

# National-Scale Estimation of Brake-Wear Particulate Emissions From On-Road Vehicles in Türkiye: A 2024 Inventory with Uncertainty and Mitigation Scenarios

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## Abstract

This research article develops a screening-level national inventory of airborne brake-wear particulate emissions from on-road vehicles in Türkiye for the year 2024. The scope is limited to brake wear only and does not include tyre wear, road wear, resuspension, or concentration and exposure modelling. The inventory combines TurkStat vehicle-kilometre statistics with EMEP/EEA Tier-2 brake-wear emission factors, including passenger-car powertrain differentiation to reflect regenerative-braking effects. Under nominal baseline assumptions, annual emissions are estimated at 5.67 kt·y<sup>-1</sup> for PM<sub>10</sub> and 2.26 kt·y<sup>-1</sup> for PM<sub>2.5</sub>. Monte Carlo framework that propagates bounded uncertainty in total activity, vehicle-category composition, passenger-car powertrain shares, guidebook-anchored emission factors, and particle-size fractions, the national totals are characterised by a median (95% interval) of 5.67 (4.87–7.19) kt·y<sup>-1</sup> for PM<sub>10</sub> and 2.26 (1.87–2.90) kt·y<sup>-1</sup> for PM<sub>2.5</sub>. Passenger cars account for approximately 45% of national PM<sub>10</sub> emissions, followed by light commercial vehicles and tractor units. Illustrative, assumption-dependent scenario analysis indicates that PM<sub>10</sub> could decrease to 4.95 kt·y<sup>-1</sup> under partial uptake of low-emission brake technologies, to 5.28 kt·y<sup>-1</sup> with greater use of auxiliary braking in heavy-duty vehicles, and to 5.47 kt·y<sup>-1</sup> under a passenger-car fleet share of 10% HEV and 10% BEV. These scenario outcomes should be interpreted as indicative screening-level projections rather than empirical or policy-evaluation results. Overall, the study provides a transparent brake-wear-only national baseline and a comparative framework for examining how selected assumptions influence estimated PM emissions in Türkiye.

**Keywords:** Brake wear; brake emissions; non-exhaust emissions; PM<sub>10</sub>; PM<sub>2.5</sub>; Türkiye

**To cite this paper:** Demirci, O.K. National-Scale Estimation of Brake-Wear Particulate Emissions From On-Road Vehicles in Türkiye: A 2024 Inventory with Uncertainty and Mitigation Scenarios. International Journal of Automotive Science and Technology. 2026; 10(2): 386-399. <https://doi.org/10.30939/ijastech..1901704>

## Research Article

### History

Received 03.03.2026  
Revised 01.04.2026  
Accepted 20.05.2026

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## 1. Introduction

Particulate matter (PM) from road transport has historically been dominated by tailpipe exhaust; however, as exhaust standards tighten and fleets modernise, non-exhaust sources such as tyre wear, brake wear, road surface wear, and resuspension are becoming an increasingly important share of traffic-related PM in many urban environments [1,2]. Brake wear is of particular regulatory and scientific interest because it produces metal-rich particles, and because measurement protocols and forthcoming limits are being developed around dedicated brake dynamometer cycles [3-7].

Türkiye has one of the largest vehicle fleets in Europe and experiences persistent urban PM exceedances in several metropolitan areas. However, national inventories and policy discussions remain primarily focused on exhaust sources, while brake

wear is rarely quantified with transparent assumptions. The absence of a baseline estimate prevents prioritisation of measurement and mitigation efforts, and it complicates evaluation of electrification pathways, since regenerative braking can substantially reduce friction brake work and thus brake-wear PM [8,9].

This paper addresses this gap by developing a national-scale, category-resolved brake-wear PM inventory for Türkiye for the year 2024. The study integrates official vehicle-kilometre activity from TurkStat, EMEP/EEA Tier-2 brake-wear emission factors supported by recent dynamometer evidence, and Monte Carlo-based uncertainty propagation. The selected analytical topics were chosen because they represent the most policy-relevant and structurally influential drivers within the scope of a screening-level brake-wear inventory. Passenger-car electrification is included because regenerative braking can directly reduce

friction-brake demand and thus brake-wear emissions. Heavy-duty auxiliary braking is considered because heavy-duty vehicles exhibit comparatively high brake-wear intensity and their service-brake demand may be reduced by retarders or engine braking under specific operating conditions. Disc-drum brake configuration is examined because brake architecture can influence airborne particle release, while the absence of detailed Türkiye-specific fleet configuration data introduces an important source of structural uncertainty. Unlike previous studies that have mainly focused on review-level synthesis, laboratory measurements, or interlaboratory testing, the present study develops a Türkiye-specific national inventory framework that combines official activity statistics, powertrain-sensitive brake-wear factors, and explicit uncertainty treatment to provide a transparent brake-wear-only baseline for 2024.

## 2. Materials and Methods

The system boundary includes airborne brake-wear particles emitted during on-road operation, reported as  $PM_{10}$  and  $PM_{2.5}$  mass. Tyre wear, road wear and resuspended road dust are excluded. Emissions are estimated for the national territory of Türkiye for calendar year 2024.

### 2.1. Activity data and fleet descriptors

In TurkStat road-vehicle statistics, “minibus” denotes passenger-carrying vehicles with 9–15 seating positions including the driver (i.e., a subset of UNECE passenger categories M2/M3, rather than N1 goods vehicles), and this classification is adopted for the minibus class mapping used in the baseline inventory. Accordingly, the baseline inventory maps minibuses to the heavy-duty passenger segment (bus/coach-type brake-wear factors). A sensitivity case that maps minibuses to light-commercial vehicles (N1) is retained only as a conservative lower-bound check [11].

National vehicle activity is taken from TurkStat’s ‘Vehicle-kilometre statistics, 2024’ press release (No. 57946), which reports total and category-disaggregated vehicle-kilometres travelled (VKT) for road motor vehicles. For context on fleet composition and electrification, TurkStat’s “Road motor vehicles” releases [12,13] are used to obtain end-2024 fuel shares of passenger cars. The inventory uses the VKT breakdown reported by TurkStat: passenger cars (57.0%), vans/light commercial vehicles (19.2%), motorcycles (8.7%), tractor units (5.7%), trucks (3.8%), minibuses (3.3%), buses/coaches (1.9%) and special-purpose vehicles (0.5%). Table 1 summarises the national activity and fleet stratification used in the inventory, combining TurkStat road-vehicle statistics with the adopted vehicle categories to compute annual vehicle-kilometres travelled (VKT) for 2024 [10].

The activity stratification in Table 1 is a key driver of national totals: inventory outcomes scale linearly with VKT, so even modest under/overestimation of annual kilometres propagates directly into PM totals. Consistent with non-exhaust PM literature, uncertainty is typically dominated by activity and class allocation when country-specific

measurements are limited, motivating the Monte-Carlo treatment adopted in this study [14,15].

As shown in Table 1, light-duty traffic accounts for the majority of national VKT, while several heavy-duty classes contribute smaller shares but can have higher brake-wear emissions per vehicle-kilometre. The emission factors and particle-size fractions used to translate activity to PM are reported in Table 2.

Table 1. TurkStat vehicle-kilometre activity used in the 2024 inventory [10].

TurkStat category	Share of VKT (%)	VKT (10 <sup>9</sup> veh-km)	EMEP/EEA mapping	Notes
Passenger cars	57.0	218.06	PC	Includes gasoline, diesel, LPG, hybrid and electric.
Vans (light commercial)	19.2	73.34	LCV (N1)	Kamyonet category in TurkStat.
Motorcycles	8.7	33.35	2-wheel	Two-wheel motor vehicles.
Tractor units	5.7	21.8	HDV (tractor)	Çekici (road tractors).
Trucks (rigid)	3.8	14.36	HDV (rigid)	Kamyon (rigid trucks).
Minibuses	3.3	12.8	HDV (small bus; M2/M3) <sup>†</sup>	Minibüs (9–15 seats incl. driver); passenger M2/M3.
Buses/coaches	1.9	7.4	HDV (bus)	
Special purpose	0.5	1.82	HDV/other	Special-purpose road vehicles.

