The PBS registration data do not record fuel type; therefore, the fraction of each vehicle class operating on petrol, diesel, or CNG must be assumed. Fractions for most classes are held constant across the study period; the 4W1/4W2 fleet split is time-varying as described in Section 3.3. All values are explicitly designated as assumptions (Table 3). Two fuel-split assumptions were revised from prior literature values using PAMA sales data (2008–2023) as described under each class below.

Motorcycles (2W) are 100% petrol; no CNG or diesel motorcycle segment exists in Punjab at material scale. Auto-rickshaws (3W) operate on a mixed base: 85% petrol / 15% CNG, constant across years, reflecting partial CNG adoption in urban centres.

Class	Description	Petrol	Diesel	CNG
2W	Motorcycles/Scooters	1.00	0.00	0.00
3W	Auto Rickshaws	0.85	0.00	0.15
4W1	Saloons/hatchbacks ($1-s(y)$ of cars)	1.00	0.00	0.00
4W2	SUVs/passenger trucks ($s(y)$, time-varying)	0.35	0.65	0.00
4WT	Taxis	0.90	0.00	0.10
LCV	Pickups/Delivery Vans	0.70	0.30	0.00
HDV	Trucks	0.00	1.00	0.00
BUS	Buses/Coaches	0.00	1.00	0.00
NRV	Tractors	0.00	1.00	0.00

Table 3. Fuel fractions by vehicle class. Values are constant across years and districts unless otherwise noted. 4W2 fleet fraction $s(y)$ is time-varying (Eq. 1); LCV split revised from PAMA sales data.

Formal-market passenger cars (4W1) are entirely petrol-fuelled per PAMA records (Pakistan Automotive Manufacturers Association (PAMA), 2026). The 4W2 (SUV/passenger-truck) class contains a diesel-dominant formal segment (led by diesel SUVs) alongside a growing petrol-only crossover segment and grey-market diesel imports; weighting these components yields 65% diesel / 35% petrol for 4W2 (Pakistan Automotive Manufacturers Association (PAMA), 2026). Commercial taxis (4WT) are 90% petrol / 10% CNG.

PAMA sales records (Pakistan Automotive Manufacturers Association (PAMA), 2026) show a petrol-dominant LCV market (Suzuki Ravi comprising ≈72% of sales), with the remainder split across diesel pickups and vans; the LCV split is assigned 70% petrol / 30% diesel. HDV, BUS, and NRV are 100% diesel.

3.6 Vehicle Kilometres Travelled

Vehicle Kilometres Travelled (VKT) denotes the average annual distance travelled by each registered vehicle on public roads. No Pakistan-specific, district-level VKT survey data are available for the study period. Class-specific VKT values were adopted as assumptions informed by comparable South Asian emission inventories (Sahu et al., 2014; Singh et al., 2022; Guttikunda, 2024) and held constant across the study period 2015–2023 as district-level travel surveys sufficient to justify spatial VKT differentiation are unavailable (Sect. 5.3).

Per-vehicle VKT is held constant across the study period 2015–2023 at the class-

specific values in Table 4, derived from Goel and Guttikunda (2015) (Table 4) using compound annual growth-rate extrapolation from the 2000–2012 trend to 2015. This reflects Pakistan-specific evidence from Asian Transport Outlook (2024): national road transport energy consumption grew at approximately 2.9% per year over 2010–2020, while the registered vehicle fleet expanded at roughly 10% per year over the same period. These divergent rates imply that average per-vehicle travel has been declining rather than increasing, because aggregate VKT growth is driven primarily by rapid fleet-size expansion rather than by increased per-vehicle mileage. Corroborating this, road transport energy intensity per unit of GDP fell from 0.61 to 0.51 TJ per USD (PPP) between 2015 and 2020 (Asian Transport Outlook, 2024), confirming that rising economic activity has not translated into proportionally higher per-vehicle travel. Constant per-vehicle VKT is therefore the assumption most consistent with these observed trends.

Class	**Description**	**VKT (km veh^{-1} yr^{-1})**
2W	Motorcycles	12,300
3W	Auto Rickshaws	57,000
4W1	Petrol Cars	11,300
4W2	SUVs/Passenger Trucks	11,300
4WT	Taxis	57,000
LCV	Pickups/Vans	32,400
HDV	Trucks	23,300
BUS	Buses	45,600
NRV	Tractors	1,900

Table 4. Per-vehicle VKT (km vehicle^{-1} year^{-1}) held constant across 2015–2023. Base values from Goel and Guttikunda (2015) (Table 4) extrapolated to 2015 via compound annual growth rate from 2000–2012 data; constant treatment justified by energy and fleet growth trends from Asian Transport Outlook (2024); see Sect. 3.6.

3.6.1 Notes on Specific Pollutants

SO_2 for CNG. Natural gas contains negligible sulphur content; SO_2 emissions from CNG combustion are effectively zero. Accordingly, all CNG EFs for SO_2 are assigned a value of 0 g km^{-1} (Intergovernmental Panel on Climate Change (IPCC), 2006).

NH_3 from diesel. NH_3 is produced primarily by three-way catalytic converters on petrol vehicles. Diesel vehicles are not equipped with three-way catalysts; the small non-zero

values assigned (0.020–0.050 g km^{-1}) reflect incomplete conversion of nitrogen precursors during combustion (Intergovernmental Panel on Climate Change (IPCC), 2006).

PM from CNG. Residual $PM_{2.5}$ values for CNG vehicles are attributable to particulate matter generated by lubricating oil combustion; the CNG fuel itself produces negligible carbonaceous soot (Intergovernmental Panel on Climate Change (IPCC), 2006).

HDV and BUS diesel NO_x. Values of 6–7 g km^{-1} are characteristic of pre-Euro technology. Equivalent Euro VI standards yield approximately 0.4 g km^{-1}, which illustrates the sensitivity of long-run emission estimates to the constant-EF assumption adopted in this inventory.

3.7 Emission Calculation

3.7.1 Core Equation

Annual emissions of pollutant p for year y, district d, vehicle class c, and fuel type f are calculated as:

$$E(y,d,c,f,p) = \underbrace{\mathrm{Fleet}(y,d,c)}_{\text{vehicles}} \times \underbrace{\mathrm{VKT}(y,c)}_{\text{km veh}^{-1}\text{yr}^{-1}} \times \underbrace{\mathrm{FS}(y,c,f)}_{\text{fraction}} \times \underbrace{\mathrm{EF}(c,f,p)}_{\text{g km}^{-1}} \times 10^{-6} \tag{3}$$

where E is expressed in t yr^{-1} and the factor 10^{-6} converts grams to tonnes.

3.7.2 Effective VKT

The intermediate quantity *EffVKT* represents the total annual distance travelled by the district–class–fuel sub-fleet:

$$\mathrm{EffVKT}(y,d,c,f) = \mathrm{Fleet}(y,d,c) \times \mathrm{VKT}(y,c) \times \mathrm{FS}(y,c,f) \quad [\mathrm{km\,yr}^{-1}] \tag{4}$$

such that Eq. (3) reduces to:

$$E(y, d, c, f, p) = \text{EffVKT}(y, d, c, f) \times \text{EF}(c, f, p) \times 10^{-6} \tag{5}$$

3.7.3 Active Fleet via Weibull Survival

PBS registration totals represent the cumulative stock of vehicles ever registered—not the subset currently operating on the road. To estimate the actively operating fleet we apply a Weibull survival function to annual new-registration cohorts, following the approach established for South Asian fleet inventories (Guttikunda, 2024).

Annual new registrations (cohort size) for each vehicle class c are derived from the incremental change in the PBS cumulative total:

$$\delta(y_0, c) = \max\big(0,\ N(y_0, c) - N(y_0 - 1, c)\big) \tag{6}$$

where $N(y_0, c)$ is the PBS registered count for class c in year y_0. For the earliest available PBS registration year (2003) the full cumulative count is treated as a single entering cohort, as no prior annual breakdown is available to resolve individual cohorts.

