

CRC Report No. A-141

**Refining Estimates of U.S.
Background PM_{2.5} to Support
Effective Urban Air Quality Planning**

Final Report

July 2026



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EXECUTIVE SUMMARY

CRC Project A-141

Refining Estimates of U.S. Background PM_{2.5} to Support Effective Urban Air Quality Planning

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July 2026

Executive Summary

The U.S. background PM_{2.5} is defined as any PM_{2.5} formed from emissions other than U.S. anthropogenic emissions, including emissions from all natural sources as well as transboundary sources originating outside U.S. borders. Biogenic emissions, wildfires, sea salt and dust are considered major natural sources of U.S. Background. Transboundary sources are mainly from Mexico and Canada, including both natural and anthropogenic emissions. Thus, U.S. background PM_{2.5} is considered the theoretical minimum PM_{2.5} achievable under U.S. regulatory policies.

In 2024, the U.S. EPA lowered the annual PM_{2.5} National Ambient Air Quality Standards (NAAQS) from 12 to 9 µg/m³. Based on 2020-2022 data, 119 counties could be in non-attainment under the new standard, with 52 counties (23 in California) projected to remain in non-attainment by 2032, even with anticipated federal emission reductions (U.S. EPA, 2024). In addition, natural sources such as wildfires have influenced PM_{2.5} trends over the last decades due to the reduction of anthropogenic emissions and climate influences (Abatzoglou & Williams, 2016; Burke et al., 2023; Wang et al., 2024). These findings suggest a growing importance of contribution of background emissions towards total PM_{2.5} concentrations, underscoring the need for a robust estimation of background PM_{2.5} to develop effective and adaptive policies, ensuring targeted emissions and pollution level reductions.

Monitoring networks and chemical transport models (CTMs) have been traditionally used to estimate background PM_{2.5}. However, accurately estimating background PM_{2.5} remains challenging due to uncertainties stemming from both observations and CTMs. The main challenge from observations is the influence of anthropogenic emissions that affect even the most remote sites. In CTM simulations, uncertainties are associated with emissions inventories, chemical interactions, meteorology, among other.

The main goal of this project was to provide robust insights into background PM_{2.5} levels, aiming to support science-based policy-making and regulatory decisions to help cities across the U.S. meet the revised NAAQS. To achieve this, we 1) developed an integrated modeling framework using CTM simulations with the Comprehensive Air Quality Model with Extensions

(CAMx) to estimate background PM_{2.5} over continental U.S. using a zero-out approach, and 2) applied machine learning (ML) algorithms combining the CTM simulations and surface observations to refine U.S. background PM_{2.5}. This approach addresses uncertainties in methods based on observations or CTM simulations alone, and builds on frameworks developed in previous studies to estimate background ozone (Skipper et al., 2021; Hosseinpour et al., 2024).

We implemented three adjustment methods, including a multi-variate linear regression model (MLR), used as a benchmark, and two ML algorithms with proven ability for PM_{2.5} bias corrections: the Random Forest (RF) and Extreme Gradient Boosting (XGB). The background concentrations are estimated for the year 2022, which is included in the latest version of EPA's Emissions Modeling Platform.

The direct (unadjusted) concentrations from CAMx provided adequate modeling results in agreement with the state of the art and established criteria for CTM simulations. PM_{2.5} concentrations followed expected spatial and seasonal patterns, with higher concentrations in winter, and across Eastern U.S. and regional hotspots in the West (e.g. California and Northwestern U.S.). Elevated concentrations also occurred between spring and fall, influenced by wildfire activity, with hotspots in western U.S., New Mexico and New Jersey.

ML adjustments were superior to the MLR benchmark, reducing the RMSE by 41% and increasing the correlation coefficient by 38 to 40% (XGB and RF, respectively). The adjusted values improved error metrics substantially, except for the Northwestern region, which was largely affected by wildfires in the period of study. Adjusted concentrations generally reduced PM_{2.5} in the Eastern U.S. and enhanced concentrations in Western U.S. and the southern part of the domain.

U.S. background concentrations, averaged across climate regions, range from 1 to 4 $\mu\text{g}/\text{m}^3$ during the summer period (April to September) and from 0.3 to 1.5 $\mu\text{g}/\text{m}^3$ during the winter period (October to March). The higher concentrations during the summer reflect the influence of wildfire activity. The highest background levels occurred in the fire prone areas noted above (Northwest, California, and New Mexico). Over the Northwest, concentrations

exceed $3 \mu\text{g}/\text{m}^3$ over large areas, with specific portions showing average background values larger than or equal to the new standard ($9 \mu\text{g}/\text{m}^3$). The Upper Midwest and Northeast region show the lowest background concentrations, with most of these regions having annual averages lower than or equal to $1 \mu\text{g}/\text{m}^3$. Mean concentrations are greater between April and September than those between October and March, with greater summer enhancements over areas affected by wildfires.

Importantly, the regions affected by wildfire activity can show substantial interannual variability, influencing the estimation of background concentrations for different years. For instance, the 2023 record-breaking wildfire season in Canada caused elevated $\text{PM}_{2.5}$ levels over the U.S. Midwest and Northeast (Chen et al., 2025), while these two regions show the lowest background levels in this study (for 2022). The seasonal and geographical differences were discussed for background $\text{PM}_{2.5}$ and its contribution to total $\text{PM}_{2.5}$. However, the analysis did not address differences in source-specific contributions to background.

These results, as well as an analysis over two regions recognized for non-attainment (San Joaquin Valley and South Coast Air Basin), suggest that wintertime concentrations offer greater opportunities for policy interventions. Results suggest that background concentrations represent a smaller fraction of the total $\text{PM}_{2.5}$ concentrations during wintertime (10-12%) than during the summer (40-48%). In the future, the increasing impact of natural emission sources, particularly wildfires, presents a major challenge for achieving the NAAQS in fire-prone regions such as the West and Northwest regions.

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