<sup>†</sup> Minibuses are passenger vehicles (M2/M3; 9–15 seats incl. driver) and are mapped to the HDV passenger (bus/coach-type) segment in the baseline. A conservative sensitivity maps minibuses to N1.

### 2.2. Brake-wear emission factors and size fractions

Tier 2 airborne brake-wear emission factors for total suspended particles (TSP) from the EMEP/EEA emission inventory guidebook for road transport non-exhaust emissions are adopted [2]. These factors are expressed in  $g \cdot veh^{-1} \cdot km^{-1}$  and are provided by vehicle class and, for passenger cars, by powertrain type (internal combustion engine, hybrid electric vehicle and battery electric vehicle). To obtain  $PM_{10}$  and  $PM_{2.5}$ , we apply the guidebook’s recommended particle size fractions for brake wear:  $PM_{10}/TSP=0.98$  and  $PM_{2.5}/TSP=0.39$ . To translate the activity totals into brake-wear particulate emissions, Table 2 lists the adopted airborne TSP brake-wear emission factors by vehicle class, together with the size fractions used to derive  $PM_{10}$  and  $PM_{2.5}$ .

Table 2 indicates that brake-wear emission factors are class-dependent and substantially larger for heavy-duty segments in fleet-average terms. Combining these factors with the VKT in Table 1 yields the national baseline emissions reported in Table 5, which are then visualised by category in Figure 1. Table 2 compiles class-level brake-wear emission factors and size-fraction conversions that are widely used in national inventories. For light commercial

vehicles (LCVs), the national split between N1-I and N1-II/III subclasses are not explicitly reported in official statistics. To account for this structural uncertainty, the baseline emission factor was constructed as a weighted mixture of the corresponding EMEP/EEA subclasses, with weights treated as uncertain rather than fixed. During Monte Carlo sampling, the subclass shares were perturbed within plausible bounds to reflect variability in fleet composition, ensuring that the resulting brake-wear estimates capture class-mix uncertainty in addition to emission-factor variability. Experimental evidence shows that reported brake PM is sensitive to test cycle, bedding-in, temperature, pad/disc material and sampling configuration; therefore, the guidebook defaults provide a defensible baseline but should be interpreted as fleet-average values rather than deterministic constants [14,16-20].

Table 2. Brake-wear emission factors (airborne TSP) and particle-size conversion used in this study.

Vehicle class	Power-train / condition	$EF_{TSP}$ (g/km)	$PM_{10}$ (mg/km)	$PM_{2.5}$ (mg/km)	Source [2]
Passenger car	ICE (medium)	0.0122	12.0	4.8	EEA guidebook
Passenger car	HEV (medium)	0.0097	9.5	3.8	EEA guidebook
Passenger car	BEV (medium)	0.0035	3.4	1.4	EEA guidebook
Light commercial (N1)	N1-I ( $\leq 1305$ kg)	0.0122	12.0	4.8	EEA guidebook
Light commercial (N1)	N1-II/III ( $> 1305$ kg)	0.0173	17.0	6.7	EEA guidebook
Motorcycles	2-wheel	0.0037	3.6	1.4	EEA guidebook
Heavy-duty vehicles	HDV (load factor 0.38–0.68)	0.0235	23.0	9.2 –	EEA guidebook, Eq. (6) range
		0.0420	41.2	16.4	
All classes	Size fractions	—	$PM_{10}/TSP = 0.98$	$PM_{2.5}/TSP = 0.39$	EEA guidebook

Note:  $PM_{10}$  and  $PM_{2.5}$  values are calculated from TSP emission factors using the guidebook-recommended size fractions ( $PM_{10}/TSP = 0.98$  and  $PM_{2.5}/TSP = 0.39$ ). Values are rounded to one decimal place.

The heavy-duty vehicle (HDV) brake-wear emission factor range (0.0235–0.0420  $g \cdot veh^{-1} \cdot km^{-1}$ ), corresponding to load factors of 0.38–0.68, was adopted directly from the EMEP/EEA Guidebook [2], where it represents typical operating conditions observed across European heavy-duty vehicle fleets under varying load and driving conditions. In the absence of Türkiye-specific load factor distributions, this range is considered a reasonable proxy for national fleet behaviour, as the Turkish heavy-duty fleet operates under a mix of urban delivery, regional transport, and long-haul freight conditions comparable to European averages. Accordingly,

the selected interval is intended to reflect realistic variability in vehicle loading rather than a fixed national average, and is treated as a bounded range within the uncertainty framework.

### 2.3. Powertrain electrification and regenerative braking

Brake wear depends on friction brake work. Electrified powertrains can recuperate a portion of deceleration energy through regenerative braking, reducing friction brake demand and thereby brake-wear emissions, albeit with dependence on drive cycle and braking aggressiveness [8-9]. In the baseline inventory, electrification effects for passenger cars are captured using the EEA powertrain-specific emission factors, combined with TurkStat's end-2024 passenger car fuel shares: hybrid 2.4% and electric 1.1% [12]. Vans and heavy-duty categories are treated as predominantly combustion-based in 2024; electrification effects are explored for passenger cars in the scenario analysis.

### 2.4. Disc–drum configuration and auxiliary braking sensitivity

The EEA factors are intended for inventory use and do not explicitly separate disc and drum brakes. Experimental evidence indicates that drum brakes can yield substantially lower airborne PM emissions than open disc brakes due to enclosure and particle retention [3-4]. To reflect uncertainty in the Turkish fleet's brake configurations, we define a sensitivity factor  $f_{DD}$  applied to light-duty emission factors, representing the national-average ratio of Turkish brake configurations to the implicit European average embedded in the EEA defaults. The baseline uses  $f_{DD} = 1.0$ ; a low-emission configuration case uses  $f_{DD} = 0.85$ ; and a high-emission case uses  $f_{DD} = 1.15$ . For heavy-duty vehicles, auxiliary braking devices (engine braking and retarders) can reduce service-brake thermal load on descents and during speed control. Since national penetration data are not available in official statistics, we represent this effect through a service-brake duty factor  $\varphi_{HDV}$  applied multiplicatively to heavy-duty emission factors (baseline  $\varphi_{HDV} = 1.0$ ; auxiliary-braking adoption reduces effective service-brake work,  $\varphi_{HDV}$  down to 0.8).

Plain-text parameters (for reproducibility):  $f_{DD}$  baseline = 1.0; low-case  $f_{DD} = 0.85$ ; high-case  $f_{DD} = 1.15$ . For heavy-duty vehicles, the service-brake duty factor is  $\varphi_{HDV} \in [0.8, 1.0]$  (baseline  $\varphi_{HDV} = 1.0$ ; auxiliary-braking adoption reduces effective service-brake work). The adopted disc–drum correction factor ( $f_{DD} = 0.85 - 1.15$ ) is intentionally bounded to represent conservative lower- and upper-limit effects reported in the literature, where enclosed drum brake architectures tend to reduce airborne particle release relative to open disc systems, while uncertainties remain regarding real-world maintenance condition and operating temperature. The selected range therefore reflects plausible fleet-average behaviour rather than a precise technology-specific reduction, and is treated probabilistically to avoid over-interpretation [3-4,14,19]. Similarly, the auxiliary braking adjustment applied to heavy-duty vehicles ( $\varphi_{HDV} = 0.8 - 1.0$ ) represents a bounded estimate of reduced service-brake usage due to engine braking and retarders on long-

haul and high-load duty cycles [14,21,22]. These bounds are consistent with variability ranges reported in experimental brake emission studies and non-exhaust emission assessments, where differences in brake design, duty cycle, and operational conditions typically lead to variations on the order of  $\pm 10\text{--}20\%$  in fleet-average emission behaviour [3–4,14,19]. Owing to the lack of fleet-level penetration data for auxiliary braking systems in Türkiye, this factor is deliberately conservative and is propagated as an uncertainty range rather than a fixed reduction, consistent with the inventory's screening-level intent. These parameters are therefore used as scenario controls for sensitivity and mitigation screening, not as directly validated national reduction coefficients. It should be emphasised that the disc–drum correction factor and the auxiliary braking adjustment are not derived from Türkiye-specific fleet measurements. Instead, they are defined as bounded, literature-informed parameters intended to represent plausible variability in brake system behaviour under real-world conditions. Accordingly, these parameters should be interpreted as scenario-based and illustrative rather than as directly observed or statistically calibrated national values.