The Weibull survival probability for a cohort of age $\tau = y - y_0$ years is:

$$S(\tau) = \exp\left[-\left(\frac{\tau}{\lambda}\right)^{\beta}\right], \quad \lambda = \frac{L_{1/2}}{(\ln 2)^{1/\beta}} \tag{7}$$

with class-specific shape parameter β and scale parameter λ derived from the median vehicle life $L_{1/2}$. Both β and $L_{1/2}$ are taken from the *high survival scenario* of Guttikunda (2024) (Table 5 therein), which parameterises three scenarios—low, medium, and high—reflecting uncertainty in how long vehicles remain in service across South Asian contexts. The high scenario is adopted here for two reasons: Pakistan has no mandatory vehicle scrappage policy; and the large informal repair sector, widespread CNG conversion, and comparatively lower vehicle replacement rates all extend operational lifetimes beyond the India-calibrated medium benchmark. Adopted parameters per class are listed in Table 5; β ranges from 2.0 (3W) to 4.0 (NRV), and $L_{1/2}$ from 12 yr (BUS, 4WT) to 22 yr (NRV).

The active fleet in inventory year y is then:

$$\text{Fleet}_{\text{active}}(y, d, c) = \sum_{y_0 \le y} \delta(y_0, c)\; w(y_0, c, d)\; S(y - y_0) \tag{8}$$

where $w(y_0, c, d) = N_{\text{PBS}}(y_0, d, c)/N_{\text{PBS}}(y_0, c)$ is district d's share of class-c PBS registrations in cohort year y_0.

The resulting active fleet is lower than the raw PBS cumulative total; province-wide, approximately 75% of registered vehicles are estimated to be actively operating in 2023. Sensitivity to the survival scenario is quantified in Sect. 5.2: switching from the high to the medium scenario reduces total $PM_{2.5}$ emissions by roughly 8–12%. Figure 2 illustrates the survival curves for each class group.

Class	**Description**	**Shape** (β)	**Median life** $L_{1/2}$ **(yr)**
2W	Motorcycles/Scooters	3.1	14
3W	Auto Rickshaws	2.0	15
4W1	Petrol Cars (saloons/hatchbacks)	3.0	16
4W2	SUVs/Passenger Trucks	2.5	15
4WT	Taxis	3.0	12
LCV	Pickups/Delivery Vans	3.0	20
BUS	Buses/Coaches	3.0	12
HDV	Trucks	3.8	18
NRV	Tractors	4.0	22

Table 5. Weibull survival parameters adopted for each vehicle class (high scenario, Guttikunda 2024, Table 5). The scale parameter $\lambda = L_{1/2}/(\ln 2)^{1/\beta}$ is derived from β and $L_{1/2}$ at run-time.

3.7.4 Technology and Fuel-Quality EF Corrections

IPCC 2006 Tier 1 emission factors represent pre-Euro (Euro 0) baseline conditions. Two correction factors are applied to the base EF for each cohort-year combination.

Technology correction (Euro II blend). Pakistan's S.R.O. 72(KE)/2009 (Government of Pakistan, Ministry of Environment, 2009) mandated Pak-II (Euro II-equivalent) standards for motor vehicles but permitted existing locally-manufactured petrol models to comply no later than 30 June 2012. Diesel vehicles were similarly regulated from July 2012 (Shaikh et al., 2022; Mir et al., 2026). Both fuel types therefore share a single

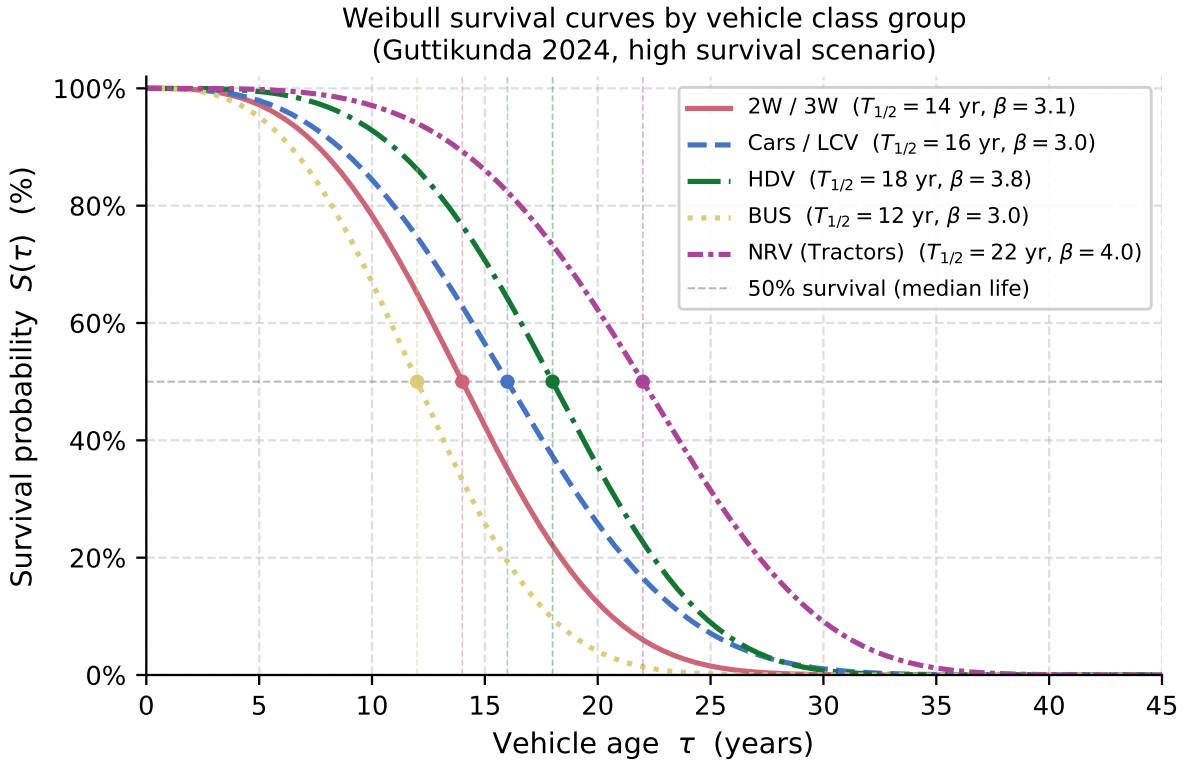


Figure 2. Weibull survival curves (Guttikunda 2024, high scenario) for the five vehicle class groups used in this inventory. Circles mark the 50% survival point at the adopted median life $L_{1/2}$; dashed vertical lines indicate the same ages. The higher shape parameters ($\beta > 2$) reflect more concentrated vehicle retirement around the median life relative to the Rayleigh ($\beta = 2$) special case.

effective compliance cutoff of mid-2012, and a unified post-2012 fleet fraction $\phi(c, y)$ is computed for each vehicle class c and inventory year y via the Weibull survival model (Sect. 3.7.3).

Because compliance in practice has been uneven, class-differentiated compliance fractions $\alpha(c)$ are applied: 30% for two- and four-wheelers (consistent with an estimated 2.5% yr^{-1} fleet penetration rate over 2012–2023; Bajwa and Sheikh 2023); 20% for light commercial vehicles; 5% for heavy trucks and buses, reflecting near-zero after-treatment uptake observed on the China–Pakistan Economic Corridor freight fleet (Shaikh et al., 2022); and 0% for non-road vehicles (agricultural tractors), for which no standard has been enforced.

