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NON-EXHAUST $PM_{2.5}$ FROM ROAD DUST RESUSPENSION IN TIRANA STREET CANYONS: AN AP-42 EMPIRICAL APPROACH AND METEOROLOGICAL INFLUENCES

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Abstract

Central Tirana is characterized by high population density and severe traffic congestion, conditions that strongly enhance road dust resuspension as a significant non-exhaust source of fine particulate matter ($PM_{2.5}$). This case study investigates the main features of the phenomenon, with particular attention to the street canyon effect caused by building height and the vertical gradients of pollutant concentration, an aspect that remains largely unexplored in the Albanian urban setting. The U.S. EPA AP-42 empirical model calibrated with local parameters (traffic intensity ≈20,000 vehicles/day, average speed 35 km/h, silt loading 0.6–1.2 g/m²), indicates that, under box-model assumptions ($V_{mix} = 1 \times 10^6$ m³/day), resuspension contributions are estimated at 5–15 µg/m³ under typical conditions, with potential increments up to 23–69 µg/m³ in sensitivity scenarios with elevated silt loading (0.4–1.2 g/m²). These values should be interpreted as indicative upper-bound screening estimates rather than precise predictions, due to the simplified nature of the box model and lack of direct vertical concentration measurements. Sensitivity analyses reveal potentially higher increments in scenarios dominated by elevated silt loading from construction and dry seasonal conditions. The proposed "Tirana Urban Canyon Resuspension Trap" is presented as a conceptual framework integrating empirical estimates, observed patterns, and established street-canyon aerodynamics. The findings highlight the urgent need for targeted mitigation measures, including regular street cleaning and traffic management, in densely built urban areas.

Keywords: road dust resuspension, $PM_{2.5}$, non-exhaust emissions, street canyon effect, urban traffic

1. INTRODUCTION

Tirana, Albania's capital, has undergone rapid urbanization, reaching a population of approximately 900,000 with particularly high density in the central districts. The city core is characterized by narrow streets, dense buildings (15–30 m), chronic traffic congestion (average speeds often below 40 km/h),

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and persistent construction activity. These factors create ideal conditions for road dust resuspension, the process by which vehicle-induced turbulence (from braking, acceleration, and tire passage) loft accumulated road-surface particles into the air, substantially contributing to ambient $PM_{2.5}$. Despite the literature on road dust resuspension in Mediterranean and Southern European cities (Amato et al., 2016; Belis et al., 2019; Vardoulakis et al., 2003), systematic investigations in the Western Balkans remain scarce. In Tirana, unique local conditions—including rapid post-socialist urbanization, intense construction activity, an aging diesel-dominated vehicle fleet (73.5% diesel, average age >13 years), and pronounced street-canyon geometry (H/W ratios 1.0–2.5)—amplify near-surface $PM_{2.5}$ exposure. These factors, combined with frequent thermal inversions and limited street maintenance, create a significant research gap. Moreover, elevated $PM_{2.5}$ levels contribute to increased cardiovascular and respiratory health risks, as documented in the latest WHO guidelines (World Health Organization, 2021). The present case study addresses this gap by applying a locally calibrated AP-42 approach and integrating meteorological reanalysis to quantify resuspension contributions under real Tirana conditions.

Although non-combustion in origin road dust resuspension is anthropogenic and in densely populated cities like Tirana, it often outweighs other non-exhaust sources such as brake and tire wear. Roadside enrichment of size- and time-resolved particles has been documented in urban traffic environments (Amato et al., 2011b). Regional studies in southern Europe and the Balkans indicate that in streets with height-to-width (H/W) ratios >1, particles become trapped near ground level, thereby increasing population exposure (Amato et al., 2016; Belis et al., 2019; Vardoulakis et al.,2003). Despite elevated winter $PM_{2.5}$ concentrations in Tirana (frequently reaching 57 $\mu g/m^3$), systematic investigation of this street-canyon trapping effect has been lacking locally (Premti, 2023, 2025). Road dust resuspension is increasingly recognized as a significant non-exhaust contributor to urban particulate matter concentrations. Recent research has mapped the spatial characteristics and exposure of resuspended $PM_{2.5}$ using advanced grid-based models (Bao et al., 2024), and non-exhaust sources, including resuspension, have been shown to contribute substantially in roadside settings (Matthaios et al., 2022; Thorpe & Harrison, 2008). Similar findings have been reported in urban road environments using the AP-42 methodology, where resuspension contributions to $PM_{2.5}$ near roads range from 5–25 $\mu g/m^3$ under typical conditions (Woo et al., 2020; Li et al., 2021). Controlled comparisons of AP-42 with direct measurements further confirm its utility as a screening tool, though it may underestimate in low-speed, congested traffic (Fitz et al., 2021). Also, though real-time on-board measurements confirm underestimation in congested low-speed traffic (Casquero-Vera et al., 2021). These studies provide a relevant benchmark for the present case in Tirana, where street-canyon geometry and local silt loading amplify near-surface exposure. The present case study quantifies road dust resuspension contributions in Tirana street canyons using a locally calibrated AP-42 approach combined with field measurements and meteorological reanalysis.