## 2.5. Emission calculation and uncertainty propagation

To compute annual brake-wear particulate emissions from national activity data, a transparent category-resolved inventory framework was adopted. Total annual emissions of pollutant  $p$  were calculated as

$$E_p = \sum_j VKT_j \times EF_{j,TSP} \times f_p \quad (1)$$

where  $j$  denotes the vehicle category,  $VKT_j$  is the annual vehicle-kilometres travelled for category  $j$ ,  $EF_{j,TSP}$  is the airborne brake-wear emission factor expressed as total suspended particles (TSP,  $\text{g}\cdot\text{veh}^{-1}\cdot\text{km}^{-1}$ ), and  $f_p$  is the size-fraction term used to derive  $\text{PM}_{10}$  or  $\text{PM}_{2.5}$  from TSP. In the deterministic baseline, the nominal guidebook fractions  $f_{\text{PM}_{10}} = 0.980$  and  $f_{\text{PM}_{2.5}} = 0.390$  were used [2].

Category-level activity was obtained from total national VKT and the category share vector:

$$VKT_j = VKT_{tot} \times s_j \quad (2)$$

where  $VKT_{tot}$  is the total annual national vehicle-kilometres travelled and  $s_j$  is the share of category  $j$  in total activity. For passenger cars, the effective brake-wear emission factor was powertrain-weighted in order to reflect regenerative-braking effects:

$$EF_{PC,TSP} = x_{ICE}EF_{ICE} + x_{HEV}EF_{HEV} + x_{BEV}EF_{BEV} \quad (3)$$

where  $x_{ICE}$ ,  $x_{HEV}$ , and  $x_{BEV}$  are the shares of internal-combustion, hybrid-electric, and battery-electric passenger cars, respectively, and  $x_{ICE} + x_{HEV} + x_{BEV} = 1$ . For light commercial vehicles, uncertainty in the national subclass mix was represented explicitly by defining the effective class-average factor as

$$EF_{LCV,TSP} = (1 - w_{N1-II/III})EF_{N1-I} + w_{N1-II/III}EF_{N1-II/III} \quad (4)$$

where  $w_{N1-II/III}$  denotes the fraction of light commercial activity associated with N1-II/III vehicles. Deterministic baseline emissions were obtained by evaluating Eqs. (1)–(4) using the nominal values reported in Tables 1 and 2. Uncertainty was then propagated through Monte Carlo simulation. A total of 20,000 Monte Carlo iterations were performed to ensure statistical convergence and stable estimation of the output uncertainty intervals. In each iteration, total VKT, category shares, passenger-car powertrain shares, light-commercial subclass mix, emission factors, and particle-size fractions were sampled from the probability distributions summarised in Table 3, and the resulting  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  totals were recalculated. The outputs were reported as the median together with the 2.5th and 97.5th percentiles, consistent with 95% uncertainty interval reporting. The total national activity was sampled as a bounded uniform distribution around the TurkStat 2024 value:

$$VKT_{tot}^{(k)} \sim U(0.95VKT_{tot,0}, 1.05VKT_{tot,0}) \quad (5)$$

where  $VKT_{tot,0} = 382.93 \times 10^9$  veh-km. This corresponds to a sampling interval of  $363.78 \times 10^9$  to  $402.08 \times 10^9$  veh-km. To preserve the sum-to-one constraint for category-level activity shares, the category share vector was sampled jointly from a Dirichlet distribution centred on the baseline composition:

$$s^{(k)} \sim \text{Dirichlet}(\alpha_s) \quad (6)$$

with

$$\alpha_s = (570, 192, 87, 57, 38, 33, 19, 5)$$

for passenger cars, vans/light commercial vehicles, motorcycles, tractor units, rigid trucks, minibuses, buses/coaches, and special-purpose vehicles, respectively. This parameterisation preserves the baseline composition while allowing moderate perturbations for dominant categories and larger relative variation for small-share categories, which is a natural property of compositional sampling. Passenger-car powertrain shares were also sampled jointly from a Dirichlet distribution to maintain exact closure:

$$(x_{ICE}, x_{HEV}, x_{BEV})^{(k)} \sim \text{Dirichlet}(5790, 144, 66) \quad (7)$$

which preserves the baseline 2024 passenger-car powertrain composition of 96.5% ICE, 2.4% HEV, and 1.1% BEV. For light commercial vehicles, the uncertain N1-II/III share was sampled as

$$w_{N1-II/III}^{(k)} \sim \text{Tri}(0.30, 0.50, 0.70) \quad (8)$$

where  $\text{Tri}(a, m, b)$  denotes a triangular distribution with lower bound  $a$ , mode  $m$ , and upper bound  $b$ . The mode of

0.50 represents a neutral central assumption in the absence of Türkiye-specific subclass statistics, while the 0.30–0.70 range was adopted as a bounded expert-judgement interval. Brake-wear emission factors were sampled explicitly from triangular distributions anchored to the guidebook central values and their reported lower–upper ranges. For passenger cars and motorcycles, the following distributions were used:

$$EF_{ICE,PC}^{(k)} \sim Tri(0.0073, 0.0122, 0.0165) \quad (9)$$

$$EF_{HEV,PC}^{(k)} \sim Tri(0.0058, 0.0097, 0.0131) \quad (10)$$

$$EF_{BEV,PC}^{(k)} \sim Tri(0.0021, 0.0035, 0.0046) \quad (11)$$

$$EF_{MC}^{(k)} \sim Tri(0.0022, 0.0037, 0.0050) \quad (12)$$

For light commercial vehicles, the subclass-specific factors were sampled as

$$EF_{N1-I}^{(k)} \sim Tri(0.0073, 0.0122, 0.0165) \quad (13)$$

$$EF_{N1-II/III}^{(k)} \sim Tri(0.0104, 0.0173, 0.0234) \quad (14)$$

and then combined using Eq. (4). For heavy-duty vehicle classes, a common heavy-duty latent brake-wear factor was used:

$$EF_{HDV}^{(k)} \sim Tri(0.0235, 0.03275, 0.0420) \quad (15)$$

This factor was applied to tractor units, rigid trucks, minibuses, buses/coaches, and special-purpose vehicles. Using a common heavy-duty draw reflects the fact that these factors are derived from the same guidebook basis and avoids imposing artificial independence among closely related heavy-duty categories. The size-fraction uncertainty was modelled in a way that preserves the physical constraint  $PM_{2.5} \leq PM_{10}$ . First, the  $PM_{10}$ /TSP fraction was sampled as

$$f_{PM10}^{(k)} \sim Beta(192, 4) \quad (16)$$

which is centred close to the guidebook value of 0.980. Next, the conditional fine-to-coarse ratio was sampled as

$$r_{2.5/10}^{(k)} = \frac{f_{PM2.5}^{(k)}}{f_{PM10}^{(k)}} \sim Beta(60, 91) \quad (17)$$

and the  $PM_{2.5}$  fraction was then calculated as

$$f_{PM2.5}^{(k)} = f_{PM10}^{(k)} \times r_{2.5/10}^{(k)} \quad (18)$$

This formulation yields an expected  $PM_{2.5}$  fraction close to the nominal guidebook value while ensuring that the sampled  $PM_{10}$  fraction never exceeds the sampled  $PM_{10}$  fraction. Unless constrained by compositional closure, the sampled inputs were treated as mutually independent. Thus, dependence was introduced only where it was structurally required, namely in the vehicle-category shares, passenger-car powertrain shares, and the  $PM_{2.5}/PM_{10}$  size-fraction relationship. To avoid conflating baseline uncertainty with scenario assumptions, the disc–drum correction factor and the heavy-duty service-brake duty factor were not sampled as stochastic inputs in the baseline Monte Carlo analysis. Instead, they were retained as deterministic sensitivity/scenario-control parameters in Sections 3.5 and 3.6. This separation improves transparency by distinguishing baseline inventory uncertainty from assumption-driven mitigation or structural sensitivity cases.

