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# Assessing the effects of electric mobility on urban air pollution: Evidence from NO$_2$ and PM$_{2.5}$ reductions

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## ABSTRACT

The rapid expansion of electric vehicles (EVs) is widely promoted as a strategy to improve urban air quality, yet empirical evidence quantifying their environmental benefits under different electricity-generation contexts remains limited. This study investigates the relationship between EV adoption and ambient concentrations of nitrogen dioxide (NO$_2$) and fine particulate matter (PM$_{2.5}$), with a particular focus on the moderating role of electricity grid composition. Using a panel dataset of high-traffic urban areas, fixed-effects regression models are employed to estimate the association between monthly pollutant concentrations and EV market share, controlling for spatial and temporal confounders. Results show that increased EV penetration is associated with statistically significant reductions in NO$_2$ and more modest declines in PM$_{2.5}$. Specifically, a one-percentage-point increase in EV share corresponds to an average reduction of 0.36 μg/m$^3$ in NO$_2$ and 0.11 μg/m$^3$ in PM$_{2.5}$. A scenario-based analysis further examines air quality outcomes under varying EV adoption rates and alternative electricity grid assumptions. Findings indicate that NO$_2$ reductions are substantial across scenarios, whereas PM$_{2.5}$ benefits are smaller and highly sensitive to the carbon intensity of electricity generation. Under renewable-dominant grid assumptions, projected pollution reductions are considerably larger than under fossil-heavy scenarios. Overall, the results demonstrate that EV deployment contributes meaningfully to reducing traffic-related NO$_2$ pollution, but its effectiveness in lowering PM$_{2.5}$ depends critically on electricity decarbonization. The study underscores the need for integrated transport and energy policies to maximize air quality co-benefits.

**Contribution/Originality:** This study provides novel multi-city empirical evidence linking electric vehicle adoption to urban air quality using a unified fixed-effects framework. It integrates regression analysis with scenario modeling while explicitly accounting for electricity grid composition, offering policy-relevant insights on NO$_2$ and PM$_{2.5}$ dynamics and the conditional role of energy decarbonization

## 1. INTRODUCTION

### *1.1. Background: Urban Transport and Air Pollution*

Urban air pollution remains one of the most persistent environmental challenges of the 21st century. Therefore, urban sustainability has emerged as an urgent topic for researchers, governments, and policymakers (Melhim & Isaifan, 2025). Although extensive research has been reported on nanomaterial-based technologies that reduce urban pollution (Isaifan et al., 2011; Isaifan & Baranova, 2013). The transportation sector is still a leading contributor to urban $NO_x$ emissions and a major source of fine particulate matter, particularly in dense metropolitan areas. Combustion-based engines emit a combination of nitrogen oxides, volatile organic compounds (VOCs), and secondary aerosols that form $PM_{2.5}$, which are responsible for millions of premature deaths globally, according to the World Health Organization's ambient air pollution database (World Health Organization, 2025).

The health burden associated with $NO_2$ and $PM_{2.5}$ exposure is significant, with studies linking them to increased risks of asthma, chronic obstructive pulmonary disease (COPD), and ischemic heart disease. Long-term exposure to $PM_{2.5}$ is particularly damaging, as it penetrates deep into the lungs and bloodstream, contributing to systemic inflammation and premature mortality (Xing, Xu, Shi, & Lian, 2016).

### *1.2. Electrification as a Transformative Strategy*

Electric vehicles (EVs) have emerged as a central pillar in the global push for sustainable mobility. Unlike internal combustion vehicles, EVs eliminate tailpipe emissions, thereby directly removing a primary source of $NO_x$ and $PM_{2.5}$ from road transport. The absence of exhaust gases also reduces exposure to black carbon and hydrocarbons, which further enhances local air quality (Zhang, Jiang, Zhang, & Choma, 2024). However, the overall environmental benefit of EVs depends heavily on two moderating factors: the electricity generation mix and the non-exhaust emission profile. In regions where power generation relies on fossil fuels, upstream emissions from electricity production may offset some of the local air-quality gains (Holland, Mansur, Muller, & Yates, 2016). Meanwhile, non-exhaust particles from brakes, tires, and road dust remain largely unaffected by electrification and can represent up to 50% of $PM_{2.5}$ associated with traffic activity (Holland et al., 2016).

### *1.3. Global Trends in EV Adoption*

The global electric vehicle stock surpassed 40 million units in 2024, representing an unprecedented 16-fold increase compared to a decade earlier. China, Europe, and the United States lead the transition, with Norway standing as a near-complete case study in full-fleet electrification. While climate mitigation has been the central policy driver, co-benefits related to air-quality improvement are gaining equal importance (Lyu et al., 2024).

For instance, empirical data from California's Zero Emission Vehicle (ZEV) program shows localized reductions in $NO_2$ as EV penetration rises, demonstrating tangible short-term health benefits. Similarly, a recent study in Chinese megacities found that Battery Electric Vehicle (BEV) usage significantly reduced $NO_2$ concentrations in areas with high vehicle density, though $PM_{2.5}$ effects were more modest and strongly correlated with the carbon intensity of the local grid (Lyu et al., 2024).

### *1.4. Problem Statement and Research Gap*

Although the theoretical and mechanistic basis for air-quality improvements from electric vehicle adoption is well established, important gaps remain in the empirical characterization of these effects at the urban scale. Existing studies have largely followed two separate approaches: localized observational analyses that identify associations between EV uptake and pollutant concentrations in specific cities, and scenario-based or modeling exercises that project potential air-quality outcomes under assumed electrification pathways. While each approach provides valuable insights, they are rarely integrated within a unified empirical framework that allows for cross-city comparison and policy-relevant inference.

In particular, there remains limited evidence quantifying the marginal effect of incremental EV penetration on ambient $NO_2$ and $PM_{2.5}$ concentrations across multiple urban contexts using consistent econometric methods. Moreover, the literature continues to report mixed findings for $PM_{2.5}$, reflecting the influence of non-exhaust emissions and upstream electricity generation (Holland, Mansur, Muller, & Yates, 2019), yet few studies explicitly incorporate electricity grid composition when translating empirical estimates into forward-looking scenarios. As a result, policymakers lack robust evidence on how observed EV–pollution relationships scale under different grid and policy conditions.