2. CHARACTERISTICS OF ROAD DUST RESUSPENSION

Several studies conducted in Mediterranean urban environments have quantified the role of road dust resuspension as a significant non-exhaust contributor to $PM_{2.5}$, often under conditions of traffic congestion, dry climate, and limited vertical dispersion similar to those observed in Tirana. These works provide useful benchmarks for contextualizing the present findings, particularly in street-canyon settings where trapping effects amplify near-surface concentrations (Vardoulakis et al., 2003; Amato et al., 2016; Belis et al., 2019). Table 1 summarizes selected results from southern European cities, illustrating typical resuspension contributions and the influence of local factors such as silt loading and seasonal dryness.

Table 1. Selected studies on road dust resuspension contributions to $PM_{2.5}$ in Southern European urban environments

Study	City	Approach	Resuspension Contribution
Amato et al. (2016). AIRUSE-LIFE+: A harmonized PM speciation and source apportionment in five southern European cities. Atmospheric Chemistry and Physics.	Barcelona (Spain), Porto, Florence, Milan, Athens	Receptor modeling + local calibration of emission factors (including AP-42-like for resuspension)	Resuspension accounts for 10–40% of $PM_{2.5}$ in traffic-dominated areas; higher in dry seasons and canyons (up to 20–30 μg/m³ increments in Barcelona, Athens).
Amato et al. (2012). Emission factors from road dust resuspension in a Mediterranean freeway. Atmospheric Environment.	Barcelona metropolitan area (Spain)	Direct measurement + AP-42 calibration for paved roads	$PM_{2.5}$ emission factors 0.001–0.01 g/VKT; resuspension contributes 5–25 μg/m³ near roads, amplified by low speed and construction.
Casquero-Vera et al. (2021). Real-time PM_{10} emission rates from paved roads... Atmospheric Environment.	Madrid (Spain)	On-board sensors + comparison to AP-42	Resuspension yields 5–25 μg/m³ increments in urban settings; AP-42 provides good screening but underestimates in congested low-speed traffic.
Amato et al. (2010). A review of the effectiveness of street sweeping. Atmospheric Environment.	Southern European cities (focus on Barcelona, Madrid)	Review of mitigation + resuspension estimates	Resuspension 10–40% of urban $PM_{2.5}$ (5–25 μg/m³); street sweeping reduces it effectively in dry Mediterranean conditions.
Amato et al. (2014). Effects of road dust suppressants on PM levels in a Mediterranean urban area (2014). PubMed/Environmental Science and Pollution Research.	Madrid (Spain)	Field trials with suppressants (CMA/$MgCl_2$) + monitoring	Resuspension is significant in dry periods; suppressants reduce PM by 20–50%, implying baseline contributions ~10–30 μg/m³ in canyons.
de la Paz D et al. (2015). Implementation of road dust resuspension in air quality simulations of particulate matter in Madrid (Spain)—Frontiers in Environmental Science 3, 72.	Madrid (Spain)	AP-42 integrated into dispersion modeling	Global resuspension factor ~0.1 g/veh·km; adds notable PM in urban background, especially under stable conditions.

Horizontal and vertical geometry in major central arteries (“Dëshmorët e Kombit” Boulevard, Rruga e Kavajës) have widths of 10–20 m with 5–10 story buildings (15–30 m tall). Resulting H/W ratios range from 1.0 to 2.5, creating classic street-canyon conditions with suppressed turbulence and prolonged residence of $PM_{2.5}$ near the surface (0–5 m) over many hours. In contrast, the peripheral zones exhibit H/W <0.5 and more rapid dispersion.

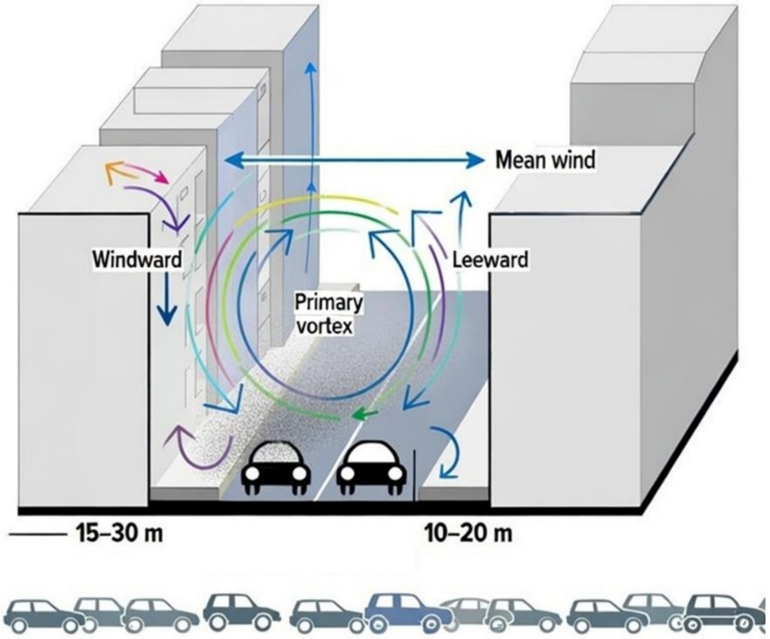

Fig. 1. Vertical trapping of resuspended particles in an urban street canyon, with the highest concentrations near breathing height

Vertical profiles of peak concentrations from resuspension occur at breathing height (0–2 m) due to direct vehicle turbulence. Between 5–15 m, levels typically decline 30–60% as canyon vortices recirculate particles downward (adapted from the classic scheme of Oke, 1988). Above the mean building height (20–30 m), freer wind flow enables more efficient dispersion.