As shown in Table 3, these uncertainty sources affect the inventory through distinct and interpretable pathways. The  $\pm 5\%$  uniform uncertainty on total national VKT acts as a global scaling factor, shifting emissions for all vehicle categories proportionally, whereas the Dirichlet perturbation applied to category VKT shares redistributes a fixed total VKT across categories while preserving the sum-to-one constraint. Relative perturbations in passenger-car powertrain shares mainly influence the weighting of powertrain-specific emission factors and become more influential under higher electrification scenarios. In contrast, brake-wear emission factors, represented by class-specific discrete ranges, constitute the dominant driver of both absolute emission levels and outcome variability due to their direct multiplicative role in the emission calculation. Finally, the Gaussian perturbations applied to particle-size fractions introduce a smaller yet systematic contribution to  $PM_{10}$  and  $PM_{2.5}$  uncertainty through the TSP-to-size-fraction conversion, a structure that facilitates clear attribution of uncertainty drivers in the results presented in the following section.

To ensure transparency and reproducibility of the mitigation scenarios, the “low-emission brakes” case was parameterised using two explicit assumptions: (i) a partial fleet adoption rate of 50% for passenger cars and light commercial vehicles, and (ii) a 40% reduction in the corresponding brake-wear emission factors for the affected share of the fleet. The 50% adoption rate was selected as a mid-range, illustrative penetration level representing partial but not full market uptake, consistent with screening-level scenario practice in non-exhaust emission studies where future technology diffusion is uncertain [14,19].

The 40% emission-factor reduction reflects a conservative fleet-average estimate derived from experimental and inter-laboratory studies reporting substantial reductions in airborne brake-wear PM emissions through improved friction materials, coatings, and enclosed braking systems [3,4,19]. In the model, these assumptions were implemented by applying a weighted emission factor formulation, where the effective emission factor was calculated as a linear combination of baseline and reduced emission factors according to the assumed adoption share. The

effective emission factor under the low-emission brake scenario was calculated as:

$$EF_{eff} = (1 - \alpha) \cdot EF_{base} + \alpha \cdot (1 - \beta) \cdot EF_{base} \quad (19)$$

where  $\alpha = 0.5$  represents the adoption rate and  $\beta = 0.4$  denotes the emission-factor reduction. These assumptions are not

based on directly observed national deployment data, but are instead constructed as illustrative mid-range scenarios informed by experimental literature. Their purpose is to enable comparative sensitivity analysis rather than to represent measured fleet-average conditions

Table 3. Monte Carlo uncertainty inputs, numerical definitions, and sampling rules used in this study.

Input	Baseline value	Distribution	Numerical definition	Implementation rule / role in model
Total national VKT, $VKT_{tot}$	$382.93 \times 10^9$ veh-km	Uniform	$U(363.78 \times 10^9, 402.08 \times 10^9)$ veh-km	Global scaling of all category emissions
Category VKT shares, $s$	$(0.570, 0.192, 0.087, 0.057, 0.038, 0.033, 0.019, 0.005)$	Dirichlet	$Dirichlet(570, 192, 87, 57, 38, 33, 19, 5)$	Jointly allocates total VKT across categories while preserving $\sum s_j = 1$
Passenger-car powertrain shares, $(x_{ICE}, x_{HEV}, x_{BEV})$	$(0.965, 0.024, 0.011)$	Dirichlet	$Dirichlet(5790, 144, 66)$	Jointly samples powertrain shares while preserving $x_{ICE} + x_{HEV} + x_{BEV} = 1$
LCV N1-II/III share, $w_{N1-II/III}$	0.50	Triangular	$Tri(0.30, 0.50, 0.70)$	Determines effective light-commercial EF via weighted mixture of N1-I and N1-II/III
Passenger-car ICE brake EF, $EF_{ICE,PC}$	0.0122 g/km	Triangular	$Tri(0.0073, 0.0122, 0.0165)$	Powertrain-specific passenger-car brake-wear TSP EF
Passenger-car HEV brake EF, $EF_{HEV,PC}$	0.0097 g/km	Triangular	$Tri(0.0058, 0.0097, 0.0131)$	Powertrain-specific passenger-car brake-wear TSP EF
Passenger-car BEV brake EF, $EF_{BEV,PC}$	0.0035 g/km	Triangular	$Tri(0.0021, 0.0035, 0.0046)$	Powertrain-specific passenger-car brake-wear TSP EF
Motorcycle brake EF, $EF_{MC}$	0.0037 g/km	Triangular	$Tri(0.0022, 0.0037, 0.0050)$	Two-wheel brake-wear TSP EF
LCV N1-I brake EF, $EF_{N1-I}$	0.0122 g/km	Triangular	$Tri(0.0073, 0.0122, 0.0165)$	Light-commercial subclass EF
LCV N1-II/III brake EF, $EF_{N1-II/III}$	0.0173 g/km	Triangular	$Tri(0.0104, 0.0173, 0.0234)$	Light-commercial subclass EF
Heavy-duty brake EF, $EF_{HDV}$	0.03275 g/km (mid-range anchor)	Triangular	$Tri(0.0235, 0.03275, 0.0420)$	Common heavy-duty EF draw used for tractor units, rigid trucks, minibuses, buses, and special-purpose vehicles
$PM_{10}/TSP$ fraction, $f_{PM_{10}}$	0.980	Beta	$Beta(192, 4)$	Samples $PM_{10}$ fraction close to guide-book nominal value
Conditional $PM_{2.5}/PM_{10}$ ratio, $r_{2.5/10}$	$\approx 0.398$	Beta	$Beta(60, 91)$	
$PM_{2.5}/TSP$ fraction, $f_{PM_{2.5}}$	0.390	Derived	$f_{PM_{2.5}} = f_{PM_{10}} \times r_{2.5/10}$	

Note: The disc-drum correction factor and the heavy-duty service-brake duty factor were not treated as stochastic inputs in the baseline Monte Carlo analysis. They were used only as deterministic sensitivity/scenario-control parameters in the scenario analysis.

### 3. Results and Discussion

Using the baseline assumptions, Türkiye's 2024 airborne brake-wear emissions are estimated at  $5.67 \text{ kt}\cdot\text{y}^{-1}$  of  $PM_{10}$  and  $2.26 \text{ kt}\cdot\text{y}^{-1}$  of  $PM_{2.5}$ . The Monte Carlo parameterisation ( $N = 20,000$ ), the corresponding national totals are characterised by a median (95% interval) of  $5.67$  ( $4.87\text{--}7.19$ )  $\text{kt}\cdot\text{y}^{-1}$  for  $PM_{10}$

and  $2.26$  ( $1.87\text{--}2.90$ )  $\text{kt}\cdot\text{y}^{-1}$  for  $PM_{2.5}$ . These probabilistic results reflect propagation of bounded uncertainty in activity, fleet composition, powertrain mix, emission factors, and size-fraction terms, and should therefore be interpreted as uncertainty-bounded inventory estimates rather than as measurement-based confidence intervals. values.