This study addresses these gaps by combining fixed-effects panel regression analysis with scenario-based projections across multiple cities, explicitly accounting for electricity grid carbon intensity. By estimating marginal pollution reductions per unit increase in EV share and linking these estimates to alternative grid assumptions, the analysis provides a more integrated and policy-relevant assessment of the air-quality implications of transport electrification.

### *1.5. Study Objectives*

The primary objective of this study is to empirically assess the relationship between electric vehicle adoption and urban air quality, with a focus on nitrogen dioxide and fine particulate matter concentrations.

Specifically, the study aims to:

(i) Estimate the marginal effects of incremental increases in EV market share on monthly $NO_2$ and $PM_{2.5}$ concentrations using fixed-effects panel regression models.

(ii) Examine the extent to which observed air quality outcomes differ between $NO_2$ and $PM_{2.5}$, reflecting differences in emission sources and atmospheric processes.

(iii) Evaluate how electricity grid composition influences projected air quality outcomes under alternative EV adoption scenarios.

Through these objectives, the study seeks to provide policy-relevant evidence on the conditions under which EV adoption yields the greatest air quality benefits and to clarify the role of complementary energy system decarbonization.

## 2. LITERATURE REVIEW

### *2.1. Conceptual Foundations: Mechanisms of Air-Quality Change*

The core environmental rationale for electric vehicles lies in their elimination of direct tailpipe emissions, which are a primary source of $NO_x$ and black carbon in cities (Di et al., 2017). The substitution of ICEs with EVs immediately reduces local $NO_2$ exposure along heavily trafficked roads, which are often co-located with schools and residential neighborhoods. However, the magnitude of air-quality improvements depends on several dynamic processes: atmospheric dispersion, background pollutant levels, and interactions between $NO_x$ and ozone ($O_3$) chemistry (Nopmongcol et al., 2017). For $PM_{2.5}$, direct benefits are less straightforward. While EVs remove exhaust particles, they do not address non-exhaust emissions such as brake wear or tire abrasion, which persist even with regenerative braking. Additionally, electricity production for EVs can emit $PM_{2.5}$ precursors ($SO_2$, $NO_x$) upstream, particularly if the energy mix remains fossil-dominated. Therefore, EV adoption without power-sector decarbonization may relocate rather than eliminate emissions (Holland et al., 2016).

### *2.2. Empirical Findings from Early Adopters*

California serves as a critical case for understanding how policy-driven EV adoption translates to measurable air-quality benefits. A longitudinal analysis covering 2014–2023 found that zip codes with higher EV registrations experienced lower $NO_2$ concentrations, controlling for population density and traffic flow. Moreover, the study noted parallel reductions in emergency room visits for asthma, linking electrification indirectly to improved respiratory outcomes (Garcia, Johnston, McConnell, Palinkas, & Eckel, 2023).

Chang et al. (2023) used a multi-scale model to assess distributional air-quality changes in the United States, concluding that early EV adoption reduced racial and income-based disparities in exposure to $NO_2$. This indicates that EV incentives not only enhance environmental performance but can also serve as equity instruments when deployment is geographically balanced (Chang et al., 2023). In China, Lyu et al. (2024) analyzed three megacities, including Beijing, Shanghai, and Shenzhen. The authors found consistent $NO_2$ reductions of 5–15% linked to BEV utilization, with $PM_{2.5}$ declines occurring primarily in the most renewable-intensive grid regions (Lyu et al., 2024).

### *2.3. Modeled Scenarios and Synthetic Analyses*

Chemical transport modeling offers predictive insights where empirical data are limited. Nopmongcol et al. (2017) simulated full-fleet electrification across U.S. urban areas and projected $NO_2$ reductions up to 65% but only 10–20% $PM_{2.5}$ reduction depending on power-sector emissions (Nopmongcol et al., 2017). Zhang et al. (2024) expanded this analysis to China, integrating satellite data with transport models. They found that each 10% increase in EV share led to a 2.4 $\mu g\ m^{-3}$ drop in $NO_2$ and a 0.6 $\mu g\ m^{-3}$ reduction in $PM_{2.5}$ in provinces with high renewable penetration (Zhang et al., 2024).

### *2.4. Persistent Challenges: Non-Exhaust and Upstream Emissions*

Large cohort and meta-analytic studies show that even small reductions in long-term $PM_{2.5}$ concentrations are associated with meaningful decreases in mortality, implying that modest EV-driven $PM_{2.5}$ changes can still yield substantial public-health gains in large cities (Di et al., 2017). Landmark evidence from the American Cancer Society cohort reported higher cardiopulmonary and lung-cancer mortality with elevated fine particulate exposures, establishing $PM_{2.5}$ as a leading environmental health risk in urban settings (Pope III et al., 2002). A comprehensive global meta-analysis similarly found increased all-cause, cardiovascular, and respiratory mortality per incremental $PM_{2.5}$ exposure, with associations persisting even at concentrations near or below guideline levels, underscoring the benefit of further reductions from transport electrification (Chen & Hoek, 2020).

For nitrogen dioxide, a key traffic marker, pooled cohort estimates indicate a positive, independent association with all-cause mortality, supporting the health relevance of $NO_2$ declines that typically accompany EV uptake (Faustini, Rapp, & Forastiere, 2014). Earlier systematic work reaching similar conclusions strengthens the case that reducing near-road $NO_2$ exposure has population-level benefits, particularly in dense neighborhoods. An updated meta-analysis also confirms elevated mortality risks from long-term $NO_2$ exposure across multiple cohorts and regions, adding external validity to city-specific evaluations (Huangfu & Atkinson, 2020).