Local factors include stop-and-go traffic (mean speed 35 km/h), a high proportion of aging diesel vehicles (73.5% diesel, average age >13 years), and ongoing construction, which elevates silt loading (0.6–1.2 g/m², consistent with regional measurements; Perrone et al., 2018). Dry Mediterranean summer and autumn periods further reduce surface moisture, roughly doubling emission rates.

To further elucidate the meteorological conditions that favour pollutant trapping within Tirana's street canyons, vertical profiles of key atmospheric variables were examined using the MERRA-2 reanalysis dataset (Buchard et al., 2017) and complementary reanalysis products, such as CAMS (Inness et al., 2019). These reanalysis data provide independent evidence of stable boundary-layer conditions but do not replace direct vertical concentration measurements. Specifically, instantaneous 3-hourly fields at 0.5° × 0.625° horizontal resolution were analyzed over the winter period (October 2020 to April 2022) for the central Tirana domain (19.7°E–19.95°E, 41.25°N–41.4°N).

The vertical profile of air temperature (Fig. 2) reveals a near surface inversion during winter months, with temperatures starting around 275–283 K (2–10°C) at 1000 hPa (surface level) and showing a slight increase aloft in the boundary layer, before the main tropospheric cooling to 220–240 K around 200–300 hPa and stabilization higher up. This thermal structure strongly suppresses vertical mixing, confining resuspended particles to the lowest atmospheric layers (0–1 km), consistent with the reduced turbulence expected in deep street canyons (H/W > 1). Complementing this, the profile of relative humidity after moist processes (Fig. 3) shows elevated values near the surface, reaching 0.5–0.7 (50–70%) at pressure levels above 900 hPa, with a sharp decrease aloft. High near-surface humidity enhances particle hygroscopic growth and favors gravitational settling or reduced upward transport, thereby amplifying exposure at breathing height. Similarly, the specific humidity profile (Fig. 4) exhibits a steep gradient, with values increasing from near-zero aloft to 0.004–0.006 kg/kg at the surface. This moisture accumulation near ground level further corroborates stable, low-dispersion conditions that prolong the residence time of resuspended PM$_{2.5}$ in densely built-up areas. These meteorological profiles provide independent evidence supporting the conceptual "Tirana Urban Canyon Resuspension Trap" framework. The combination of thermal inversions, high near-surface relative humidity, and moisture accumulation creates a persistent low-turbulence boundary layer that traps vehicle-induced dust resuspension close to the ground, explaining the elevated wintertime PM$_{2.5}$ concentrations observed locally despite comparable emission sources in more open peripheral zones.

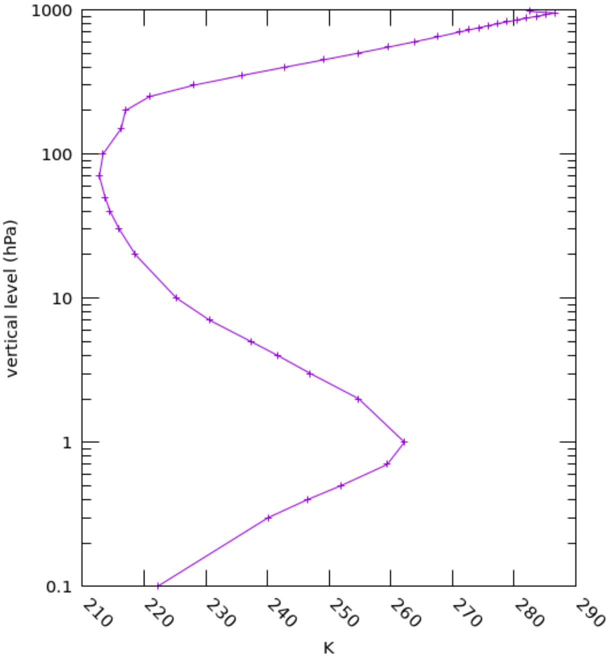

Fig. 2. Vertical profile of air temperature (K) from MERRA-2 over central Tirana during winter 2020–2022 (NASA Giovanni)

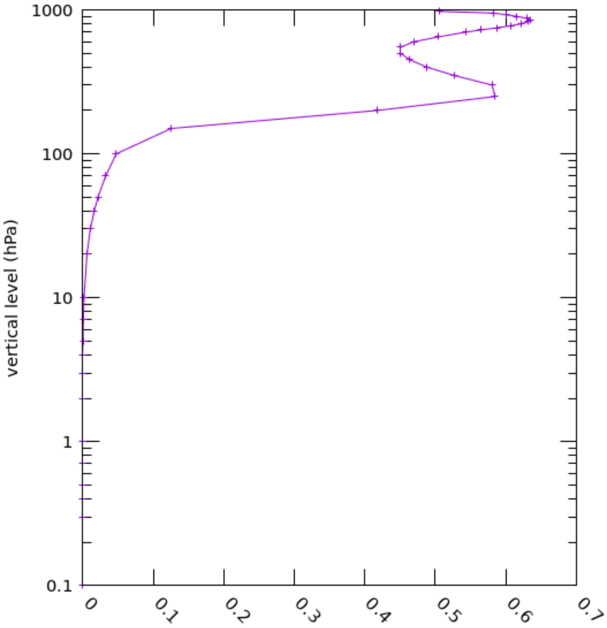

Fig. 3. Vertical profile of relative humidity after moist processes over the same period and domain