### 3.1. Normalised indicators for international comparison

To support cross-country and cross-study comparison beyond national totals, Table 4 reports normalised indicators expressed per vehicle-kilometre and per capita. These indicators complement the national totals and are useful for benchmarking policy ambition and data needs across jurisdictions.

Table 4. Normalised indicators for Türkiye's 2024 brake-wear inventory (baseline). Population for per-capita normalisation follows TurkStat ABPRS 2024 [17].

Indicator	PM <sub>10</sub>	PM <sub>2.5</sub>
National total (t·y <sup>-1</sup> )	5676	2257
Normalised per VKT (mg·veh·km <sup>-1</sup> )	14.82	5.89
Normalised per 10 <sup>9</sup> veh·km (t·(10 <sup>9</sup> veh·km) <sup>-1</sup> )	14.82	5.89
Per capita (g·person <sup>-1</sup> ·y <sup>-1</sup> )	66.3	26.3

To communicate how the national brake-wear inventory distributes emissions across the fleet, Figure 1 summarises the baseline 2024 PM<sub>10</sub> estimates by vehicle category derived from TurkStat activity data and the adopted emission factors. Normalising the inventory (Table 4) helps interpret national totals in policy-relevant units (e.g., per capita or per VKT) and supports comparisons across countries and years. This approach is commonly recommended in non-exhaust PM reviews, where absolute totals can be misleading without accounting for differences in fleet activity and urbanisation [14,15].

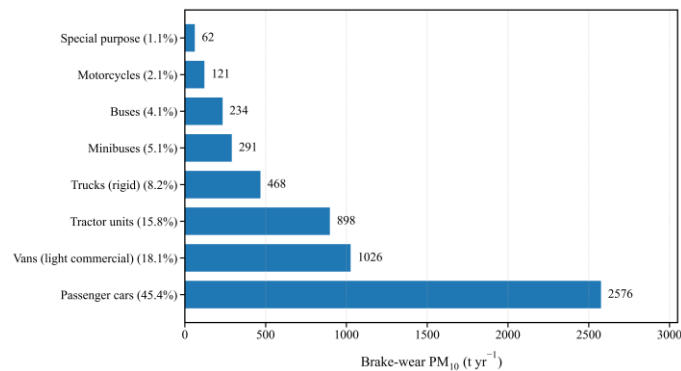


Figure 1. Estimated annual brake-wear PM<sub>10</sub> emissions by vehicle category for Türkiye in 2024 (baseline scenario).

Figure 1 indicates that the national total is dominated by high-activity light-duty traffic, while heavy-duty classes can contribute disproportionately when normalised per vehicle-kilometre. This motivates separating the fine (PM<sub>2.5</sub>) and coarse (PM<sub>10</sub>–PM<sub>2.5</sub>) fractions across categories, as reported in Figure 2. From an exposure perspective, these totals are consistent with the wider finding that non-exhaust sources increasingly dominate urban traffic PM as tailpipe controls tighten. The class mix also matters because electrified light-duty fleets may reduce brake wear via recuperation, whereas heavy-duty duty cycles can retain high friction-brake demand [14,18,19].

Brake wear particles span a wide size spectrum; Figure 2 decomposes each category's PM<sub>10</sub> total into PM<sub>2.5</sub> and coarse fractions using the guidebook size-fraction approach adopted in this study.

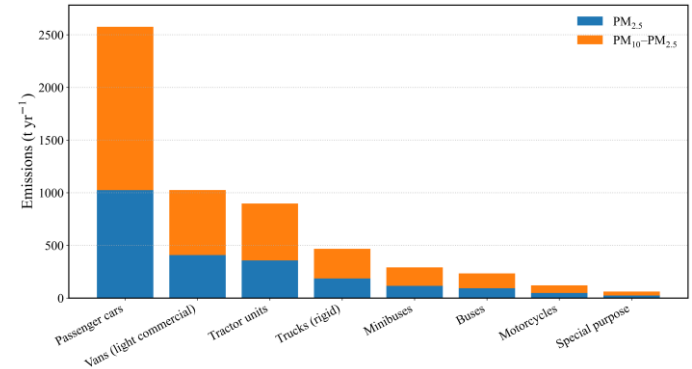


Figure 2. Composition of brake-wear PM<sub>10</sub> by vehicle category (stacked PM<sub>2.5</sub> and coarse fraction).

Across vehicle categories, the coarse fraction constitutes the majority of PM<sub>10</sub>, while PM<sub>2.5</sub> remains non-negligible in terms of health-relevant exposure and regulatory reporting. Although the PM<sub>2.5</sub> mass share is smaller, this does not imply lower health relevance, as fine particles penetrate deeper into the respiratory tract and can carry redox-active metals originating from pad and disc materials. Accordingly, recent reviews recommend reporting both PM<sub>10</sub> and PM<sub>2.5</sub>—and, where feasible, size-resolved number metrics—to support risk-informed mitigation strategies [14,15]. In this context, Figure 3 presents a Pareto-style ranking of vehicle categories by their contribution to national PM<sub>10</sub>, together with the cumulative share, to identify the dominant drivers of the inventory.

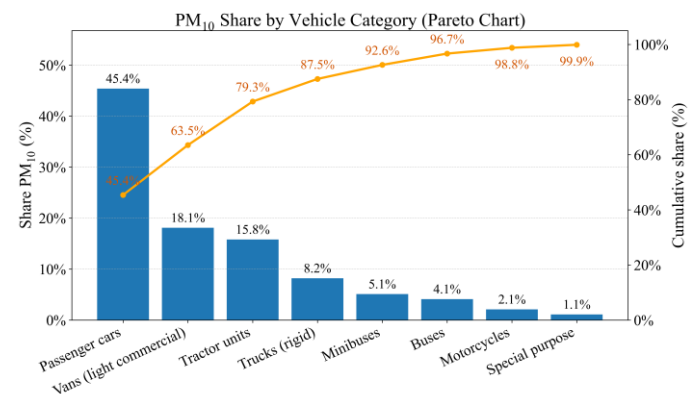


Figure 3. Pareto-style breakdown of PM<sub>10</sub> shares by vehicle category with cumulative share.

The Pareto breakdown in Figure 3 shows a highly concentrated contribution structure for national brake-wear PM<sub>10</sub>. Passenger cars dominate the inventory (45.4%), followed by light commercial vans (18.1%) and tractor units (15.8%). Together,

these top three categories account for 79.3% of total  $PM_{10}$ , indicating that a limited subset of the fleet drives most of the mass emissions. Extending the set to include rigid trucks (8.2%) raises the cumulative share to 87.5%, and adding minibuses (5.1%) yields 92.6%. By contrast, the remaining categories—buses (4.1%), motorcycles (2.1%), and special-purpose vehicles (1.1%)—each contribute only marginally, pushing the cumulative share to ~99.9%. This concentration implies that targeted measures focused on the highest-contributing categories can plausibly deliver a large fraction of achievable reductions without requiring uniform intervention across the entire fleet, consistent with mitigation frameworks in recent non-exhaust PM syntheses that prioritise sources where activity and emission intensity coincide [14,19].

However, the absolute inventory totals and, in some cases, the relative spacing between category contributions are sensitive to the adopted uncertainty assumptions for activity, composition, emission factors, and particle-size fractions. To evaluate the robustness of the national totals under the revised stochastic framework, Figure 4 summarises the Monte Carlo results for both  $PM_{10}$  and  $PM_{2.5}$ , reported as the median and 95% uncertainty interval.