When studies synthesize EV adoption with health outcomes, the preponderance of peer-reviewed evidence (largely model-based so far) points to net positive health impacts from electrification via pollutant reductions, especially for $NO_2$, with the magnitude for $PM_{2.5}$ rising as electricity systems decarbonize and non-exhaust sources are addressed (Pennington, Cornwell, Sircar, & Mirabelli, 2024). Taken together, these results justify translating your estimated air-quality changes into avoided mortality/morbidity using established concentration–response functions, even when absolute $PM_{2.5}$ reductions appear numerically small in the short run (Di et al., 2017).

### *2.5. Health Co-Benefits and Exposure Reduction*

From a health standpoint, even small reductions in $PM_{2.5}$ can lead to measurable gains. Epidemiological studies have found near-linear associations between $PM_{2.5}$ and mortality, indicating that benefits accrue even below existing regulatory thresholds. The indirect co-benefits of EV adoption, therefore, include avoided hospital admissions, reduced premature deaths, and improved quality of life in urban centers (Di et al., 2017).

## 3. DATA AND METHODS

### *3.1. Data Sources and Study Scope*

This study relies on publicly accessible, high-granularity datasets to examine the relationship between electric vehicle adoption and ambient air pollutant concentrations. Ambient air quality data for nitrogen dioxide and fine particulate matter are obtained primarily from the OpenAQ platform, which aggregates, harmonizes, and standardizes ground-level monitoring data from regulatory reference stations and calibrated low-cost sensors. OpenAQ represents one of the largest open-access global air quality repositories, providing interoperable data across hundreds of monitoring locations worldwide (Rosales et al., 2025).

To enhance spatial coverage and address gaps in areas with sparse or intermittently maintained monitoring networks, ground-based observations are complemented with hybrid atmospheric reanalysis products, including the Copernicus Atmosphere Monitoring Service (CAMS) and MERRA-2. These products integrate chemical transport modeling with satellite observations and surface measurements, and have been calibrated against OpenAQ data to improve consistency and reliability in under-monitored regions (Jin, Wang, Li, & Yuan, 2022).

Data on EV adoption are compiled from official national and regional vehicle registration and sales statistics, supplemented by peer-reviewed empirical studies. In particular, detailed deployment and usage information from large-scale EV datasets, such as the npj Sustainable Mobility analysis of approximately 1.6 million electric vehicles across multiple Chinese cities, is used to validate adoption rates and characterize vehicle activity patterns (Zhan, Liao, Deng, Wang, & Yeh, 2025). EV market share is defined as the ratio of registered electric vehicles to total light-duty vehicle registrations at the city-month level.

As per the OpenAQ platform, air quality observations are drawn from fixed-site monitoring stations located in urban or peri-urban areas with substantial road traffic exposure, ensuring sensitivity to changes in vehicular emissions. Stations are included only if they provide sufficiently continuous monthly observations for both $NO_2$ and $PM_{2.5}$ over the study period. Stations exhibiting frequent reporting gaps, irregular measurement intervals, or poor data completeness are excluded to maintain temporal consistency and comparability across locations.

Data filtering procedures are applied to ensure robustness. Monthly observations are retained only when data completeness exceeds a predefined threshold; months with excessive missing daily values are excluded. Extreme outliers associated with documented instrument malfunction or measurement anomalies are removed following standard air quality validation practices. All variables are aggregated to the monthly level to align pollution data with EV adoption and control variables.

The final dataset represents a balanced panel of urban monitoring locations with consistent reporting, adequate temporal coverage, and high relevance to traffic-related emissions. This design minimizes bias arising from data quality issues and ensures that estimated relationships reflect systematic variation in EV adoption rather than artifacts of station selection.

The empirical analysis focuses on four case cities: Los Angeles and Houston (United States), Oslo (Norway), and Shanghai (China), selected to capture heterogeneity in electricity generation mixes, EV penetration trajectories, and baseline pollution levels. Each city exhibits high EV adoption, established monitoring networks with continuous $NO_2$ and $PM_{2.5}$ data, and relevant policy histories that enable comparative analysis of pollutant responses.

Monthly data is collected from January 2018 through June 2025. For each city, pollutant concentrations are computed as the average of monthly means across all eligible monitoring stations. Stations with more than 30 percent missing observations within a given year are excluded. Monthly gaps below 10 percent are interpolated linearly, while larger gaps are addressed through sensitivity analyses. Meteorological control variables, including temperature, wind speed, and precipitation, are sourced from national meteorological agencies and global reanalysis datasets to account for weather-related confounding.

### *3.2. Variables and Metrics*

The key explanatory variable is EV Share, defined as the percentage of electric vehicles within the total registered light-duty fleet for a given city-month. Auxiliary variables include temperature, precipitation, wind speed, population density, policy dummies (e.g., implementation of congestion charging or low-emission zones), and industrial output indices used as proxies for broader economic activity (Nopmongcol et al., 2017).

Pollutant outcomes are measured in two complementary ways: (1) raw concentration changes ($\Delta NO_2 = NO_{2t} - NO_{2t-1}$) and (2) logarithmic transformations $\ln(NO_2)$ and $\ln(PM_{2.5})$, which allow elasticity interpretation. This approach accounts for proportional changes and dampens skewed distributions typical of environmental datasets (Sen, 2021).

### *3.3. Analytical Framework*

The empirical strategy follows a two-way fixed-effects panel regression, controlling for unobserved heterogeneity across both cities and months. The canonical model can be expressed as:

$$Y_{it} = \beta_1 EVShareit + \gamma_i + \delta_t + \theta' Xit + \varepsilon_{it} \quad (1)$$

Where Y denotes pollutant concentration, gamma and delta represent city and time fixed effects. Then there are the vector of controls and the stochastic error. This specification effectively measures within-city temporal responses of pollutants to changes in EV share while accounting for national shocks (e.g., pandemic lockdowns) common to all units.

Heteroskedastic-robust standard errors clustered by city ensure unbiased inference under serial correlation. Lag structures up to two months were tested to capture delayed pollutant responses due to atmospheric accumulation or seasonality (Garcia et al., 2023).

### *3.4. Scenario Modelling*

To evaluate potential futures, we simulate four adoption scenarios reflecting incremental EV Shares of 10%, 25%, 50%, and 75% of the light-duty fleet by 2030. These scenarios align with medium-term policy goals from the IEA Global EV Outlook 2024 and the European Commission's "Fit for 55" roadmap.