The effective EF multiplier for a cohort registered in year y_0 is:

$$f_{\text{tech}}(c, y_0) = \begin{cases} 1 & y_0 \leq 2012 \\ 1 - \alpha(c)\big[1 - r_{\text{E2}}(f, p)\big] & y_0 > 2012 \end{cases} \tag{9}$$

where $\alpha(c)$ is the class compliance fraction and $r_{\text{E2}}(f, p)$ is the Euro II-to-Euro 0 EF ratio for fuel f and pollutant p. IPCC 2006 Tier 2 ratios adopted here are: petrol CO 0.40, VOC 0.20, NOx 0.21, PM 0.67; diesel CO 0.52, VOC 0.50, NOx 0.52, PM 0.30.

Fuel quality correction (diesel, post-2015). Euro II-equivalent fuel specifications limit diesel sulphur to $\leq$500 ppm, compared with $\sim$5,000 ppm typical of pre-reform High Speed Diesel (HSD) in Pakistan (Mir et al., 2023, 2026). Because SO_2 emissions scale directly with fuel sulphur content, adoption of Euro II fuel from 2015 implies a factor-of-ten reduction in diesel SO_2 EFs; particulate EFs are also reduced, though less sharply (Intergovernmental Panel on Climate Change (IPCC), 2006). Accordingly, the fuel-quality correction factor is:

$$f_{\text{fuel}}(y, f, p) = \begin{cases} 0.10 & \text{Diesel},\ y \geq 2015,\ p{=}\text{SO}_2 \\ 0.75 & \text{Diesel},\ y \geq 2015,\ p{\in}\text{PM} \\ 1 & \text{otherwise} \end{cases} \tag{10}$$

where PM denotes $PM_{2.5}$.

The combined effective EF for cohort y_0 emitting in year y is:

$$\begin{aligned} \text{EF}_{\text{eff}}(c, f, p, y_0, y) = \text{EF}_{\text{base}}(f, p) \\ \times f_{\text{tech}}(c, f, y_0) \times f_{\text{fuel}}(y, f, p) \end{aligned} \tag{11}$$

Because f_{tech} depends on vehicle class c, fuel type f, and cohort vintage y_0, while f_{fuel} depends on emission year y, both corrections are evaluated numerically for each cohort–year combination during inventory computation.

4 Results and Discussion

Province-wide emission totals are computed by summing Eq. (3) across all 36 districts for each year 2015–2023. Fleet sizes are derived from PBS provincial registration data (see Sect. 3.2.1); VKT and fuel split inputs are the class-specific values defined in Sects. 3.6 and 3.5. Following the screening-level inventory conventions of Sahu et al. (2014) and Pandey and Venkataraman (2014), results are presented as first-order best estimates with quantified uncertainty bounds (Sect. 5).

4.1 Effect of Corrections on Emission Estimates

Applying Weibull scrappage and EF corrections substantially reduces estimated emissions relative to a naive calculation using raw PBS cumulative fleet counts and constant pre-Euro EFs. For $PM_{2.5}$, corrections reduce the 2023 provincial estimate from 20,276 to 14,238 tonnes per year, a reduction of 30%. SO_2 is most strongly affected: the diesel fuel-quality correction reduces estimates by approximately 70% across all study years (e.g. 17,567 to 5,285 tonnes per year in 2015), reflecting the factor-of-ten sulphur reduction associated with Euro II fuel adoption. CO estimates are reduced by 12% in 2015 and 30% by 2023, with the growing share of post-2012 cohorts (which carry the Euro II technology blend) driving the increasing correction magnitude over time. NO_x corrections are more moderate (8–20%), as the Euro II NO_x ratio is closer to the Euro 0 baseline than for CO or PM.

4.2 Aggregate Emission Trends

Figure 3 presents total annual emissions for all six pollutants. CO dominates by mass, driven by the large two-wheeler fleet (>18 million motorcycles by 2023) and their high per-vehicle petrol CO emission factor (12 g km^{-1}). NO_x is dominated by heavy commercial vehicles despite their small fleet share, reflecting diesel EFs of 6–7 g km^{-1} for HDV and BUS. All pollutants exhibit a broadly positive trend driven primarily by fleet growth, moderated by the growing share of post-2012 Euro II-compliant vehicles in the Weibull-

weighted active fleet.

Emissions peak around 2021 and decline in 2022–2023, a pattern corroborated by Pakistan Automotive Manufacturers Association (PAMA) sales records (Pakistan Automotive Manufacturers Association (PAMA), 2026). Nationally, new vehicle sales fell 38% between 2022 and 2023, with passenger car registrations contracting 59%, motorcycle sales declining 34%, and three-wheeler sales falling 53%. This contraction reflects Pakistan's acute macroeconomic distress during this period. The country experienced a severe balance-of-payments crisis driven by post-pandemic inflation, the catastrophic 2022 floods, and rapid currency depreciation; this culminated in a US$3 billion IMF Stand-By Arrangement in June 2023 (International Monetary Fund, 2023; Government of Pakistan, Finance Division, 2023). Import restrictions on vehicles and components from late 2022 disrupted supply chains for locally assembled vehicles and reduced consumer demand (Government of Pakistan, Finance Division, 2023). New vehicle registrations fell sharply. With fewer cohorts entering the Weibull-weighted active fleet, aggregate activity and emissions contracted. PBS published 2022 vehicle counts as a flat copy of 2021 (denoted '(R)' in the PBS 2024 Statistical Pocket Book; Sect. 3.4). After correction by midpoint interpolation between 2021 and 2023, the 2022 emission estimate is thus an artefact of the interpolation rather than an observation: the corrected 2022 value distributes the 2021-to-2023 change symmetrically across both years. PAMA data show that nationally, 2022 new vehicle sales were in fact broadly similar to 2021 (-1%), with the genuine contraction concentrated entirely in 2023 (-38%). The emission decline visible in Figure 3 for 2022 therefore reflects this interpolation smoothing, while the 2023 decline is real.

4.3 Emission Contributions by Vehicle Class

Table 6 presents province-wide emissions disaggregated by vehicle class for 2015, 2021, and 2023, with percentage change relative to the 2015 base year.

Figure 4 shows emission contributions by vehicle class for the reference year 2023. Two-wheelers account for the majority of CO and VOC by mass due to fleet dominance. HDV and BUS together contribute a disproportionate share of NO_x and $PM_{2.5}$ relative