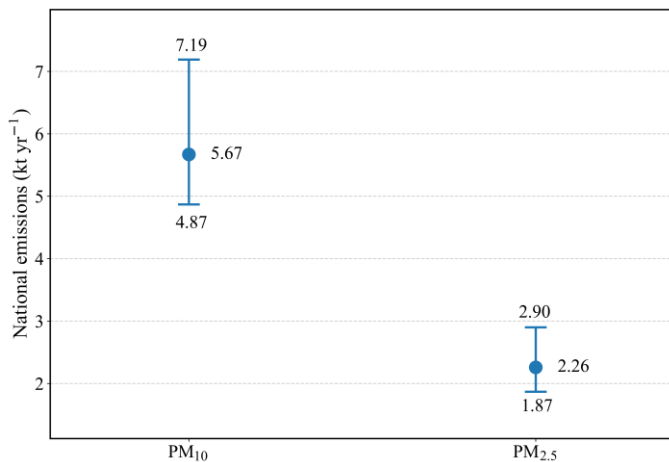


Figure 4. Monte-Carlo uncertainty intervals for national brake-wear  $PM_{10}$  and  $PM_{2.5}$  (median values with 95% uncertainty intervals; central markers denote medians).

Figure 4 shows that uncertainty is non-negligible but bounded within the adopted input structure. The reported intervals reflect propagation of the specified sampling assumptions rather than observational confidence limits, and they therefore provide a transparent measure of modelled inventory uncertainty under the present screening-level framework. This treatment is particularly important for brake-wear inventories, because guidebook-based emission factors and fleet-structure assumptions can vary materially in the absence of country-specific measurement datasets [14,15].

### 3.2. Sensitivity analysis of uncertainty drivers

Beyond reporting interval estimates, it is also useful to identify which sampled inputs exert the greatest influence on the simulated national total. Accordingly, a screening-level sensitivity analysis was performed using Spearman rank correlations between the sampled uncertain inputs and the simulated national brake-wear  $PM_{10}$  total ( $N = 20,000$ ). Figure 5 visualises the relative influence of the sampled terms.

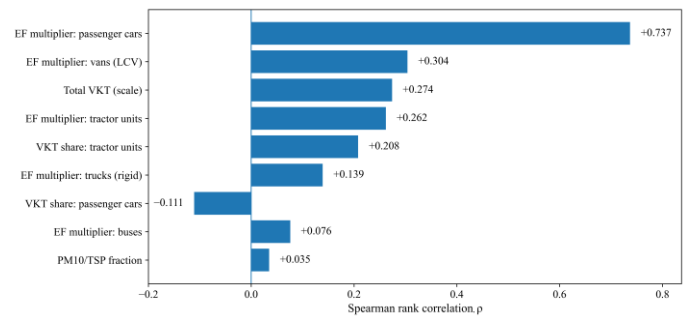


Figure 5. Screening-level sensitivity of the national brake-wear  $PM_{10}$  total to uncertain inputs (signed Spearman rank correlations from Monte-Carlo sampling;  $N = 20,000$ ).

As shown in Figure 5, uncertainty in emission factors is the dominant driver of variability in the national  $PM_{10}$  total. In particular, the emission-factor multiplier for passenger cars exhibits the strongest association with the inventory outcome ( $\rho = 0.737$ ), reflecting both the large activity share of this category and the direct multiplicative role of emission factors in the calculation. Emission-factor uncertainty for light commercial vehicles ( $\rho = 0.304$ ) and tractor units ( $\rho = 0.262$ ) also contributes substantially, consistent with their prominence in the overall fleet activity. The negative correlation observed for the passenger-car VKT share reflects the sum-to-one constraint among category shares: increases in one category necessarily reduce others, leading to compensatory effects rather than a physically negative contribution. Figure 5 provides the corresponding Spearman rank correlation coefficients and helps distinguish primary from secondary uncertainty drivers. In general, emission-factor terms associated with dominant vehicle groups remain the principal controls on simulated national  $PM_{10}$ , whereas total VKT and category-allocation variables play a secondary but still interpretable role. Lower-ranked inputs, including particle-size fraction terms, tend to have weaker correlations because their bounded variability is smaller and their influence is exerted after the main TSP emission calculation. Overall, the results indicate that a limited set of input assumptions dominates uncertainty propagation in the present inventory, which is useful for prioritising future data-improvement efforts.

### 3.3. Category breakdown

Table 5 reports the baseline national brake-wear  $PM_{10}$  and  $PM_{2.5}$  emissions for 2024 disaggregated by vehicle category, to-

gether with each category's share of the national total. The results show a strongly concentrated contribution structure, with passenger cars accounting for the largest fraction of national  $PM_{10}$ , followed by light commercial vans and tractor units, while the remaining categories contribute comparatively smaller shares. This pattern is consistent with the Pareto-style ranking presented earlier and reflects the combined effects of category activity (VKT allocation) and category-specific emission factors. Uncertainty propagation and sensitivity screening have already been reported above, providing context for the robustness of the category-level results discussed here. jurisdictions.

Table 5. Baseline brake-wear  $PM_{10}$  and  $PM_{2.5}$  emissions by vehicle category.

Category	$PM_{10}$ (t/y)	Share $PM_{10}$ (%)	$PM_{2.5}$ (t/y)	Share $PM_{2.5}$ (%)
Passenger cars	2576	45.4	1025	45.4
Vans (light commercial)	1026	18.1	408	18.1
Motorcycles	121	2.1	48	2.1
Tractor units	898	15.8	357	15.8
Trucks (rigid)	468	8.2	186	8.2
Minibuses	291	5.1	116	5.1
Buses	234	4.1	93	4.1
Special purpose	62	1.1	24	1.1

The category-level results in Table 5 confirm a strongly skewed contribution structure across the vehicle fleet. Passenger cars account for roughly 45% of national brake-wear  $PM_{10}$  because they represent approximately 57% of total vehicle kilometres travelled. Light commercial vehicles contribute around 18%, while heavy-duty categories (tractor units, trucks, and buses) together contribute about 30%, despite a smaller share of total VKT, reflecting their higher per-kilometre brake-wear emission factors. Motorcycles contribute only a small fraction (around 2%), consistent with their lower vehicle mass and brake-wear emission intensity.

This concentrated contribution structure implies that targeted mitigation measures focusing on high-impact categories can deliver a large fraction of achievable reductions without requiring uniform intervention across the entire fleet, in line with recent non-exhaust PM mitigation frameworks that prioritise sources where activity and emission intensity coincide [14,19].

### 3.4. Electrification signal in the 2024 Turkish fleet

With end-2024 passenger car shares of 2.4% hybrid and 1.1% battery electric [12], the inventory indicates only a modest reduction in national brake-wear PM relative to an all-ICE passenger-car counterfactual ( $\approx 33 \text{ t y}^{-1}$  of  $PM_{10}$ , or  $\sim 0.6\%$  of the national total). This small signal is expected at current fleet penetration, even though vehicle-level studies report large reductions in brake wear under regenerative braking (64–95% depending on cycle and braking aggressiveness) [8-9]. A scenario with

10% hybrid and 10% battery electric passenger cars reduces national  $PM_{10}$  by  $\sim 206 \text{ t y}^{-1}$  ( $\sim 3.6\%$ ), showing that brake-wear benefits will become more visible as electrification progresses.

### 3.5. Sensitivity to disc–drum mix and heavy-duty auxiliary braking

The disc–drum configuration sensitivity ( $f_{DD} = 0.85 - 1.15$ ) shifts the national  $PM_{10}$  estimate by approximately  $\pm 6 - 8\%$ , reflecting the dominance of light-duty activity. The heavy-duty service-brake duty factor  $\phi_{HDV}$  has a smaller but still meaningful effect: reducing  $\phi_{HDV}$  from 1.0 to 0.8 lowers national brake-wear  $PM_{10}$  from 5.67 to 5.28  $\text{kt y}^{-1}$  ( $-6.9\%$ ), because heavy-duty categories contribute about one-third of emissions. These findings suggest that while electrification is a long-term pathway, near-term mitigation can also arise from targeted heavy-duty operational and technology measures (e.g., retarder use on mountainous corridors) and from low-emission brake materials and coatings.