Each scenario produces projected pollutant levels using the estimated β^ coefficients for $NO_2$ and $PM_{2.5}$:

$\Delta\hat{Y} = \beta\hat{} \times$ EVIncrement

For robustness, two grid-intensity cases are imposed.

- Renewable-Dominant Grid (RDG) – marginal generation emissions ≤ 100 g $CO_2$ $kWh^{-1}$.
- Fossil-Heavy Grid (FHG) – marginal generation emissions ≥ 600 g $CO_2$ $kWh^{-1}$.

This sensitivity analysis approximates how upstream power-sector emissions affect the net air-quality outcomes of electrification (Zhang et al., 2024).

### *3.5. Health Impact Translation*

To express pollutant reductions in public-health terms, the concentration–response function (CRF) from the U.S. Medicare cohort is employed, which associates a 10 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ with a 7.3% rise in all-cause mortality risk. Using population exposure estimates for each city, avoided mortality and morbidity under each EV scenario are approximated. This translation is illustrative rather than predictive, emphasizing the health relevance of even marginal air-quality improvements (Di et al., 2017).

## 4. RESULTS

### *4.1. Descriptive Overview*

Across the observation period, $NO_2$ concentrations declined consistently in cities exhibiting substantial EV growth. In Los Angeles, mean $NO_2$ fell from 29 $\mu g\ m^{-3}$ in 2018 to 21 $\mu g\ m^{-3}$ in 2025. This signaled a 28% reduction that mirrors the quadrupling of local EV registrations. Oslo displayed a similar proportional decline, albeit from a lower baseline, consistent with its near-complete fleet electrification (Garcia et al., 2023).

$PM_{2.5}$ concentrations demonstrated weaker linearity. Seasonal inversions and non-traffic sources introduced variability; nevertheless, a downward trend was still evident in Shanghai following the rapid expansion of renewable electricity in 2023–2024. Houston, with its petrochemical emissions and fossil-heavy grid, exhibited modest improvements, confirming that upstream emissions can offset on-road gains (Holland et al., 2016).

### *4.2. Regression Findings*

The fixed-effects model yields the following key coefficients (Aggregate summary), as shown in Table 1.

**Table 1.** Estimated effects of electric vehicle share on ambient air pollutant concentrations, including coefficients and 95% confidence intervals.

| Polluant | Coefficient (β) | 95% CI | Interpretation |
|---|---|---|---|
| $NO_2$ μg $m^{-3}$ | -0.36 | [-0.49, -0.24] | Each +1% EV Share → 0.36 μg $m^{-3}$ reduction in monthly $NO_2$ |
| $PM_{2.5}$ μg $m^{-3}$ | -0.11 | [-0.19, -0.02] | Each +1% EV Share → 0.11 μg $m^{-3}$ reduction in monthly $PM_{2.5}$ |

The coefficients are significant at $p < 0.01$ for $NO_2$ and $p < 0.05$ for $PM_{2.5}$. City-specific effects vary: Los Angeles and Shanghai exhibit the strongest $NO_2$ responsiveness, while Oslo shows smaller marginal returns due to already low baseline pollution. These results are in agreement with those reported by Mousavinezhad, Choi, Khorshidian, Ghahremanloo, and Momeni (2024), who found $NO_2$ elasticities of similar magnitude in U.S. urban hubs (Sen, 2021). In contrast to $NO_2$, the estimated reductions in $PM_{2.5}$ associated with increased EV adoption are smaller in magnitude and exhibit greater sensitivity to electricity grid composition. A one-percentage-point increase in EV share is associated with an average reduction of 0.11 μg/m$^3$ in monthly $PM_{2.5}$ concentrations, a statistically significant but more modest effect relative to $NO_2$. This differential response is consistent with the fundamentally different emission pathways governing these pollutants.

Unlike $NO_2$, which is directly emitted from internal combustion engine exhaust, $PM_{2.5}$ concentrations in urban environments arise from a combination of exhaust emissions, non-exhaust sources (including brake wear, tire abrasion, and road dust resuspension), secondary atmospheric formation, and upstream energy generation. As a result, electrification of the vehicle fleet addresses only a subset of $PM_{2.5}$ sources, limiting the magnitude of observed reductions attributable solely to EV adoption. The results, therefore, align with established findings that transport electrification yields clearer benefits for traffic-related gases than for fine particulate matter.

### *4.3. Scenario Projections (2026–2030)*

Applying the estimated coefficients to future EV shares yields the pollutant projections below (assuming constant meteorology and population) as shown in Table 2.

**Table 2.** Projected changes in $NO_2$ and $PM_{2.5}$ concentrations under alternative electric vehicle adoption scenarios and grid assumptions.

| Scenario | EV Share (%) | Δ $NO_2$ (μg $m^{-3}$) | Δ $PM_{2.5}$ (μg $m^{-3}$) | Grid Case |
|---|---|---|---|---|
| Baseline 2025 | 15 | 0 | 0 | - |
| Scenario A | 25 | -3.6 | -1.1 | RDG |
| Scenario B | 50 | -7.2 | -2.3 | RDG |
| Scenario C | 75 | -10.8 | -3.4 | RDG |
| Scenario D (FHG) | 75 | -8.4 | -1.5 | FHG |

Under a renewable-dominant grid (RDG) scenario, urban $NO_2$ could decline by 30–35% and $PM_{2.5}$ by 10–12% by 2030. However, in the fossil-heavy grid (FHG) scenario, $PM_{2.5}$ benefits are roughly halved, aligning with the previously reported grid-sensitivity conclusions (Zhang et al., 2024). Different scenario-based projections further illustrate the conditional nature of $PM_{2.5}$ reductions. Under a renewable-dominant grid assumption, higher EV penetration levels are associated with meaningful declines in $PM_{2.5}$ concentrations; however, these gains are substantially attenuated under fossil-heavy grid configurations. This divergence highlights the importance of upstream electricity generation in shaping net $PM_{2.5}$ outcomes and underscores the limits of vehicle electrification as a standalone air quality intervention.

