CRC Report No. SM-F-2 / A-134

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Executive Summary

November 2024

COORDINATING RESEARCH COUNCIL, INC.
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Sustainability and Local Air Quality Impacts of Future Electrification and New Vehicle Emission Regulation Scenarios in the U.S.

by

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Executive Summary

This report provides an in-depth examination of the impact of vehicle electrification on air quality, with a particular focus on particles that are 2.5 microns or less in diameter ($PM_{2.5}$), ozone, nitrogen oxides (NOx), sulfur oxides (SOx), carbon monoxide (CO), and greenhouse gas (GHG) emissions within the scenarios based on the EPA's Notice of Proposed Rulemaking (NPRM) in New York, Los Angeles, Chicago, and Houston. The study specifically examines the projected impacts for the year 2035, considering different levels of vehicle electrification. It is important to note that the analysis focuses on a single summer month for each city, which corresponds to the period of peak electricity demand and elevated ozone levels. Additionally, the selected months—July for New York, Los Angeles, and Chicago, and May for Houston—were chosen due to historically high levels of $PM_{2.5}$ during these periods. This seasonal focus is intended to capture the most critical air quality impacts but may not fully represent year-round variations.

1. Defining the scenarios:

a) Medium Electrification Baseline (MedE-BL): This scenario assumes 18% of Light-Duty Vehicles (LDV) are electric vehicles (EVs), reflecting the "No Action" case of the EPA NPRM. This percentage refers to the share of the entire vehicle fleet, not just new sales, and this is true for the other scenarios as well.

b) Medium Electrification with Tier 4 Controls (MedE-T4): Maintains an 18% EV share for LDV as in MedE-BL but assumes 30% of Medium-Duty Vehicles (MDV) with Internal Combustion Engines (ICE) meet the Tier 4 emission standards.

c) High Electrification Baseline (HighE-BL): Assumes a higher electrification rate with a 29% EV share for LDV, based on the "Proposal" case of the EPA NPRM.

d) High Electrification with Tier 4 Controls (HighE-T4): Mirrors the 29% EV share for LDV as in HighE-BL and incorporates 30% of MDV ICE complying with Tier 4 emission standards.
e) Full Electrification (FullE): Envisions 100% EV adoption across all vehicle categories, serving as an extreme benchmark scenario. It's important to note that this scenario is a bookend, acknowledging that such a widespread shift is not achievable by 2035.

2. Air Quality Modeling:

In this study, we employed a comprehensive modeling approach to assess the air quality impacts of vehicle electrification across major U.S. urban areas, including New York, Los Angeles, Chicago, and Houston. We used a combination of the Weather Research and Forecasting (WRF) model, the Sparse Matrix Operator Kernel Emissions (SMOKE) model, and the Community Multiscale Air Quality (CMAQ) modeling system to simulate meteorological conditions, emissions, and pollutant concentrations at a fine spatial resolution of 1 km. Emission inputs were derived from the 2017 National Emissions Inventory (NEI) data, and future vehicle fleet compositions and electrification scenarios were based on the EPA's Notice of Proposed Rulemaking (NPRM). To project vehicle populations and activity from 2017 to 2035, we utilized authoritative sources such as the Federal Highway Administration (FHWA) for New York and Chicago, the Texas Transportation Institute (TTI) for Houston, and the EMFAC2017 model from the California Air Resources Board (CARB) for Los Angeles. These projections were incorporated into the Motor Vehicle Emission Simulator (MOVES) model to estimate future emissions under various scenarios.

Additionally, we used the EPA's National Electric Energy Data System (NEEDS) dataset to project power plant decommissioning, considering the expected phase-out of less efficient coal-fired plants by 2025. To project the deployment of renewable energy sources by 2035, we incorporated data from the National Renewable Energy Laboratory's (NREL) 2022 Standard Scenarios Report. These projections were then applied in the Avoided Emissions and geneRation Tool (AVERT) to model changes in power plant emissions associated with the increased electricity demand from electric vehicles. These simulations provided a detailed analysis of changes in $PM_{2.5}$, ozone, and their precursors, allowing for an in-depth examination of the potential air quality and health benefits of vehicle electrification.

2.1. $PM_{2.5}$ results

The study revealed reductions in $PM_{2.5}$ concentrations across all examined cities under various electrification scenarios. While the absolute reductions varied, the relative changes provided insight into the effectiveness of each scenario. The reductions observed in the FullE scenario were the most substantial, with a decrease of 2.29 μg/m³ in Chicago, which corresponds to a 22.15% reduction relative to the baseline case. In Los Angeles, $PM_{2.5}$ concentrations decreased by up to 1.45 μg/m³ (17.19%), marking the highest reduction for that city across all scenarios. Interestingly, even in scenarios with partial electrification, such as the HighE-T4 scenario, reductions were observed, with $PM_{2.5}$ levels in Los Angeles decreasing by 1.39 μg/m³ (16.46%). New York also saw consistent reductions across scenarios, with a maximum decrease of 0.90 μg/m³ (7.11%) in the FullE scenario. It is important to contextualize these reductions within the broader scope of total emissions levels. For example, the reductions in $PM_{2.5}$ concentrations, while impactful, represent a fraction of the total emissions. This highlights the complexity of achieving large-scale improvements in air quality solely through vehicle electrification. The percentage reductions relative to the baseline case provide a clearer understanding of the effectiveness of each scenario. For a detailed comparison of $PM_{2.5}$ reductions across all scenarios and regions, including both absolute and percentage changes relative to the baseline case, refer to Table 1.