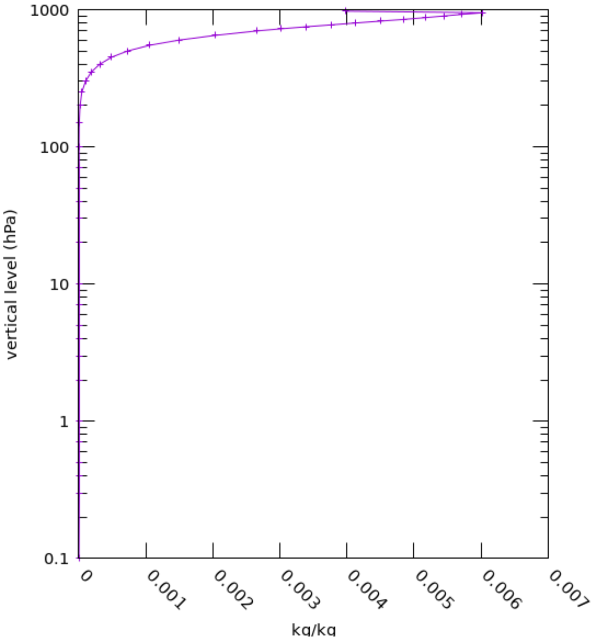

Fig. 4. Vertical profile of specific humidity (kg/kg) over the same period and domain

3. METHODOLOGY

The contribution of road dust resuspension to $PM_{2.5}$ concentrations was quantified using the original U.S. EPA AP-42 empirical model (U.S. EPA, 2011, Chapter 13.2.1: Paved Roads) following the standard methodology without modifications to the core equations. The model was locally calibrated only for input parameters (silt loading, traffic speed, vehicle weight) as described below. This screening-level approach has been widely applied and validated in Mediterranean urban environments for comparative and policy-oriented assessments (Amato et al., 2012; Li et al., 2021; Fitz et al., 2021).

The $PM_{2.5}$ emission factor ($EF_{PM_{2.5}}$, in g/VKT – grams per vehicle-kilometer traveled) is calculated as:

$$EF_{PM_{2.5}} = k \cdot \left(\frac{S_L}{12}\right)^a \cdot \left(\frac{W}{3}\right)^b \cdot f_{(RH)} \cdot f_{(S)} \qquad (3.1)$$

where:
$k = 0.10$ /VKT (particle size multiplier for $PM_{2.5}$, adapted to metric units and locally calibrated)
S_L = road surface silt loading (0.4–1.2 g/m^2)
$a = 1.0$, $b = 0.5$ (empirical exponents for fine particles)
W = mean vehicle weight = 1.9 tones
$f_{(RH)}$ = relative humidity correction factor = $\max(0.1, 1 - (RH/100)^3)$
$f_{(S)}$= vehicle speed correction factor = $f_{(S)} = \left(S/88\right)^{0.45}$
RH = average relative humidity = 70 %
S = average traffic speed = 35 km/h

Silt loading values were varied over the range 0.4–1.2 g/m^2, reflecting regional measurements and the influence of ongoing construction, seasonal dryness, and limited street cleaning in central Tirana. Annual average daily traffic (AADT) was set at 20,000 vehicles/day, and a representative road segment length of 1 km was used for simplified calculations.

To estimate the concentration increment (µg/m^3), a basic box-model approach was applied:

$$\text{Estimated contribution} \approx \frac{EF_{PM_{2.5}} \cdot (AADT) \cdot L \cdot 10^6}{V_{mix}} \qquad (3.2)$$

where V_{mix}= effective daily mixing volume = 1×10^6 m^3/day (an estimate representative of urban canyon conditions with mean building heights of ~20–30 m).

In the simplified box model, the effective mixing volume was defined as:

$$V_{mix} = W \times L \times H_{eff}$$

where W is the average street canyon width, L is the representative segment length, and H_{eff} is the effective mixing height characterizing the vertical extent of pollutant mixing within the canyon. We consider H_{eff} as a first-order proxy of the boundary layer height that confines the near-surface aerosol concentration under low-wind, stable conditions.

Sensitivity analyses to key parameters (silt loading, relative humidity, vehicle speed, and precipitation effects) were performed and visualized through five high-resolution MATLAB-generated figures 5-9 (using a gray base color scheme with red highlights for reference/typical values).

The AP-42 methodology was selected as a screening-level empirical approach suitable for data-scarce urban environments. While it does not resolve micro-scale turbulence or canyon vortex dynamics, it remains widely applied for comparative and policy-oriented assessments of road dust resuspension. The simplified box model used to convert emissions into concentration increments does not represent detailed dispersion processes; rather, it provides order-of-magnitude estimates under conservative mixing assumptions, though integration in more advanced models has improved urban PM simulations (de la Paz et al., 2015). Therefore, the resulting $PM_{2.5}$ contributions should be interpreted as indicative estimates for exposure in rather than precise predictions.