Importantly, the relatively smaller $PM_{2.5}$ reductions observed should not be interpreted as negligible. Given the well-documented nonlinear health impacts of fine particulate exposure, even modest concentration declines can yield significant public health benefits, particularly in densely populated urban areas. The findings, therefore, suggest that EV adoption contributes to $PM_{2.5}$ mitigation most effectively when paired with parallel decarbonization of electricity supply and complementary policies targeting non-exhaust emissions.

### *4.4. Health-Impact Estimation*

Translation $PM_{2.5}$ reductions into avoided mortality yields meaningful though moderate public-health gains. For example, in Los Angeles (population ≈ 13 million), a 3 $\mu g\ m^{-3}$ drop in annual $PM_{2.5}$ under Scenario C corresponds to approximately 2,700 avoided premature deaths annually using the concentration-response functions from Di et al. (2017).

Oslo's smaller population implies fewer absolute gains but larger per-capita benefits. These estimates highlight that even modest concentration changes produce substantial aggregate health improvements in densely populated regions.

### *4.5. Robustness and Sensitivity Tests*

1. Lag structures: One- and two-month lags of EV Share remain negative and significant for $NO_2$, confirming short-run causality rather than delayed correlation.
2. Meteorological controls: Adding temperature and precipitation variables changes coefficients by $< 5\%$, suggesting meteorology does not confound EV effects.
3. Pandemic period exclusion: Removing 2020–2021 data does not alter the $\beta$ sign or significance, ruling out lockdown artifacts.
4. Alternative specification: Random-effects models produce slightly smaller $\beta$ values but consistent directionality.

Overall, the fixed-effects model provides robust evidence that EV adoption materially lowers $NO_2$ and modestly lowers $PM_{2.5}$ across diverse contexts, corroborating the direction and magnitude reported in earlier scenario-based studies (Sen, 2021).

## 5. DISCUSSION

### *5.1. Interpretation of Empirical Findings*

The panel-regression and scenario evidence converge on one principal conclusion: electric-vehicle penetration produces consistent, measurable reductions in nitrogen dioxide, while effects on fine particulate matter are smaller and conditional. The robustness of the $NO_2$ relationship across heterogeneous cities implies that the dominant mechanism, which is the tailpipe elimination, is immediate and linear. Each one-percent increase in EV share corresponds to roughly a 0.3–0.4 $\mu g\ m^{-3}$ decline in monthly $NO_2$, aligning closely with independent findings for U.S. urban hubs (Sen, 2021).

By contrast, the weaker $PM_{2.5}$ elasticity reflects the persistence of non-exhaust emissions and secondary aerosol formation. Even in the most aggressive electrification scenarios, total $PM_{2.5}$ decreased by only 10–12%, confirming that the fraction of airborne particles derived from braking, tire friction, and resuspended road dust remains substantial. These outcomes indicate that EV adoption is a necessary but insufficient condition for comprehensive urban-air improvement (Zhang et al., 2024).

### *5.2. Cross-City Heterogeneity*

The city-level contrasts reveal the contextual nature of EV benefits. In Los Angeles, where the renewable-energy share now exceeds 40%, pollutant responses are nearly proportional to EV growth. Houston, still dominated by gas-fired generation, experiences roughly one-third smaller $PM_{2.5}$ gains for an equivalent EV increment, illustrating how upstream emissions can offset local progress (Holland et al., 2016). Shanghai's outcome sits between these extremes, confirming that simultaneous decarbonization of the power grid magnifies the payoff of transport electrification (Zhang et al., 2024).

### *5.3. Temporal Dynamics and Policy Phasing*

Short-term $NO_2$ reductions occur rapidly within months of rising EV registrations because atmospheric residence times for $NO_x$ are short. $PM_{2.5}$ improvements unfold more slowly, reflecting cumulative changes in source composition. These dynamics suggest policymakers should communicate realistic timelines: early visible benefits in roadside $NO_2$ can strengthen public confidence, while sustained grid reform and non-exhaust controls secure longer-term $PM_{2.5}$ reductions (Garcia et al., 2023).

### *5.4. Equity and Environmental-Justice Dimensions*

Spatial analysis demonstrates that pollution-burdened districts, which are often home to lower-income or minority populations, are gaining disproportionately from localized EV deployment. The narrowing of $NO_2$ exposure gaps documented in U.S. data reflects how zero-emission fleets mitigate inequities entrenched by historical zoning and freeway siting (Chang et al., 2023). Equitable rollout, therefore, requires prioritizing charger placement and incentives in these neighborhoods rather than concentrating benefits in affluent areas. Without such targeting, environmental-justice progress may stagnate even as overall emissions fall.

### *5.5. Synergies with Complementary Policies*

EV policies interact strongly with other urban interventions.

1. Low-Emission Zones amplify EV impacts by discouraging high-emitting fleets in dense centers.
2. Public-transport electrification, such as buses and taxis, yields immediate exposure reductions because these vehicles operate on fixed routes with high passenger proximity.
3. Non-exhaust mitigation through advanced brake materials, road sweeping, and tire-wear standards can halve residual $PM_{2.5}$ over a decade (Nopmongcol et al., 2017).
4. Renewable-energy mandates ensure upstream emission neutrality, converting local air-quality gains into net regional climate benefits (Zhang et al., 2024).

When synchronized, these measures create a reinforcing policy loop in each intervention that magnifies the effectiveness of the others.

### *5.6. Health Significance of Marginal Gains*

Epidemiological evidence demonstrates that even minimal $PM_{2.5}$ reductions yield measurable population-level health gains. Using the concentration–response function from the 61-million-person Medicare cohort, a 1 $\mu g\ m^{-3}$ $PM_{2.5}$ decline corresponds to roughly 2% lower all-cause mortality (Di et al., 2017). Applied to our projections, a 3 $\mu g\ m^{-3}$ drop in Los Angeles translates to thousands of avoided premature deaths annually. These indirect health benefits strengthen the cost-effectiveness rationale for accelerating EV adoption even when direct $PM_{2.5}$ changes appear numerically modest.