### 3.6. Mitigation scenarios and policy relevance

Recent experimental and vehicle-level studies indicate that brake-wear particulate emissions can be substantially reduced through a combination of improved friction materials, coated discs, and greater reliance on regenerative or auxiliary braking, with reported reductions ranging from moderate to order-of-magnitude under controlled conditions [3,9]. However, translating such technology-level findings to the national scale requires explicit assumptions on fleet penetration, real-world operating conditions, and the extent to which friction braking is actually displaced in everyday driving. Accordingly, a scenario-based approach is adopted to connect the baseline inventory to actionable policy and technology levers while preserving transparency and reproducibility.

The mitigation scenarios in Table 6 are formulated as policy-relevant, illustrative cases rather than near-term deployment forecasts. In particular, the “low-emission brakes” case is parameterised using bounded assumptions on adoption and emission-factor reduction to reflect uncertainty in real-world durability, maintenance sensitivity, and heterogeneous operating environments; reported reductions under controlled testing can be higher but may not transfer one-to-one to fleet-average conditions. Accordingly, scenario outputs are interpreted comparatively across measures (portfolio insight) rather than as compliance projections. For clarity, the scenario parameters used here are literature-informed but are not directly observed national fleet-average values. In particular, the low-emission brake case combines an assumed technology uptake with a bounded emission-factor reduction selected for screening-level analysis, while the heavy-duty auxiliary-braking case represents a conservative service-brake displacement assumption rather than a measured national utilisation rate. Accordingly, the scenario outputs are intended to indicate the direction and approximate magnitude of potential reductions under the tested assumptions, rather than to represent empirical outcomes or near-term forecasts. These pa-

parameter values (50% adoption and 40% reduction) should be interpreted as illustrative mid-range assumptions grounded in experimental literature, rather than as observed national fleet-average values. jurisdictions.

Table 6. Illustrative mitigation scenarios for Türkiye's brake-wear PM<sub>10</sub> (2024 activity baseline)

Scenario	Assumption	PM <sub>10</sub> (kt/y)
Baseline	EEA factors; TurkStat 2024 VKT; current electrification	5.67
Minibus mapping sensitivity	Minibuses mapped to N1-II/II I instead of HDV passenger	5.59
Higher passenger-car electrification	Passenger cars: 10% HEV, 10% BEV (others ICE)	5.47
Auxiliary braking in HDV	$\varphi_{HDV} = 0.8$ for HDV categories	5.28
Low-emission brakes (illustrative)	50% of passenger cars and vans adopt brakes with 40% lower EF	4.95

Note: "Baseline" denotes the deterministic point estimate evaluated at nominal inputs; percentage changes are relative to this value. Scenario values are illustrative and assumption-dependent; they are intended as comparative projections for screening-level policy discussion rather than empirical outcomes or deployment forecasts. The low-emission brake scenario assumes 50% fleet penetration and 40% emission-factor reduction, implemented through weighted emission factors (see Section 2.5).

Table 6 reports the national brake-wear PM<sub>10</sub> outcomes associated with each scenario, expressed both in absolute terms and as changes relative to the baseline. The scenarios are ordered by decreasing reduction magnitude to facilitate policy interpretation. Among the mitigation options, interventions targeting the dominant light-duty vehicle activity base emerge as the most influential at the national level, reflecting the large contribution of passenger cars and light commercial vehicles to total vehicle kilometres travelled.

The "low-emission brakes" scenario yields the largest reduction among the individual measures considered. Operational measures targeting heavy-duty vehicles, represented by increased use of auxiliary braking, provide a smaller but still non-negligible reduction, consistent with the high per-kilometre brake-wear intensity of these categories despite their lower activity share. Increased passenger-car electrification produces a more modest reduction under the assumed penetration levels, indicating that brake-wear benefits from electrification remain sensitive to both fleet turnover and recuperation effectiveness.

In contrast to these mitigation levers, the minibus mapping case in Table 6 is included as a classification sensitivity check rather than a policy intervention. Its purpose is to bound uncertainty arising from the correspondence between national vehicle statistics and brake-wear factor groupings, and it should therefore be interpreted separately from technology- or behaviour-driven mitigation scenarios.

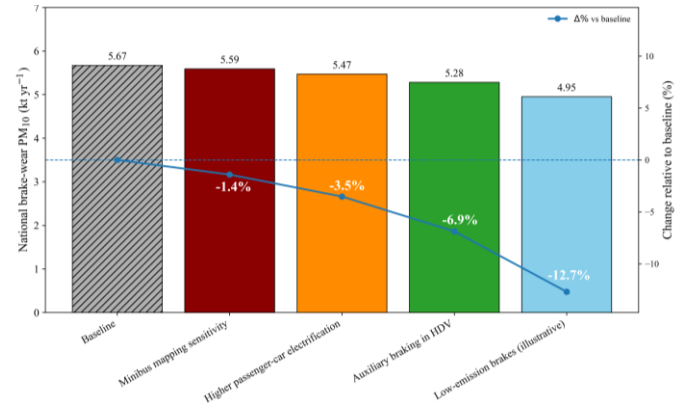


Figure 6. National PM<sub>10</sub> under illustrative mitigation scenarios (2024 activity baseline).

Figure 6 provides a visual comparison of the baseline and scenario outcomes, highlighting the relative effectiveness of different mitigation pathways at the national scale. Presenting the results in this ordered form clarifies that no single measure alone delivers a large reduction under conservative assumptions; rather, meaningful mitigation would likely require a combination of improved friction materials, targeted heavy-duty braking strategies, and continued electrification of the passenger-car fleet.

Importantly, the scenario results should be interpreted in light of the underlying uncertainty of the baseline inventory and the simplifying assumptions inherent in national-scale modelling. The analysis is therefore not intended to rank specific technologies definitively, but to indicate the direction and approximate magnitude of potential reductions achievable under realistic adoption constraints. In this context, the consistency of the scenario ranking with the broader literature supports the robustness of the inventory framework while underscoring the value of transparent, assumption-driven scenario analysis for policy discussion. The scenario parameters used in this analysis are therefore best interpreted as illustrative and assumption-driven inputs, rather than as empirically validated national coefficients.

### 3.7. Interpretation and policy-relevant implications

The scenario results indicate that mitigation effectiveness is primarily driven by high-activity light-duty vehicle groups, which dominate total vehicle kilometres travelled. Among the tested cases, the low-emission brake scenario yields the largest reduction ( $\approx -12.7\%$ ), followed by auxiliary braking in heavy-duty vehicles ( $\approx -6.9\%$ ) and increased passenger-car electrification ( $\approx -3.6\%$ ). These differences reflect the relative importance of activity distribution and emission-factor modification within the inventory structure.

The results also show that operational measures in heavy-duty vehicles can provide non-negligible reductions despite their smaller share of total activity, due to their higher per-kilometre emission intensity. In contrast, electrification effects remain limited under current fleet shares, but are expected to increase as penetration grows.

Overall, the findings should be interpreted as scenario-based, assumption-dependent outcomes that indicate the relative magnitude and direction of potential reductions, rather than as direct policy or regulatory projections.

### 3.8. Internal consistency and literature-based plausibility assessment

In the absence of country-specific measurement data for brake-wear emissions in Türkiye, an independent validation of the model results is not feasible within the scope of the present study. Therefore, this section does not attempt to provide a formal validation of the inventory outputs. Instead, it presents a limited internal consistency check together with a literature-based plausibility assessment to contextualise the results within the broader body of experimental and inventory research.

First, the national totals are translated into implied fleet-average emission factors by dividing the aggregated emissions by the total vehicle kilometres travelled reported in Table 1. These implied values are reported solely as a transparency check to confirm that the aggregation procedure and unit conversions are internally consistent. Since the same European Environment Agency (EMEP/EEA) guidebook emission factors are used as model inputs, the implied emission factors do not provide an independent validation of the model, but rather demonstrate arithmetic consistency within the adopted framework.