3.2 Field measurements

$PM_{2.5}$ and black carbon (BC) were measured at an urban background site in central Tirana (Faculty of Natural Sciences, University of Tirana) from 22 October 2020 to 4 March 2022. Sampling was performed with a LVS6-RV reference sampler (CEN EN 12341:2014 compliant) operating at a flow rate of 2.3 $m^3\ h^{-1}$. Filters (Whatman PTFE, 46.2 mm diameter, 2 µm pore size) were conditioned for 48 h at 20 ± 1 °C and 50 ± 5 % RH before and after sampling and weighed on a microbalance (resolution 1 µg, MYA 5.4Y.F). Field blanks and duplicates were included for quality control (variability < 5 %). All procedures followed ISO 17025 principles to ensure data quality and reproducibility. Black carbon was determined by multi-wavelength absorption using the MABI instrument (ANSTO) at seven wavelengths (405–1050 nm) and standard mass absorption coefficients for $PM_{2.5}$ (4–11 $m^2\ g^{-1}$). Instrument calibration and regular maintenance were performed to guarantee the reliability of the measurements.

4. RESULTS AND DISCUSSION

While direct vertical measurements of $PM_{2.5}$ concentrations were not available in this study, the observed near-surface temperature inversions and high relative humidity from MERRA-2 reanalysis are consistent with stable boundary-layer conditions known to limit dispersion upward and enhance near-ground exposure in street canyons (Vardoulakis et al., 2003; Oleniacz & Bogacki, 2023).

Table 2. Monthly Average Concentrations (2020–2022)

Month	**Temperature (°C)**	**Relative Humidity (%)**	**$PM_{2.5}$ (µg/m³)**	**BC (µg/m³)**	**$PM_{2.5}$/BC Ratio**
January	7.2	78.1	24.8	5.12	4.8
February	8.4	74.5	19.6	4.38	4.5
March	11.1	68.9	15.9	3.21	5.0
April	14.8	64.2	10.4	1.68	6.2
May	19.6	62.7	7.2	0.95	7.6
June	24.3	58.4	6.8	1.12	6.1
July	–	–	–	–	–
August	–	–	–	–	–
September	–	–	–	–	–
October	15.4	74.9	19.1	3.05	6.3
November	13.2	78.6	17.3	3.62	4.8
December	10.1	81.3	23.7	5.04	4.7

Table 3. Statistics performed for all measurements, 2020–2022

Parameter	**Annual Mean**	**Minimum**	**Maximum**	**Standard Deviation**	**Dust/Resuspension Implications**
Temperature (°C)	14.1	1.4	31.9	7.2	Negative correlation with PM$_{2.5}$ ($r \approx -0.35$) higher in cold months
Relative Humidity (%)	72.8	41.8	96.1	13.4	Weak positive correlation with PM$_{2.5}$ ($r \approx +0.25$) favours accumulation
PM$_{2.5}$ (µg/m^3)	16.1	1.8	57.3	11.8	Elevated episodes in winter, strong local + regional influence
BC (µg/m^3)	3.15	0.14	8.86	2.1	Primarily from traffic + residential combustion
PM$_{2.5}$ / BC Ratio	~5.2	~2	~12	~2.3	>6 indicates significant non-exhaust contribution (dust, brake/tire wear)
Dust Contribution Indicator (PM$_{2.5}$ 5·BC)	~1.1	–12	~8	~4.5	Positive values mainly in spring, early autumn, and road dust resuspension is potentially dominant

Model calculations for representative conditions in Tirana's silt loading (S_L) of 0.8 g/m^2, relative humidity (RH) of 70 %, and mean vehicle speed (S) of 35 km/h, yield a base PM$_{2.5}$ emission factor from road dust resuspension of approximately 0.0023 g/VKT. This value aligns with the lower end of reported emission factors for urban paved roads in Mediterranean and European contexts, where resuspension is modulated by frequent congestion, moderate silt accumulation from construction and dry periods, and limited street cleaning.

Sensitivity analyses reveal strong dependence on key parameters:

Silt loading variation (0.4–1.2 g/m^2, after humidity and speed corrections) shows the PM$_{2.5}$ emission factor ranging from 0.0012 g/VKT (at 0.4 g/m^2) to 0.0035 g/VKT (at 1.2 g/m^2). These levels are consistent with urban Mediterranean freeways and congested streets, where reported PM$_{2.5}$ resuspension factors often fall in the range of 1–10 mg/VKT (0.001–0.010 g/VKT), though higher values (up to 10–20 mg/VKT for PM$_{2.5}$ fractions) appear in drier or construction influenced zones (e.g., Amato et al., 2012, for Mediterranean freeways showing PM$_{2.5}$ components around 2–9 mg/VKT in resuspension profiles). Estimated daily PM$_{2.5}$ concentration increment from resuspension was:

At S_L = 0.4 g/m^2 → **23 µg/m^3**
At S_L = 0.8 g/m^2 → **46 µg/m^3**
At S_L = 1.2 g/m^2 → **69 µg/m^3**