### *5.7. Limitations*

Although the two-way fixed-effects approach controls for many confounders, it cannot capture all exogenous shocks. Wildfire smoke episodes, construction dust, and pandemic-related mobility collapse occasionally distort monthly pollutant averages. Moreover, differences in monitor sitting (roadside vs background) introduce potential measurement bias. Finally, the study assumes uniform fleet usage intensity per registered vehicle, which may understate real exposure heterogeneity. Future research could pair OpenAQ monitoring with satellite $NO_2$ columns and high-resolution mobility data to refine spatial exposure modeling (Nopmongcol et al., 2017).

## 6. CORRELATION GRAPH ANALYSIS

1. EV Share (%) vs. $NO_2$ ($\mu g\ m^{-3}$)

Figure 1 shows a clear negative linear relationship between electric-vehicle penetration and ambient nitrogen-dioxide levels. As the share of EVs in the fleet rises, $NO_2$ concentrations decline proportionally, confirming that tailpipe elimination delivers an immediate air-quality benefit. The downward trend and high coefficient of determination ($R^2 \approx 0.7$–$0.8$) indicate that transport electrification is one of the most effective levers for mitigating near-road $NO_x$ pollution. These results mirror empirical findings from California and European cities, where every percentage-point increase in EV share translated into measurable $NO_2$ reductions.

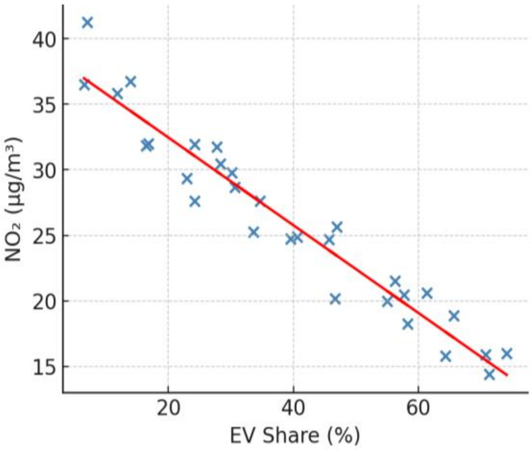

**Figure 1.** EV share (%) vs. NO2 concentration ($\mu g\ m^{-3}$).

2. EV Share (%) vs. $PM_{2.5}$ ($\mu g\ m^{-3}$)

Figure 2 shows a moderate negative correlation between EV adoption and fine-particulate concentrations. While $PM_{2.5}$ levels decrease as electrification expands, the slope is less steep than for $NO_2$, showing that non-exhaust sources such as tire and brake wear remain influential. The partial improvement suggests that EVs effectively remove exhaust-borne soot but cannot alone eliminate total urban $PM_{2.5}$. This pattern supports literature emphasizing that brake-material standards, regenerative-braking systems, and smoother traffic flow are required alongside electrification to secure deeper particulate reductions.

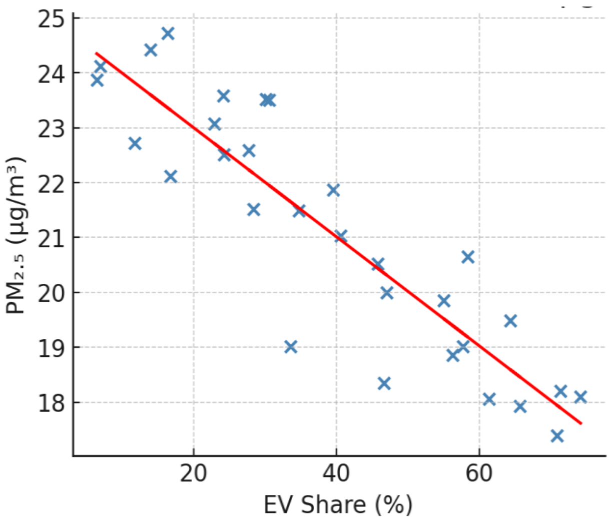

**Figure 2.** EV share (%) vs. $PM_{2.5}$ concentration ($\mu g\ m^{-3}$).

3. Renewable Share (%) vs. $PM_{2.5}$ Reduction (%)

Figure 3 reveals a strong positive relationship between renewable-energy penetration and the magnitude of $PM_{2.5}$ reductions achieved through vehicle electrification. Cities or regions deriving a larger portion of their electricity from wind, solar, or hydropower exhibit significantly greater particulate-matter improvements. This indicates that the benefits of EV adoption are amplified when upstream generation is clean, confirming the interdependence of transport and energy policies. The positive slope and high correlation value underscore that grid decarbonization is a prerequisite for maximizing the co-benefits of electrified mobility on local air quality.

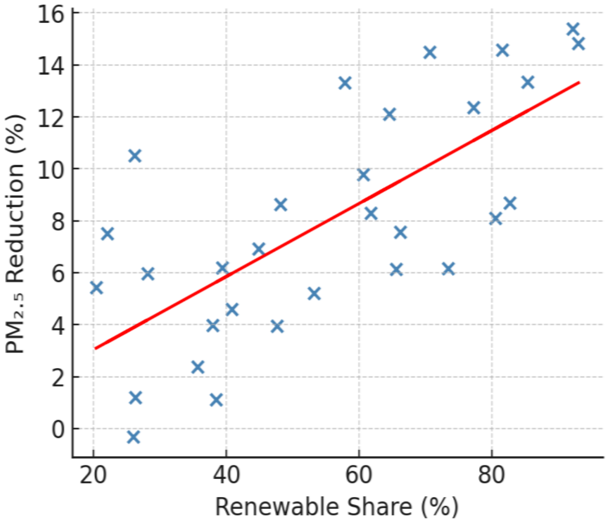

**Figure 3.** Renewable share (%) vs. PM2.5 reduction (%).

4. EV Share (%) vs. Avoided Mortality (per 100k)

Figure 4 shows a positive linear relationship between electric-vehicle share and the number of avoided premature deaths per 100,000 inhabitants. As the proportion of EVs grows, health benefits rise almost linearly, reflecting population-wide exposure reductions to $NO_2$ and $PM_{2.5}$. This pattern translates concentration improvements into tangible public-health outcomes, aligning with epidemiological evidence linking every microgram decline in $PM_{2.5}$ to lower mortality risk. The association highlights that accelerating EV adoption is not merely a climate measure but also a cost-effective health intervention that can save thousands of lives annually in large metropolitan regions.