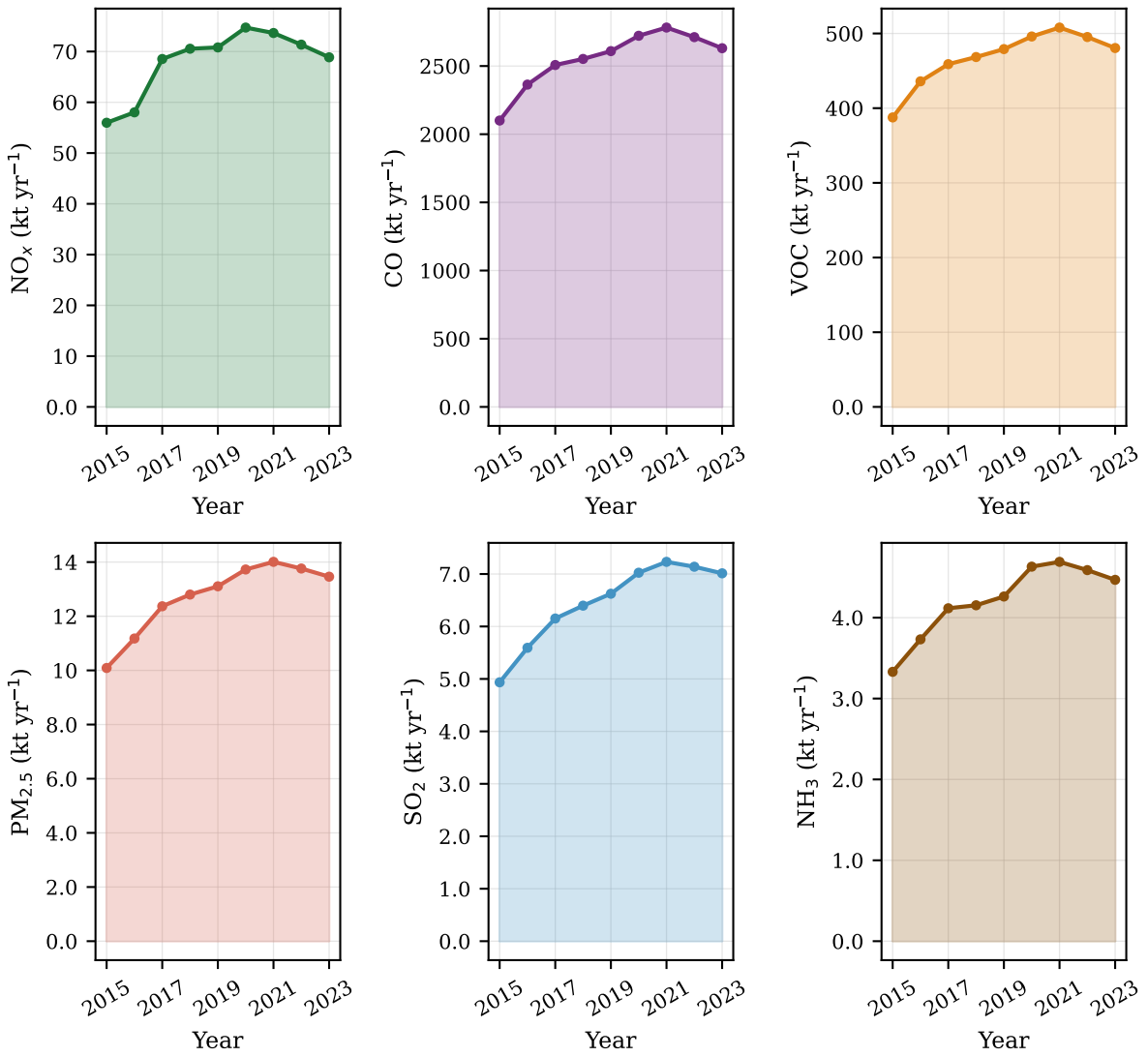


Figure 3. Estimated annual road transport emissions by pollutant, Punjab Province, 2015–2023 (kt yr^{-1}). CO dominates by mass, driven by the large two-wheeler fleet and high petrol CO emission factors. Uncertainty bounds are quantified in Sect. 5.

to their fleet share (<2% of registered vehicles), with per-vehicle EFs 60–70 times higher than motorcycles for NO_x and 20 times higher for $PM_{2.5}$.

4.4 Spatial Distribution of Emissions

Figure 5 presents the spatial distribution of total road transport emissions across all districts of Punjab for 2023. Emissions are allocated proportionally to district-level PBS fleet registration counts, reflecting the assumption that district fleet shares are the primary spatial driver of emission intensity in the absence of district-specific VKT data. Lahore, Faisalabad, and Rawalpindi emerge as the highest-emission districts, consistent

Class	NO_x (t yr^{-1})			CO (kt yr^{-1})			$PM_{2.5}$ (t yr^{-1})			SO_2 (t yr^{-1})		
	2015	**2021** (Δ %)	**2023** (Δ %)	**2015**	**2021** (Δ %)	**2023** (Δ %)	**2015**	**2021** (Δ %)	**2023** (Δ %)	**2015**	**2021** (Δ %)	**2023** (Δ %)
2W	11,661	14,743 (+26%)	13,977 (+20%)	1,432	1,856 (+30%)	1,767 (+23%)	6,162	8,244 (+34%)	7,898 (+28%)	3,072	4,257 (+39%)	4,104 (+34%)
3W	2,105	3,291 (+56%)	3,067 (+46%)	189	310 (+63%)	291 (+54%)	401	813 (+102%)	805 (+100%)	154	375 (+144%)	384 (+149%)
4W1	7,471	8,814 (+18%)	7,914 (+6%)	369	452 (+23%)	409 (+11%)	388	534 (+38%)	495 (+27%)	630	983 (+56%)	931 (+48%)
4W2	797	1,695 (+113%)	2,584 (+224%)	10.1	21.4 (+112%)	32.6 (+223%)	129	271 (+109%)	411 (+218%)	55.0	126 (+130%)	196 (+256%)
4WT	1,082	1,630 (+51%)	1,456 (+35%)	51.0	80.0 (+57%)	72.2 (+42%)	40.1	73.6 (+84%)	69.4 (+73%)	40.0	99.9 (+150%)	101 (+152%)
LCV	4,083	5,587 (+37%)	5,392 (+32%)	99.3	137 (+38%)	132 (+33%)	562	775 (+38%)	748 (+33%)	350	511 (+46%)	496 (+42%)
HDV	7,346	11,231 (+53%)	10,374 (+41%)	12.4	18.8 (+52%)	17.4 (+41%)	892	1,324 (+48%)	1,219 (+37%)	244	407 (+67%)	380 (+56%)
BUS	17,035	21,646 (+27%)	19,458 (+14%)	23.0	28.2 (+23%)	25.2 (+10%)	1,073	1,461 (+36%)	1,334 (+24%)	436	694 (+59%)	649 (+49%)
NRV	7,476	6,996 (-6%)	6,464 (-14%)	12.0	11.2 (-6%)	10.3 (-14%)	890	826 (-7%)	761 (-14%)	304	289 (-5%)	269 (-11%)
Total	**59,058**	**75,632** (+28%)	**70,688** (+20%)	**2,198**	**2,914** (+33%)	**2,758** (+25%)	**10,539**	**14,320** (+36%)	**13,742** (+30%)	**5,285**	**7,743** (+47%)	**7,510** (+42%)

Table 6. Provincial road transport emissions by vehicle class and pollutant, Punjab, for 2015, 2021, and 2023. Units: t yr^{-1} for NO_x, $PM_{2.5}$, and SO_2; kt yr^{-1} for CO. Percentage change (Δ%) is relative to the 2015 base year. Class codes: 2W = motorcycles; 3W = auto-rickshaws; 4W1 = petrol cars; 4W2 = diesel cars/SUVs; 4WT = taxis; LCV = pickups/vans; HDV = trucks; BUS = buses; NRV = tractors. All values use the Weibull HIGH scenario active fleet with Euro II technology and fuel-quality corrections applied.

with their dominant fleet sizes. Rural districts in western and south-western Punjab (Layyah, Bhakkar, D.G. Khan, Rajanpur) show the lowest emission totals, owing to smaller registered fleets.

District-level $PM_{2.5}$ spatial patterns are stable across years because district emissions are proportional to fleet shares; the growth across the study period reflects the province-wide fleet expansion documented in Section 3.2.1. Lahore, Faisalabad, and Rawalpindi consistently account for the largest district emission burdens.

4.5 Cross-Check Against National Estimates

Provincial totals are compared against national-level road transport emission estimates for Pakistan. Punjab accounts for approximately 53–56% of Pakistan's registered vehicle fleet (Punjab Bureau of Statistics (PBS), 2023); if emission intensity per vehicle is uniform across provinces, this fleet share implies a corresponding Punjab contribution to national road transport emissions.