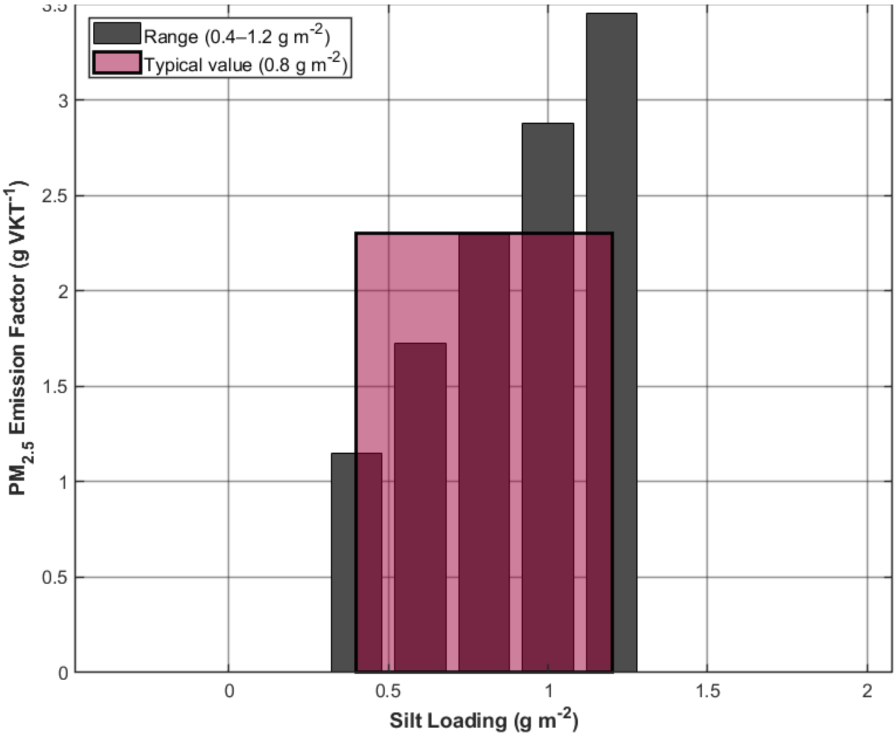

Fig. 5. Sensitivity of $PM_{2.5}$ Emission Factor to Road Surface Silt Loading

These increments indicate that road dust resuspension can constitute a substantial and frequently potentially dominant fraction of near-surface $PM_{2.5}$ in narrow, canyon-like streets, especially during winter when observed mean concentrations average 20.2 µg/m³ (versus the annual mean of 16.1 µg/m³). In comparison, studies in European urban street canyons and Mediterranean cities report resuspension contributions often accounting for 10–50 % of ambient $PM_{2.5}$ in traffic-dominated areas, with peaks exceeding 50 % under dry, low-dispersion conditions (e.g., Amato et al., 2016; Belis et al., 2019). The higher relative contributions estimated here for Tirana reflect the combination of elevated silt loading from local sources (construction, aging vehicle fleet) and pronounced street-canyon trapping, similar to patterns in coastal urban areas with industrial influences (Costa et al., 2023), which limits vertical dispersion and prolongs particle residence near breathing height.

Further sensitivities highlight mitigation opportunities in the Relative humidity (40–90 %). Under very dry conditions (RH = 40 %), the emission factor rises to ~0.0033 g/VKT. At high humidity (RH = 90 %), it falls to ~0.0009 g/VKT, a reduction of approximately 70–75 %. This underscores the strong suppressive effect of moisture on resuspension, consistent with seasonal patterns observed across southern European cities where dry summer/autumn periods double or triple emission rates compared to wetter conditions.

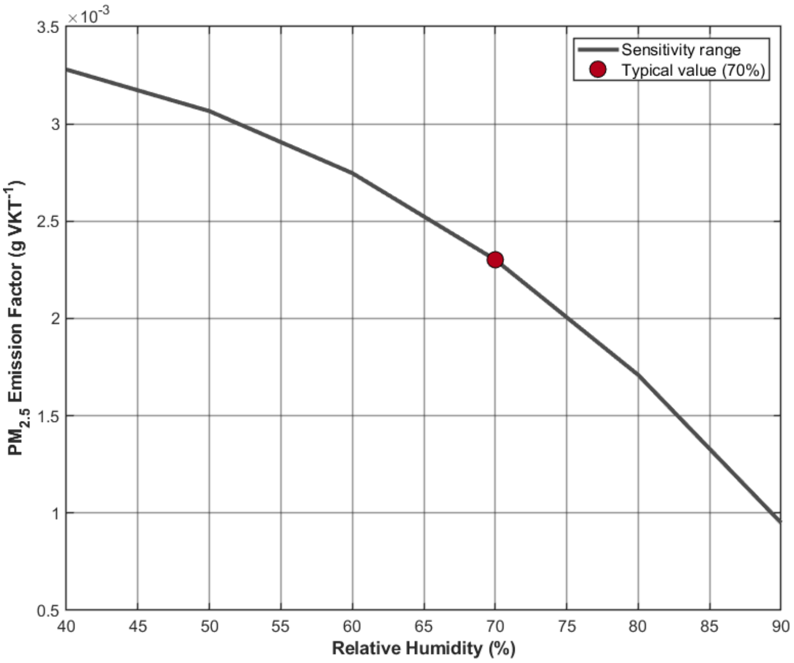

Fig. 6. Sensitivity of $PM_{2.5}$ Emission Factor to Relative Humidity

Vehicle speed (20–60 km/h): The emission factor increases from ~0.0018 g/VKT at 20 km/h to ~0.0029 g/VKT at 60 km/h (60 % rise for a threefold speed increase). Lower speeds in congested Tirana streets, therefore, act as a natural brake on resuspension emissions, aligning with broader evidence that traffic calming reduces non-exhaust PM in urban settings.

Monthly precipitation impact assessments further show that effective emission factors during wetter periods can decrease by 20–80 % relative to dry baselines, explaining part of the observed seasonal variability in $PM_{2.5}$ levels and reinforcing the potential of weather-dependent management strategies (e.g., enhanced cleaning during dry spells).