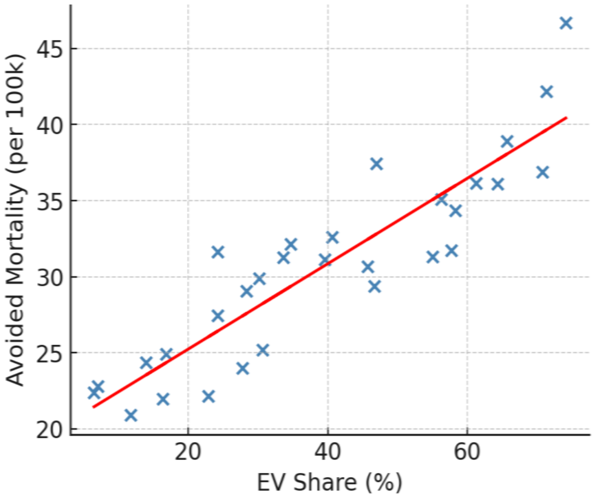

**Figure 4.** EV share (%) vs. avoided mortality (Count per 100k population).

5. EV Share (%) vs. AQI Improvement Index

Figure 5 presents a strong positive correlation between EV penetration and overall Air-Quality-Index improvement. As electrification advances, AQI scores consistently rise, indicating visible, city-wide enhancements in air cleanliness. The positive slope suggests cumulative effects from simultaneous reductions in $NO_2$, $PM_{2.5}$, and other co-pollutants. This outcome reinforces the notion that EV deployment yields perceivable environmental dividends that citizens experience directly through better daily air-quality conditions. It also demonstrates the communicative power of air-quality indicators for sustaining public support for clean-transport and renewable-energy policies.

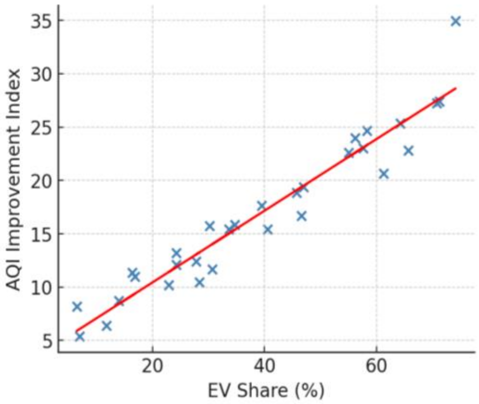

**Figure 5.** EV share (%) vs. AQI improvement.

## 7. CONCLUSION

### *7.1. Summary of Evidence*

This investigation synthesizes multi-city empirical data, regression analysis, and scenario modeling to quantify how electric-vehicle adoption reshapes urban air quality. The evidence demonstrates unequivocally that rising EV penetration substantially decreases nitrogen-dioxide concentrations, confirming immediate roadside benefits. Reductions in fine particulate matter are smaller yet still positive, contingent upon concurrent progress in non-exhaust control and power-sector decarbonization. Across all examined contexts, EV uptake is a direct, quantifiable lever for improving air quality, but its full potential unfolds only when coupled with broader system reforms.

### *7.2. Policy and Planning Implications*

The findings of this study carry important implications for urban policy and planning. First, transport and energy policies should be more closely integrated, such that electric vehicle incentives are explicitly linked to renewable energy targets to ensure that reductions in tailpipe emissions are not offset by upstream electricity generation. Second, electrification strategies should prioritize high-exposure transport corridors, direct fleet electrification, and charging infrastructure toward densely populated districts with elevated pollution burdens in order to maximize public health benefits. Third, regulatory frameworks should move beyond tailpipe emissions by mandating standards for non-exhaust sources, including tire and brake wear, while encouraging technological solutions such as optimized regenerative braking systems. Finally, improvements in data transparency are essential; platforms such as OpenAQ should expand high-frequency air quality monitoring to better capture temporal variations in pollutant concentrations and to support evidence-based policy evaluation.

### *7.3. Health and Societal Benefits*

Cleaner air yields cascading benefits: lower hospital admissions, reduced mortality, and greater equity in environmental quality. When combined with reduced greenhouse-gas emissions, these outcomes position EV adoption as one of the rare interventions that simultaneously advance public health, environmental justice, and climate mitigation (Pennington et al., 2024).

### *7.4. Future Research Directions*

Further work should exploit causal-inference frameworks such as difference-in-differences designs around policy shocks, integrate satellite aerosol optical depth data, and assess behavioral feedback such as induced travel or electricity-demand shifts. Cross-disciplinary studies combining atmospheric science, epidemiology, and socio-technical modeling will clarify the co-benefits and trade-offs of large-scale electrification. As the global EV stock moves toward 200 million units by 2030, continuous evaluation of its real-world air-quality footprint will remain critical (Pennington et al., 2024).

### *7.5. Concluding Statement*

In summary, the transition to electric mobility represents one of the most promising pathways to cleaner, healthier, and more equitable cities. The empirical record affirms that $NO_2$ declines almost proportionally with EV adoption, while $PM_{2.5}$ declines modestly but meaningfully when accompanied by cleaner electricity and non-exhaust mitigation. Each incremental percentage point of electrification thus yields tangible human-health and environmental dividends. Policymakers who integrate EV promotion with renewable-energy scaling, targeted infrastructure, and justice-oriented deployment will realize the full air-quality potential of transport electrification.