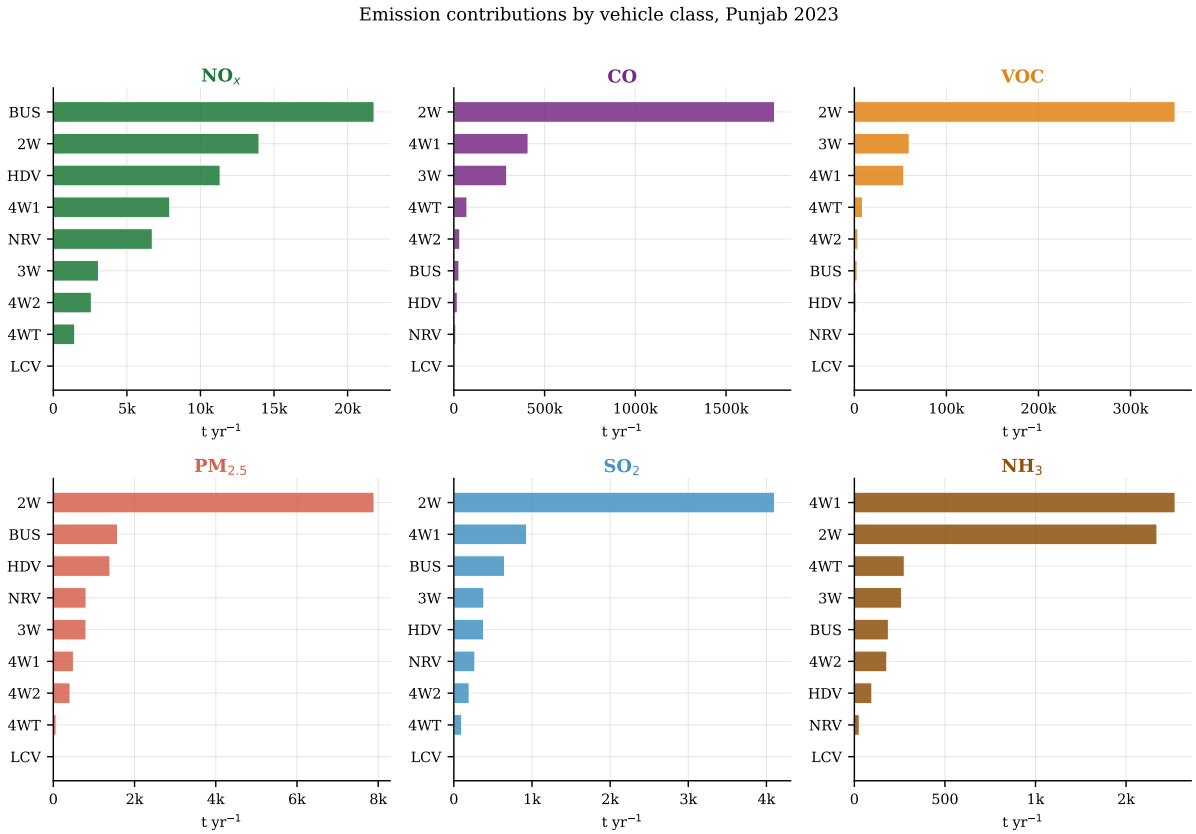


Figure 4. Estimated emission contributions by vehicle class, reference year 2023, for all six inventory pollutants (t yr^{-1}). Classes are ranked from lowest to highest within each panel. Two-wheelers (2W) dominate CO and VOC by mass; heavy commercial vehicles (HDV, BUS) rank highest for NO_x, $PM_{2.5}$, and SO_2 despite their small fleet share, reflecting high per-vehicle diesel emission factors.

Mir et al. (2026) developed a GAINS-model multi-pollutant scenario assessment for Pakistan's transport sector and reported national road transport totals for 2024 (Table S5 of that study). Table 7 compares Punjab 2023 estimates from this inventory against those national totals via a 55% fleet-share scaling. The two inventories use fundamentally different activity anchors: this inventory is vehicle-count-based, drawing active fleet estimates from PBS district registration records corrected by a Weibull survival function; Mir et al. (2026) anchor activity to the EnerNEO national energy model, calibrating vehicle-kilometres of travel to Pakistan Energy Yearbook fuel consumption totals. Each anchor has complementary strengths: this inventory resolves fleet structure and geography at district level; the GAINS approach implicitly captures informal and unregistered fleet activity through fuel balances. Divergences in the comparison below therefore reflect methodological choices rather than errors in either inventory.

$PM_{2.5}$ shows good agreement (implied national 25.9 kt yr^{-1} vs. Mir et al. 2026 national 21.5 kt yr^{-1}, ratio 1.20). $PM_{2.5}$ EFs for diesel vehicles are comparatively stable across methodological tiers, and the near-unity ratio provides mutual plausibility support for both inventories despite the one-year difference in reference year (2023 vs. 2024).

CO diverges substantially (implied national 5,033 kt yr^{-1} vs. 986 kt yr^{-1}, ratio 5.1), and the gap is traceable to both activity and emission-factor differences. On the activity side, the GAINS baseline fleet (Table S2 of Mir et al. 2026) models approximately 1 million gasoline motorcycles nationally—an order of magnitude below the 14 million active units estimated here for Punjab alone from PBS registration data; the fuel-consumption anchor of EnerNEO implies substantially lower 2W activity than PBS-derived vehicle counts suggest. On the emission-factor side, Mir et al. (2026) draw CO EFs from the GAINS South Asia regional database without Pakistan-specific PEMS or dynamometer validation; the authors themselves note that, due to the absence of local measurements, CO and VOC estimates for two- and three-wheelers "should be interpreted as best-available approximations rather than direct measurements" (p. 5 and p. 19 of that study). This inventory applies IPCC Tier 1 defaults for conventional gasoline 2W (17 g km^{-1}), consistent with measurement campaigns in comparable South Asian fleets (Mahesh et al., 2019; Grieshop et al., 2012); given that Pakistan's motorcycle fleet comprises a large proportion of pre-catalyst, carburetted two- and four-stroke engines, the Tier 1 default is considered the more appropriate choice for uncontrolled fleet conditions.

SO_2 shows the opposite pattern (implied national 13.7 kt yr^{-1} vs. 97.2 kt yr^{-1}, ratio 0.14), driven by explicitly different fuel-quality assumptions. This inventory applies a factor-of-ten correction to diesel SO_2 EFs from 2015, reflecting Pakistan's documented shift to 500-ppm Euro II-equivalent diesel. Mir et al. (2026) acknowledge (Section 2.3) that the GAINS model "does not explicitly incorporate functional adjustments for fuel sulfur content" in its emission factors; their reported SO_2 total of 97.2 kt yr^{-1}, with passenger cars contributing 57% of that total, is consistent with high-sulphur fuel assumptions and no time-varying sulphur correction. The fuel-quality correction applied here is tied to a documented regulatory event and is therefore considered more defensible

for post-2015 years.

NOx is ≈2.2× lower in this inventory (implied national 135.4 kt yr^{-1} vs. 294.5 kt yr^{-1}, ratio 0.46). Mir et al. (2026) apply technology-disaggregated GAINS EFs with a large proportion of Euro I heavy vehicles (Table S4 of that study), yielding higher HDV and bus NOx EFs than the IPCC Tier 1 defaults used here. The Euro II technology-blend correction applied to post-2012 diesel cohorts (at 5% compliance for HDV/BUS) in this inventory partially offsets the Tier 1 EF but does not fully close the gap, suggesting that NOx may be modestly underestimated for the heavy-vehicle segment.

$PM_{2.5}$ agreement across two independent methodologies provides the strongest plausibility support for this inventory. CO and SO_2 divergences are fully traceable to explicit, documented differences in activity anchors and fuel-quality assumptions; the more concrete and auditable parameterisations in this inventory (explicit sulphur correction, PBS-derived fleet counts, published IPCC EFs) are considered the more appropriate choices for a provincial inventory where local data can be interrogated directly.

Pollutant	**This inventory Punjab 2023** (kt yr^{-1})	**Implied national (Punjab ÷ 0.55)** (kt yr^{-1})	**Mir et al. (2024) Pakistan national** (kt yr^{-1})	**Ratio (implied/M2024)**
NO_x	74.5	135.4	294.5	0.46
CO	2,768	5,033	986.2	5.10
$PM_{2.5}$	14.2	25.9	21.5	1.20
SO_2	7.5	13.7	97.2	0.14

Table 7. Cross-check of Punjab 2023 estimates against national benchmarks. Col. 2: this inventory's provincial totals (2023). Col. 3: implied Pakistan national total assuming Punjab accounts for 55% of national road transport emissions (proportional to fleet share). Col. 4: road transport totals from Mir et al. (2026) Table S5 (2024 baseline). Col. 5: ratio of implied national (col. 3) to Mir et al. national (col. 4); ratio near 1.0 indicates consistency. Divergence in CO and SO_2 reflects methodological differences discussed in the text.