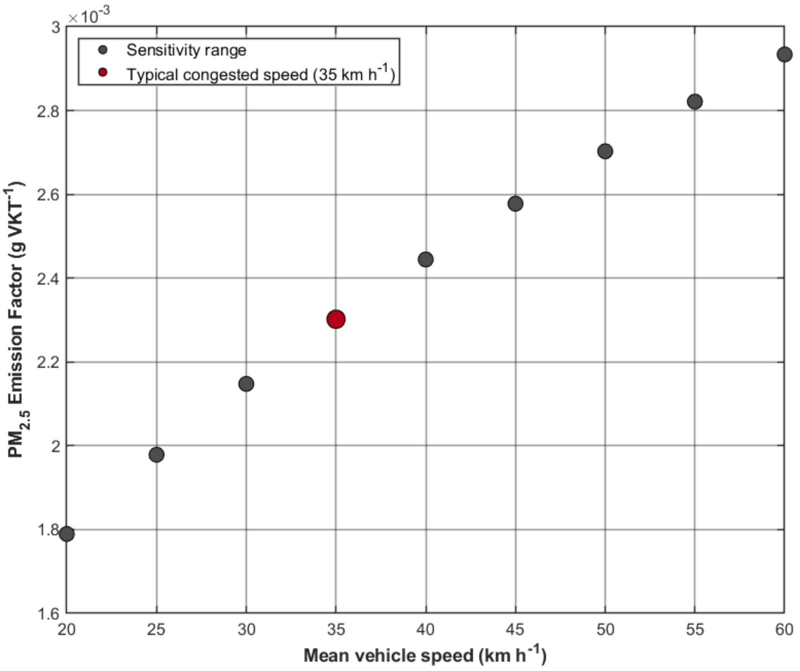

Fig. 7. Sensitivity of $PM_{2.5}$ emission factor to vehicle speed

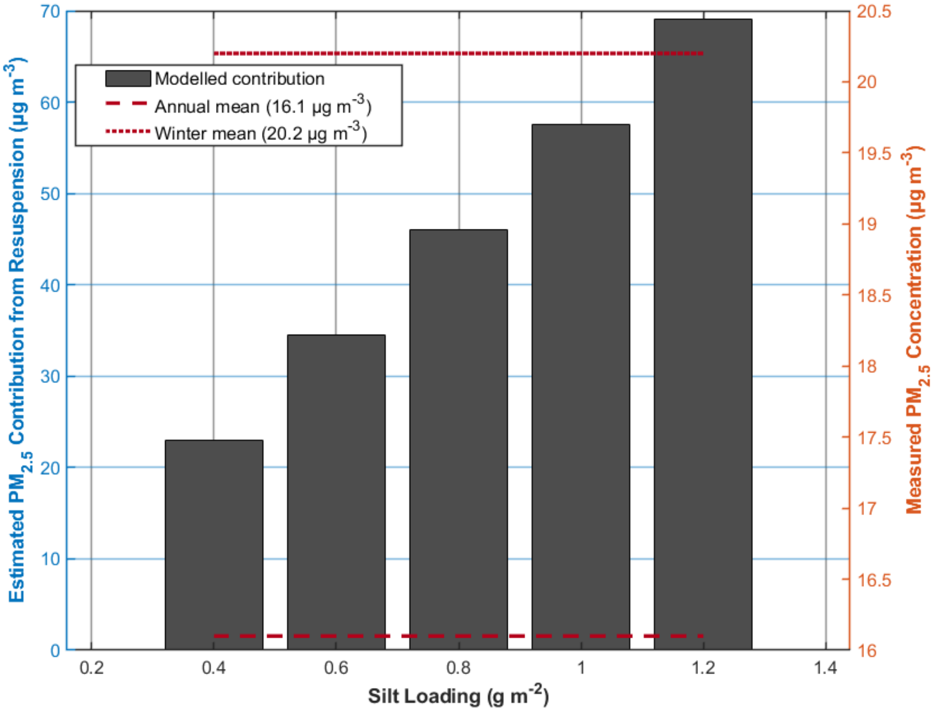

Fig. 8. Comparison of estimated resuspension contribution with measured $PM_{2.5}$