To avoid methodological inconsistency, no comparison is made with combined tyre + brake emission factors. Such comparisons would not be appropriate, as the present study explicitly considers brake wear only, whereas combined factors include additional non-exhaust sources that are outside the system boundary of this analysis.

Instead, the plausibility of the results is assessed by comparing the derived fleet-average brake-wear emission factors with ranges reported in experimental dynamometer studies and recent literature. Previous studies indicate that brake-wear  $PM_{10}$  emission factors for passenger cars typically fall within a broad range (approximately 3–20  $mg \cdot km^{-1}$ ), depending on braking conditions, vehicle characteristics, and measurement protocols [3–7]. Heavy-duty vehicle emission factors are generally higher and exhibit substantial variability due to differences in load, duty cycle, and braking intensity.

Within this context, the fleet-average  $PM_{10}$  emission factor obtained in this study (14.8  $mg \cdot km^{-1}$ ) lies within the expected range reported in the literature for mixed vehicle fleets. Similarly, the corresponding  $PM_{2.5}$  value (5.9  $mg \cdot km^{-1}$ ) is consistent with typical fine-particle fractions observed in brake-wear studies. These comparisons suggest that the magnitude of the estimated emissions is broadly plausible and consistent with existing experimental evidence, when differences in system boundary, fleet composition, and aggregation level are taken into account.

It is emphasised that this assessment represents an order-of-magnitude plausibility check rather than a validation. The results should therefore be interpreted as screening-level estimates

derived from guidebook-based emission factors and national activity data. A rigorous validation of the inventory would require dedicated measurement campaigns under representative Turkish driving conditions, including vehicle-category-specific brake-wear emission factors and locally resolved particle-size distributions.

### 3.9. Limitations

This study provides a screening-level national brake-wear inventory and scenario analysis; nevertheless, several data and modelling limitations should be considered when interpreting the results.

*Data limitations:* (i) Activity statistics reported by TurkStat do not directly resolve braking intensity, road grade, and the urban driving share, all of which can systematically influence brake-wear emissions across regions and duty cycles. (ii) National disc–drum distributions and the penetration/utilisation of auxiliary braking (e.g., retarder/engine braking) for heavy-duty vehicles are not available as official statistics; therefore, these effects are represented through bounded scenario assumptions rather than directly observed inputs. (iii) Türkiye-specific measurement datasets for airborne brake-wear size fractions ( $PM_{10}/TSP$  and  $PM_{2.5}/TSP$ ) remain limited; consequently, size fractionation relies on literature- and guidebook-based values, which may not fully reflect local vehicle mix, materials, and operating conditions [2].

*Model limitations:* (i) The accounting framework quantifies brake wear only and does not include tyre wear, road wear, or resuspension; therefore, the results should not be interpreted as total non-exhaust PM. (ii) Emissions are estimated using fleet-average factors and do not resolve speed-dependent braking dynamics, thermal effects, bedding-in behaviour, or detailed friction-material composition, implying that micro-scale variability across driving environments is not explicitly modelled. (iii) The Monte-Carlo analysis propagates uncertainty in key input parameters but cannot eliminate structural uncertainty related to factor representativeness and potential correlations among inputs. (iv) The analysis is national-aggregate and does not spatially allocate emissions to provinces or street canyons; thus, concentration and exposure impacts are outside the scope of this paper.

### 4. Conclusions

This study provides a transparent, screening-level national estimate of airborne brake-wear particulate emissions in Türkiye and explores how these emissions may respond under a set of illustrative mitigation and sensitivity scenarios. Under the assumptions adopted, the results suggest that measures affecting high-activity light-duty vehicle groups may have a comparatively larger influence on national brake-wear PM totals, while heavy-duty operational measures and passenger-car electrification may also contribute to reductions of smaller magnitude. These scenario outcomes should be interpreted as indicative and

assumption-dependent rather than as a basis for definitive prioritisation of mitigation measures or regulatory action.

Significant studies have been conducted in the literature, particularly on brake pads containing natural reinforcements [23-28]. The findings may nevertheless serve as a useful reference point for future refinement of national non-exhaust emission inventories and for discussion of emerging policy questions related to brake wear. In this sense, the study is better understood as providing a transparent comparative framework for exploratory assessment, rather than a direct basis for regulatory alignment or compliance evaluation [20].

Scenario analysis indicates that, under the illustrative and assumption-based conditions considered in this study, mitigation effectiveness is primarily influenced by interventions targeting high-activity light-duty vehicle groups. These scenario results should be interpreted as indicative and assumption-dependent outcomes, rather than as definitive or directly generalisable estimates of real-world emission reductions. Among the scenarios examined, the low-emission brake case is estimated to produce the largest reduction in national brake-wear  $PM_{10}$ , lowering it from  $5.67$  to  $4.95$   $kt \cdot y^{-1}$  ( $\approx -12.7\%$ ). Increased use of auxiliary braking in heavy-duty vehicles is associated with a reduction to  $5.28$   $kt \cdot y^{-1}$  ( $\approx -6.9\%$ ), while increased passenger-car electrification (10% HEV and 10% BEV) is estimated to result in a more modest reduction to  $5.47$   $kt \cdot y^{-1}$  ( $\approx -3.6\%$ ). These values reflect scenario-specific assumptions and should not be interpreted as empirical fleet-average reductions or near-term policy outcomes. Although heavy-duty vehicles account for a smaller share of total vehicle kilometres travelled, their high brake-wear intensity explains the non-negligible influence of targeted operational measures in the scenario analysis.

The inclusion of a vehicle-classification sensitivity case shows that inventory outcomes can shift depending on category mapping assumptions, even when total activity remains unchanged. This sensitivity highlights the importance of transparent and harmonised vehicle classification for policy communication and regulatory alignment. The derived fleet-average brake-wear emission factors ( $14.8$   $mg \cdot km^{-1}$  for  $PM_{10}$  and  $5.9$   $mg \cdot km^{-1}$  for  $PM_{2.5}$ ) are consistent with the order of magnitude reported in the literature, when differences in system boundary and fleet composition are taken into account [2].

Beyond emission magnitude, the results may be relevant for broader discussions on air quality and sustainability. However, it is important to emphasise that the present study is limited to a national-level emission inventory and does not include spatial distribution, atmospheric dispersion, concentration modelling, or exposure assessment. Therefore, no direct conclusions can be drawn regarding air-quality improvements or public health impacts. The estimated emission reductions should instead be interpreted as indicative inputs that may inform future integrated assessments linking emissions with air quality, exposure, and health outcomes.

Beyond mitigation magnitude, the results underline the broader policy relevance of brake-wear control. The estimated

reductions identify the approximate scale of brake-wear PM mitigation that could be achieved under the tested assumptions. However, because the present analysis is limited to emissions and does not include dispersion, concentration, exposure, or health modelling, these findings should not be interpreted as direct estimates of air-quality or public-health benefits [29]. The scenario-based structure adopted in this work is compatible with emerging European regulatory attention to non-exhaust emissions and supports alignment of national inventories with evolving policy frameworks [20].

Future work should focus on a limited number of key priorities to improve the robustness and applicability of national brake-wear inventories. First, Türkiye-specific measurements of brake-wear emission factors and particle-size fractions under representative driving conditions are needed to reduce reliance on guidebook values. Second, improved data on brake technologies and usage patterns, including disc-drum distributions and heavy-duty auxiliary-braking utilisation, would help refine model assumptions. Third, spatial disaggregation of national emissions, coupled with atmospheric dispersion and exposure modelling, is required to establish links between emissions, air quality, and public health. Finally, extension toward particle-number metrics and brake material characterisation would support more comprehensive environmental and health assessments.

### Conflict of Interest Statement

The author declare no conflict of interest in the study.

### Declaration of Generative AI in the Writing Process

The author declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

### Data Availability Statement

All compiled activity inputs are from publicly available TurkStat releases.

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