4.6 $PM_{2.5}$ Emissions and Health Implications

Primary $PM_{2.5}$ from diesel exhaust makes HDV, BUS, and LCV the dominant vehicle-class sources, despite their small fleet shares. The 2021 WHO Air Quality Guidelines annual mean of 5 μg m^{-3} (World Health Organization (WHO), 2021) is routinely exceeded by an order of magnitude in Pakistan's major cities; road transport contributes an estimated

20–35% of urban primary $PM_{2.5}$ (Bajwa and Sheikh, 2023). The spatial concentration of heavy-diesel activity in Lahore (≈18% of provincial HDV registrations) and Faisalabad means public health exposure is highly unequal across districts: urban populations receive elevated $PM_{2.5}$ doses relative to rural areas where fleet density is lower. Targeted HDV and BUS emission controls are therefore a high-priority public health intervention.

4.7 Role of Sulphur Dioxide

Road-transport SO_2 arises from combustion of sulphur-bearing diesel and petrol; HDV and BUS dominate, with negligible contributions from CNG-fuelled 3W and 4WT (pipeline gas is effectively sulphur-free). The step reduction in SO_2 from 2015 (Figure 3) reflects Euro II-equivalent diesel specifications reducing sulphur from ∼5,000 ppm to ≤500 ppm. SO_2 is both a direct respiratory irritant and a secondary $PM_{2.5}$ precursor; transition to ultra-low sulphur diesel (≤10 ppm) would eliminate road-transport SO_2 in a single fuel-quality step.

5 Uncertainty and Limitations

5.1 Registered vs. Active Fleet

PBS data record *registered* vehicles rather than *active* vehicles on the road. A vehicle that has been scrapped or abandoned remains in the cumulative total unless formally deregistered, and Pakistan operates no systematic end-of-life vehicle tracking mechanism. This inventory addresses the bias through a Weibull survival function (Sect. 3.7.3), following the cohort-based survival approach applied to South Asian fleets by Guttikunda (2024). Annual new-registration cohorts are estimated from the incremental change in the PBS cumulative total; each cohort is then discounted by a Weibull probability $S(\tau)$ as it ages, with class-specific median lives of 12–22 years (high survival scenario). Province-wide, roughly 75% of PBS registered vehicles are estimated to be actively operating in 2023.

A residual uncertainty remains because the 2003 base cohort is treated as entering the fleet with age zero, whereas the actual average age of vehicles registered by 2003 was

likely several years. This conservatively understates scrappage for the earliest cohorts and therefore slightly overestimates the active fleet in the early study years relative to a full vintage reconstruction. The survival scenario is adopted from the Guttikunda (2024) high scenario rather than calibrated to Pakistan-specific data, which are unavailable. Switching to the medium scenario (shorter $L_{1/2}$) reduces province-level $PM_{2.5}$ by approximately 8–12% (see Table 8 and Fig. 6).

Pollutant	Year	Baseline ($t\,yr^{-1}$)	Medium ($t\,yr^{-1}$)	High ($t\,yr^{-1}$)	High vs Medium (%)
NO_x	2015	71,714	55,197	59,058	+7.0
	2018	88,614	66,424	72,755	+9.5
	2021	89,842	66,922	75,632	+13.0
	2023	93,485	60,682	70,688	+16.5
CO	2015	2,506,984	1,948,114	2,198,202	+12.8
	2018	3,157,852	2,274,454	2,671,656	+17.5
	2021	3,764,988	2,366,586	2,913,727	+23.1
	2023	3,926,790	2,117,319	2,757,670	+30.2
$PM_{2.5}$	2015	13,391	9,592	10,539	+9.9
	2018	17,119	11,586	13,152	+13.5
	2021	19,126	12,077	14,320	+18.6
	2023	20,276	11,063	13,742	+24.2
SO_2	2015	17,567	4,791	5,285	+10.3
	2018	22,375	6,024	6,850	+13.7
	2021	22,864	6,546	7,743	+18.3
	2023	24,388	6,063	7,510	+23.9

Table 8. Sensitivity of provincial road transport emissions to vehicle survival scenario (Guttikunda 2024 Table 5). Medium scenario uses $T_{1/2}$ as fitted for India; High scenario is adopted here for Pakistan, reflecting the absence of mandatory vehicle scrappage and the prevalence of informal maintenance networks.

5.2 Emission Factor Assumptions

Base EFs are IPCC 2006 Tier 1 pre-Euro values. Two time-varying corrections are applied (Sect. 3.7.4): a technology correction that reduces EFs for post-2012 registration cohorts according to class-differentiated Euro II compliance shares (5–30%), and a fuel-quality correction that reduces diesel SO_2 and particulate EFs from 2015. Despite these adjustments, residual uncertainty remains in both the compliance shares and the timing of the fuel quality transition. The fuel quality correction is applied uniformly from 2015

based on the nominal year of Euro II fuel introduction; actual market penetration of lower-sulphur diesel may have been gradual. In the absence of Pakistan-specific in-use EF measurements, the IPCC Tier 1 base values scaled by these correction factors represent the best available estimate. Compliance fractions range from 5% (diesel HDV/BUS) to 30% (petrol light-duty vehicles); varying these uniformly by ±50% of their central values changes the effective emission factor multiplier for post-cutoff petrol cohorts from approximately 0.83 (half compliance) to 0.63 (1.5× compliance) for CO, and produces a variation of roughly ±8–13% in provincial CO and ±5–10% in provincial NO_x for 2023, when post-2012 cohorts constitute approximately 70–85% of the Weibull-weighted active fleet.

5.3 Uniform VKT Across Districts

VKT is applied uniformly across all 36 districts within each vehicle class. Vehicles in metropolitan Lahore plausibly accumulate considerably greater annual mileage than those in rural districts such as Rajanpur or Bhakkar. District-level VKT surveys are unavailable for Punjab; consequently, the district-level spatial disaggregation captures only differences in fleet size, not differential travel intensity.

Because Eq. (3) is linear in VKT, a ±50% uniform variation in per-vehicle VKT—which brackets the spread of comparable South Asian fleet surveys (Goel and Guttikunda, 2015; Sahu et al., 2014)—propagates directly to a ±50% variation in all provincial emission totals. This is the dominant parametric uncertainty in the inventory, substantially exceeding the 8–20% Weibull scenario range (Table 8). For example, the 2023 province-wide $PM_{2.5}$ estimate of 14,238 t yr^{-1} would range from approximately 7,100 to 21,400 t yr^{-1} under ±50% VKT variation. District-level VKT surveys are therefore the single highest-priority data need for future inventory iterations.

5.4 Uniform Fuel Splits Across Districts

Constant class-specific fuel fractions are applied uniformly across all 36 districts. CNG shares are expected to be higher in urban districts (Lahore, Faisalabad, Gujranwala) where

CNG station density is elevated, and lower in rural districts where refuelling infrastructure is sparse. This spatial uniformity likely produces overestimation of CNG-related emissions for rural districts and corresponding underestimation for major urban districts.

As a directional sensitivity, replacing the 3W CNG fraction (15%) with 0% or 30% changes provincial 3W $PM_{2.5}$ estimates by approximately ±2%; the effect on provincial totals is smaller given 3W's fleet share. For the 4W2 diesel fraction, varying between 50% and 80% (bracketing the 65% central assumption) produces a variation of approximately ±12% in 4W2 NO_x estimates. Fuel split uncertainty is therefore secondary to VKT uncertainty for provincial totals but may be more consequential for individual vehicle classes, particularly where district-level fuel infrastructure differs markedly from the provincial average.