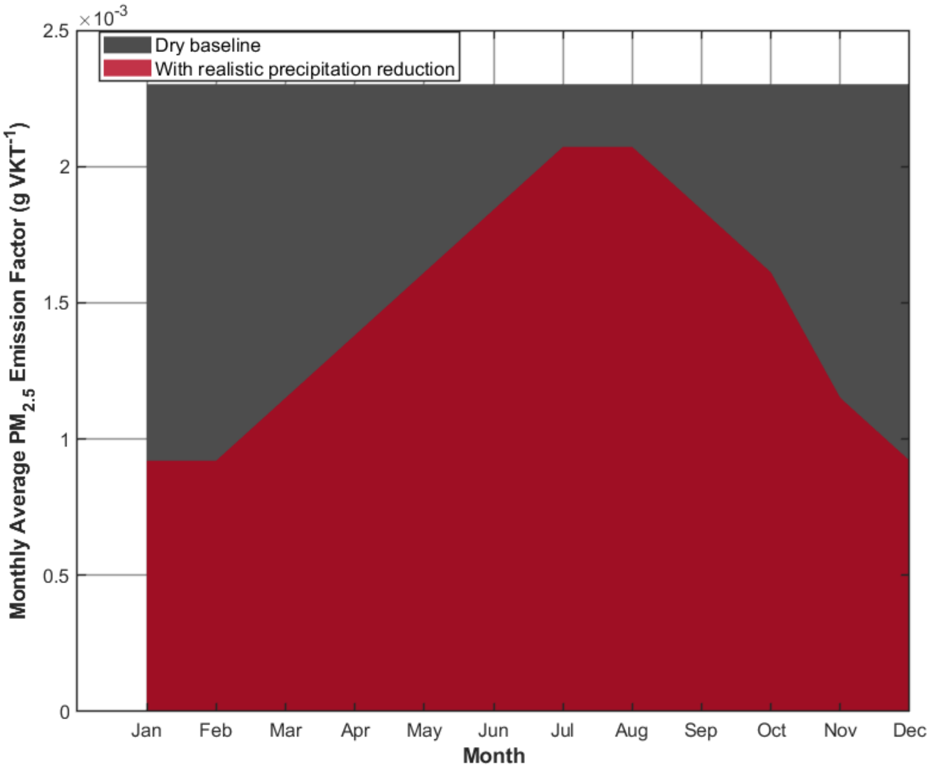

Fig. 9. Impact of Seasonal Precipitation on $PM_{2.5}$ Emission Factor (Tirana Climate)

The estimated resuspension contributions (5–15 μg m^{-3} baseline, up to 23–69 μg m^{-3} in sensitivity scenarios with elevated silt loading) are comparable to those reported in Mediterranean street canyons (Amato et al., 2016; Belis et al., 2019; Matthaios et al., 2022) and highlight the dominant role of non-exhaust sources during winter in Tirana. These levels frequently exceed WHO 24-h guidelines and contribute to increased cardiovascular and respiratory health risks associated with $PM_{2.5}$ exposure (World Health Organization, 2021).

Proposed conceptual framework: "Tirana Urban Canyon Resuspension Trap."
The combination of narrow streets (10–15 m width), tall buildings (H = 20–30 m), and slow-moving traffic generates a distinctive trapping mechanism: particles are initially lofted by vehicle turbulence but then retained near breathing height by low-velocity canyon recirculation. This "resuspension trap" has not previously been described in the Albanian setting and contrasts with more open morphologies (e.g., peripheral Athens) where dispersion occurs more readily. In zones with H/W >1.5 (common in the Blloku district and along Rruga e Kavajës), local resuspension is likely to represent a substantial fraction (potentially dominant under certain conditions) of near-surface $PM_{2.5}$, especially during periods of low vertical dispersion and elevated silt loading, as inferred from the $PM_{2.5}$/BC ratios and modeled estimates. Unlike previous Mediterranean studies that focus primarily on brake/tire wear or traffic exhaust in canyons (Amato et al., 2016; Belis et al., 2019), the Tirana case highlights road dust resuspension as the potentially dominant non-exhaust source during winter, driven by a unique combination of high silt loading (0.6–1.2 g/m^2 from construction), very low average speeds (≤35 km/h), and pronounced thermal inversions confirmed by MERRA-2 profiles which are consistent with dynamic evaluation methods in other urban case studies showing variable emission characteristics (Li et al., 2023). This framework is

not a new predictive model, but a synthesis of empirical AP-42 estimates, measured $PM_{2.5}$/BC ratios (>5 indicating non-exhaust dominance), and meteorological evidence of low vertical dispersion, offering a practical tool for policy prioritization in similar under-studied Balkan capitals. Comparable applications of AP-42 in other urban settings (Woo et al., 2020; Li et al., 2021; Fitz et al., 2021) have yielded resuspension contributions in the same order of magnitude (5–25 $\mu g/m^3$), underscoring the broader transferability of these findings to similar Balkan and Mediterranean cities with canyon-like morphologies and limited street maintenance. Future site-specific studies employing vertical profiling (e.g., lidar-based machine learning approaches; Ma et al., 2021), spatial monitoring, or detailed chemical analysis would further refine emission estimates and strengthen the evidence base for policy implementation in post-socialist urban environments.

5. CONCLUSIONS

Road dust resuspension constitutes a major non-exhaust contributor to near-surface $PM_{2.5}$ in the dense street canyons of central Tirana, driven by high silt loading (0.6–1.2 g/m^2), low average vehicle speeds (≈35 km/h), ongoing construction activity, and meteorological conditions that limit vertical dispersion (near-surface thermal inversions and elevated humidity documented via MERRA-2 profiles). The EPA AP-42 model, combined with field measurements of $PM_{2.5}$ (annual mean 16.1 $\mu g/m^3$, winter peaks >50 $\mu g/m^3$) and black carbon, yields indicative daily concentration increments from resuspension in the range of 5–15 $\mu g/m^3$ under baseline conditions, with potential increases up to 23–69 $\mu g/m^3$ in sensitivity scenarios at higher silt loading levels. These findings, while based on screening-level empirical modeling and indirect source attribution, highlight the pronounced role of street-canyon geometry (H/W ratios 1.0–2.5) in trapping resuspended particles near breathing height. The conceptual “Tirana Urban Canyon Resuspension Trap” framework integrates empirical AP-42 estimates, measured $PM_{2.5}$/BC ratios, and meteorological reanalysis into a practical synthesis. This framework can guide targeted urban policy measures (regular street cleaning, traffic calming, dust suppressants) in Balkan capitals with similar rapid densification and limited street maintenance. Future research should include direct vertical $PM_{2.5}$ profiling and chemical source apportionment to refine these screening estimates.

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