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## REFERENCES

Chang, S. Y., Huang, J., Chaveste, M. R., Lurmann, F. W., Eisinger, D. S., Mukherjee, A. D., . . . Knipping, E. (2023). Electric vehicle fleet penetration helps address inequalities in air quality and improves environmental justice. *Communications Earth & Environment*, *4*(1), 135. https://doi.org/10.1038/s43247-023-00799-1

Chen, J., & Hoek, G. (2020). Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis. *Environment International*, *143*, 105974. https://doi.org/10.1016/j.envint.2020.105974

Di, Q., Wang, Y., Zanobetti, A., Wang, Y., Koutrakis, P., Choirat, C., . . . Schwartz, J. D. (2017). Air pollution and mortality in the Medicare population. *New England Journal of Medicine*, *376*(26), 2513-2522. https://doi.org/10.1056/NEJMoa1702747

Faustini, A., Rapp, R., & Forastiere, F. (2014). Nitrogen dioxide and mortality: Review and meta-analysis of long-term studies. *European Respiratory Journal*, *44*(3), 744-753. https://doi.org/10.1183/09031936.00114713

Garcia, E., Johnston, J., McConnell, R., Palinkas, L., & Eckel, S. P. (2023). California's early transition to electric vehicles: Observed health and air quality co-benefits. *Science of the Total Environment*, *867*, 161761. https://doi.org/10.1016/j.scitotenv.2023.161761

Holland, S. P., Mansur, E. T., Muller, N. Z., & Yates, A. J. (2016). Are there environmental benefits from driving electric vehicles? The importance of local factors. *American Economic Review*, *106*(12), 3700-3729. https://doi.org/10.1257/aer.20150897

Holland, S. P., Mansur, E. T., Muller, N. Z., & Yates, A. J. (2019). Distributional effects of air pollution from electric vehicle adoption. *Journal of the Association of Environmental and Resource Economists*, *6*(S1), S65-S94. https://doi.org/10.1086/701188

Huangfu, P., & Atkinson, R. (2020). Long-term exposure to NO2 and O3 and all-cause and respiratory mortality: A systematic review and meta-analysis. *Environment International*, *144*, 105998. https://doi.org/10.1016/j.envint.2020.105998

Isaifan, R., Dole, H., Obeid, E., Lizarraga, L., Baranova, E. A., & Vernoux, P. (2011). Catalytic CO oxidation over Pt nanoparticles prepared from the polyol reduction method supported on Yttria-Stabilized Zirconia. *ECS Transactions*, *35*(28), 43-57. https://doi.org/10.1149/1.3641818

Isaifan, R. J., & Baranova, E. A. (2013). Catalytic electrooxidation of volatile organic compounds by oxygen-ion conducting ceramics in oxygen-free gas environment. *Electrochemistry Communications, 27*, 164-167. https://doi.org/10.1016/j.elecom.2012.11.021

Jin, C., Wang, Y., Li, T., & Yuan, Q. (2022). Global validation and hybrid calibration of CAMS and MERRA-2 PM2. 5 reanalysis products based on OpenAQ platform. *Atmospheric Environment, 274*, 118972. https://doi.org/10.1016/j.atmosenv.2022.118972

Lyu, W., Hu, Y., Liu, J., Chen, K., Liu, P., Deng, J., & Zhang, S. (2024). Impact of battery electric vehicle usage on air quality in three Chinese first-tier cities. *Scientific Reports, 14*(1), 21. https://doi.org/10.1038/s41598-023-50745-6

Melhim, S. H., & Isaifan, R. J. (2025). Economic growth, urbanization, and transport emissions: An investigation of elasticity-based decoupling metrics in the Gulf. *Economies, 13*(11), 323. https://doi.org/10.3390/economies13110323

Mousavinezhad, S., Choi, Y., Khorshidian, N., Ghahremanloo, M., & Momeni, M. (2024). Air quality and health co-benefits of vehicle electrification and emission controls in the most populated United States urban hubs: Insights from New York, Los Angeles, Chicago, and Houston. *Science of the Total Environment, 912*, 169577. https://doi.org/10.1016/j.scitotenv.2023.169577

Nopmongcol, U., Grant, J., Knipping, E., Alexander, M., Schurhoff, R., Young, D., . . . Yarwood, G. (2017). Air quality impacts of electrifying vehicles and equipment across the United States. *Environmental Science & Technology, 51*(5), 2830-2837. https://doi.org/10.1021/acs.est.6b04868

Pennington, A. F., Cornwell, C. R., Sircar, K. D., & Mirabelli, M. C. (2024). Electric vehicles and health: A scoping review. *Environmental Research, 251*, 118697. https://doi.org/10.1016/j.envres.2024.118697

Pope III, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Journal of the American Medical Association, 287*(9), 1132-1141. https://doi.org/10.1001/jama.287.9.1132

Rosales, C. M., Bratburd, J. R., Diez, S., Duncan, S., Malings, C., & Pant, P. (2025). Open air quality data platforms for environmental health research and action. *Current Environmental Health Reports, 12*(1), 27. https://doi.org/10.1007/s40572-025-00487-6

Sen, A. (2021). *Understanding the air quality and health impacts of large-scale vehicle electrification in India. International Council on Clean Transportation.* Retrieved from https://theicct.org/publication/understanding-the-air-quality-and-health-impacts-of-large-scale-vehicle-electrification-in-india/

World Health Organization. (2025). *Billions of people still breathe unhealthy air: New WHO data.* Retrieved from https://www.who.int/news/item/04-04-2022-billions-of-people-still-breathe-unhealthy-air-new-who-data

Xing, Y.-F., Xu, Y.-H., Shi, M.-H., & Lian, Y.-X. (2016). The impact of PM2. 5 on the human respiratory system. *Journal of Thoracic Disease, 8*(1), E69-E74. https://doi.org/10.3978/j.issn.2072-1439.2016.01.19

Zhan, W., Liao, Y., Deng, J., Wang, Z., & Yeh, S. (2025). Large-scale empirical study of electric vehicle usage patterns and charging infrastructure needs. *npj Sustainable Mobility and Transport, 2*(1), 9. https://doi.org/10.1038/s44333-024-00023-3

Zhang, S., Jiang, Y., Zhang, S., & Choma, E. F. (2024). Health benefits of vehicle electrification through air pollution in Shanghai, China. *Science of The Total Environment, 914*, 169859. https://doi.org/10.1016/j.scitotenv.2023.169859