5.5 Exclusion of "Other Vehicles"

The PBS "Other Vehicles" category is excluded owing to the absence of a representative IPCC Tier 1 EF for this heterogeneous class. This category typically constitutes less than 2% of total registered vehicles in Punjab; the resulting underestimation of provincial emissions is therefore minor.

5.6 Hot-Running Exhaust Only

The IPCC Tier 1 approach captures hot-running exhaust emissions only. Cold-start excess emissions and evaporative (fuel vapour) emissions, which are most significant for VOC and CO, are not separately quantified. Inclusion of these emission components would require Tier 2 or Tier 3 methods dependent on vehicle technology distributions and trip-length data that are unavailable at the district level.

5.7 Traffic Congestion and Idling

Congestion-related idling emissions are not explicitly modelled. In heavily congested urban centres such as Lahore, Faisalabad, and Rawalpindi, vehicles spend substantial fractions of operating time at or near idle; actual CO and VOC emissions in these districts

may therefore be substantially higher than inventory estimates. This represents a known systematic underestimation affecting urban districts.

6 Conclusions

This study presents a district-level road transport emission inventory for Punjab, Pakistan, for 2015–2023. Annual emissions of six road-transport air pollutants and precursor species (NOx, CO, VOC, $PM_{2.5}$, SO_2, NH_3) are estimated across 36 districts and nine vehicle classes using an IPCC 2006 Tier 1 framework extended with two Tier 2 refinements: Weibull cohort-survival correction of PBS registered vehicle counts, and time-varying emission factor adjustments for technology vintage and diesel fuel quality.

CO emissions are dominated by the two-wheeler fleet, which accounts for over 80% of registered vehicles; heavy commercial vehicles (HDV, BUS) contribute disproportionately to NOx and $PM_{2.5}$ relative to fleet share. SO_2 exhibits a step-change reduction from 2015 coinciding with adoption of Euro II-equivalent diesel fuel specifications. Lahore and the industrialised northern districts (Faisalabad, Gujranwala) account for approximately 50–60% of provincial emission totals owing to concentrated fleet size.

The dominant uncertainty is VKT ($\pm$50%, propagating linearly to all totals); Weibull survival scenario uncertainty contributes 8–20% on provincial totals. The complete district-level dataset is made publicly available to enable future air-quality modelling, health-impact assessment, and monitoring network design across Punjab's 36 administrative districts. Future inventory revisions should prioritise district-specific VKT surveys, measured emission factors calibrated to Pakistan's in-use fleet, and extended spatial coverage to Khyber Pakhtunkhwa and Sindh provinces.

Statements and Declarations

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Competing interests. The author declares no competing interests.

Author contributions. Mahad Naveed conceived the study, compiled and cleaned the source data, developed the emission calculation pipeline, produced all figures and tables, and wrote the manuscript in its entirety.

Data availability. The complete district-level emission dataset (36 districts, 9 vehicle classes, 9 years [2015–2023], six pollutants) is provided as a supplementary file (`emissions_by_district_class_fuel.csv`). Raw PBS vehicle registration data are publicly available from the Punjab Bureau of Statistics (`https://bos.punjab.gov.pk/statistical_pocket_book`).

Ethics approval. Not applicable.

Consent to participate. Not applicable.

Consent for publication. Not applicable.

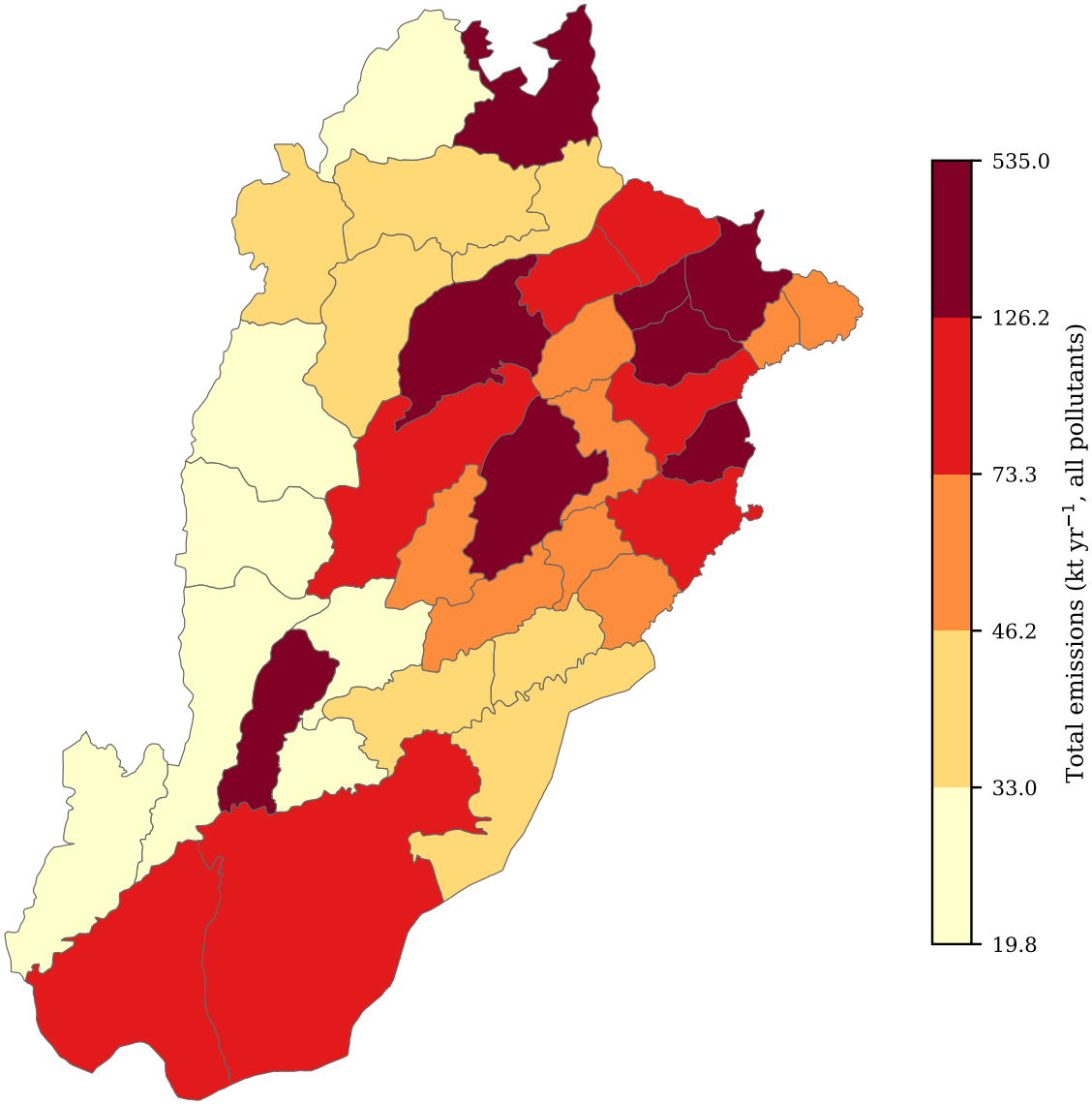


Figure 5. Spatial distribution of estimated road transport emissions by district, Punjab Province, 2023 (kt yr^{-1}, sum over all pollutants, dominated by CO which accounts for >95% of the mass total). Because emissions are proportional to district fleet shares, this map is effectively a fleet-density index; the same district ranking applies for $PM_{2.5}$ and NO_x individually. District boundaries from GADM 4.1.

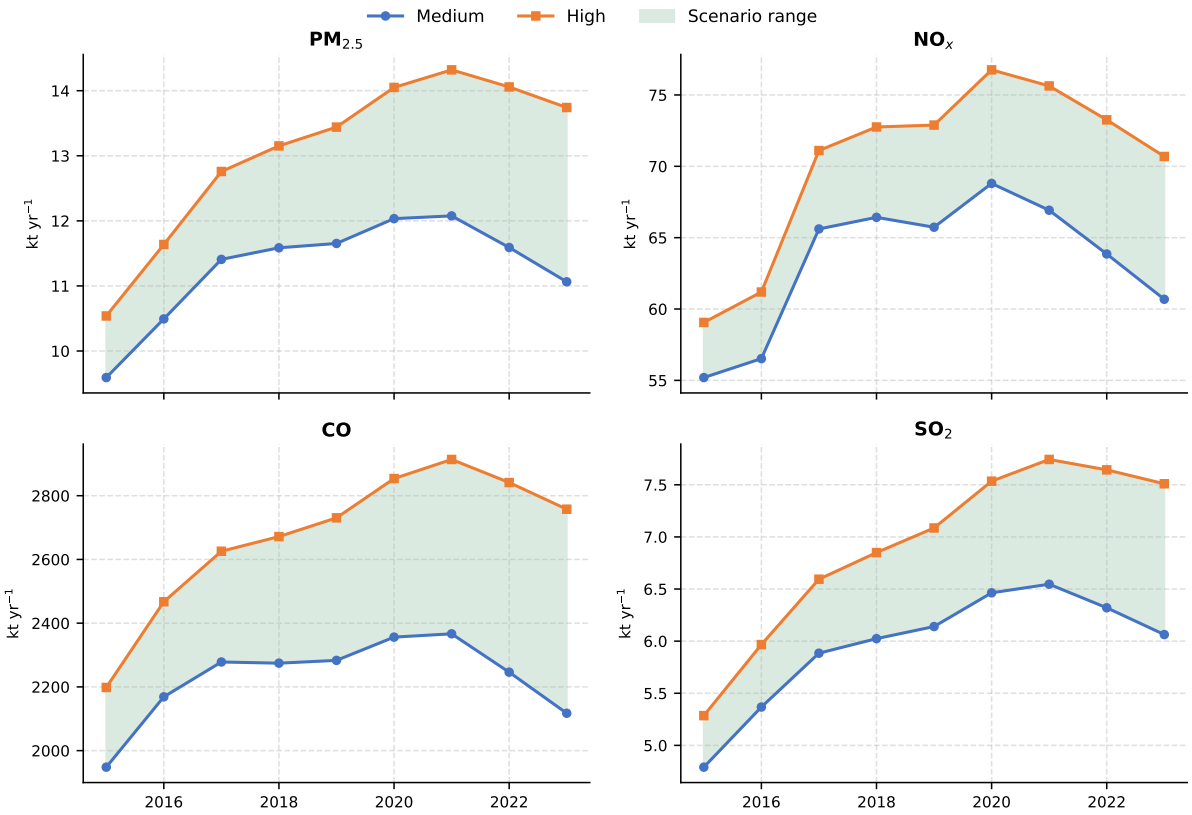


Figure 6. Provincial road transport emissions under the medium and high vehicle survival scenarios (Guttikunda 2024 Table 5), Punjab, 2015–2023. Shaded bands indicate the scenario range. The high scenario (adopted as the main estimate) consistently exceeds the medium scenario by 8–20% across pollutants, with the gap widening over time as older high-survival cohorts accumulate.

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A Data Cleaning Rules

All seven correction rules (Fix 1–Fix 7) are implemented via Eq. (2) and summarised in Table 2 in the main text. Full trigger conditions, affected vehicle types, year ranges, and rationale for each rule are provided in Supplementary Methods S1.

B District Vehicle Fleet, 2023

Table 9 presents the registered vehicle fleet for the ten highest-fleet districts of Punjab Province for 2023, derived from PBS district-level registration data (Punjab Bureau of Statistics (PBS), 2023). Districts are ranked by 2023 total fleet size; units are thousands of registered vehicles (×1,000). Annual fleet tables for 2019–2022 are available as supplementary data (`emissions_by_district_class_fuel.csv`).

	Registered vehicles (×1,000)								
District	**2W**	**3W**	**4W**	**4WT**	**LCV**	**BUS**	**HDV**	**NRV**	**Total**
Lahore	4,823	224	1,561	28	127	66	44	62	6,935
Faisalabad	1,553	25	80	5	17	4	6	14	1,703
Multan	1,425	23	128	11	22	6	7	21	1,641
Rawalpindi	965	33	107	8	59	15	9	4	1,201
Gujranwala	925	15	22	3	8	2	2	20	998
R.Y.Khan	870	1	17	0	4	1	1	28	922
Sialkot	750	34	32	0	8	2	0	13	840
Bahawalpur	626	9	24	3	5	1	1	15	684
D.G.Khan	617	1	7	2	2	1	1	27	658
Sargodha	551	46	9	2	4	2	3	19	636
Top-10 subtotal	13,106	411	1,987	63	256	99	73	224	16,219
All 36 districts	18,434	603	2,068	70	294	110	84	531	22,194

Table 9. Registered vehicle fleet by vehicle class for the ten highest-fleet districts of Punjab Province, 2023 (PBS data (Punjab Bureau of Statistics (PBS), 2023)). Districts are ranked by 2023 total fleet size.

C Weibull-Corrected Active Fleet, 2023

The PBS registration counts in Appendix B represent the *cumulative* stock of vehicles ever registered—they include scrapped, abandoned, and permanently inactive vehicles that have never been formally deregistered. The emission calculations in this inventory apply a Weibull survival function (Guttikunda 2024, high scenario) to estimate the *actively operating* subset of each cohort (Sect. 3.7.3).

Table 10 shows the Weibull-corrected active fleet for 2023. Province-wide, the active fleet in 2023 is approximately 17.7 million vehicles, compared with 22.2 million in the raw PBS register—a reduction of ≈20%, reflecting cumulative attrition of older cohorts. The correction is proportionally smallest for long-lived categories (NRV/tractors: $L_{1/2} = 22\,\text{yr}$) and largest for classes with shorter median lives (BUS, 4WT: $L_{1/2} = 12\,\text{yr}$). Active fleet tables for 2019–2022 are provided in the supplementary file (`emissions_by_district_class_fuel.csv`).

	Active vehicles (×1,000, Weibull-corrected)								
District	**2W**	**3W**	**4W**	**4WT**	**LCV**	**BUS**	**HDV**	**NRV**	**Total**
Lahore	3,455	149	1,340	16	118	32	36	51	5,196
Multan	1,065	19	129	10	22	4	5	38	1,291
Faisalabad	1,110	16	53	5	15	3	6	23	1,231
Rawalpindi	720	25	114	10	50	8	7	5	938
Gujranwala	690	16	27	3	9	2	1	24	773
R.Y.Khan	631	0	14	2	3	1	1	36	688
Bahawalpur	465	7	165	3	5	2	1	22	671
Sialkot	558	29	24	1	8	3	1	22	645
D.G.Khan	452	0	12	1	3	2	1	57	528
Sargodha	413	40	23	1	5	1	5	25	515
Top-10 subtotal	9,560	302	1,901	51	239	58	63	302	12,475
All 36 districts	13,904	468	2,101	67	306	83	83	708	17,719

Table 10. Estimated *actively operating* vehicle fleet by district, 2023 (thousands of vehicles, Weibull survival-weighted, high scenario). Districts ranked by 2023 total active fleet; only top-10 districts shown; provincial totals cover all 36 districts. Full 2019–2023 district-year tables are provided in the supplementary data file (`emissions_by_district_class_fuel.csv`). Abbreviations: 2W = motorcycles; 3W = auto-rickshaws; 4W = passenger cars (4W1+4W2); 4WT = taxis; LCV = pickups/vans; BUS = buses; HDV = trucks; NRV = tractors.