Table 1. Maximum $PM_{2.5}$ concentrations reductions across scenarios (μg/m³ and % change relative to baseline)

Scenario	New York	Los Angeles	Chicago	Houston
MedE-BL	0.50 (4.68%)	1.30 (11.63%)	0.26 (1.83%)	0.03 (0.25%)
MedE-T4	0.51 (4.74%)	1.31 (11.69%)	0.34 (2.35%)	0.04 (0.28%)
HighE-BL	0.51 (4.74%)	1.38 (12.35%)	0.40 (2.87%)	0.05 (0.41%)
HighE-T4	0.52 (4.81%)	1.39 (12.40%)	0.48 (3.38%)	0.06 (0.45%)
FullE	0.90 (7.11%)	1.45 (12.95%)	2.29 (15.99%)	0.34 (2.68%)

2.2. Complex Ozone Chemistry:

The impact of vehicle electrification on ozone concentrations is influenced by complex interactions between NOx and volatile organic compounds (VOCs). Ozone formation is highly sensitive to the relative levels of these precursors, resulting in different chemical regimes: NOx-limited and NOx-saturated (also known as VOC-limited). In NOx-limited regions, where VOCs are abundant and NOx is scarce, reducing NOx emissions typically leads to a decrease in ozone formation due to the reduced availability of NOx for ozone production. Conversely, in NOx-saturated regions, where NOx levels are high and VOCs are the limiting factor, reducing NOx can paradoxically result in increased ozone concentrations. This occurs because NOx also participates in reactions that remove ozone from the atmosphere, and reducing NOx decreases these removal reactions more than it decreases the production reactions.

The study's simulations revealed both increases and decreases in ozone concentrations, depending on the specific region and scenario. For instance, the MedE-BL scenario showed increases in ozone concentrations of up to 1.87 ppb in New York, 0.69 ppb in Los Angeles, 1.09 ppb in Chicago, and 0.12 ppb in Houston. These increases highlight the complexity of ozone chemistry and the challenges in achieving consistent air quality improvements across different regions. The FullE scenario resulted in the most overall reductions in ozone concentrations, with decreases of up to 9.58 ppb (17.86%) in Los Angeles and 4.03 ppb (6.81%) in New York. However, localized increases were still observed in certain urban centers like eastern Los Angeles, where ozone levels increased due to the NOx-saturated regime. Other scenarios also demonstrated notable changes. For example, the HighE-T4 scenario led to directional reductions in ozone concentrations across multiple cities, with decreases of 1.66 ppb (3.21%) in Los Angeles and 0.96 ppb (1.66%) in New York. Similarly, the MedE-T4 scenario showed reductions in Los Angeles of 1.11 ppb (2.15%) and in Chicago of 0.49 ppb (2.15%).

These results underscore the variability in ozone responses to vehicle electrification, with both beneficial reductions and unexpected increases occurring across different regions and scenarios. For a more detailed comparison, including percentage changes relative to the baseline, refer to Table 2.

Table 2. Maximum ozone concentrations reductions across scenarios (ppb and % change relative to baseline)

Scenario	New York	Los Angeles	Chicago	Houston
MedE-BL	0.64 (1.11%)	0.86 (1.67%)	0.44 (1.67%)	0.28 (0.60%)
MedE-T4	0.73 (1.27%)	1.11 (2.15%)	0.49 (2.15%)	0.30 (0.64%)
HighE-BL	0.86 (1.50%)	1.40 (2.73%)	0.58 (2.73%)	0.45 (0.98%)
HighE-T4	0.96 (1.66%)	1.66 (3.21%)	0.62 (3.21%)	0.47 (1.03%)
FullE	4.03 (6.81%)	9.58 (17.86%)	3.39 (17.86%)	2.58 (5.63%)

2.3. Secondary Organic Aerosols (SOA) and $PM_{2.5}$ Increase in Eastern Los Angeles:

An anomaly was observed in eastern Los Angeles, where $PM_{2.5}$ concentrations increased under the FullE scenario. This increase was due to heightened SOA levels, influenced by local increases in VOCs and changes in the NOx/VOCs balance. In the case of East LA, gas-to-particle chemistry occurred. Notably, air quality improves in some parts of LA with fewer internal combustion engines on the roads, as pollutants like NOx decrease due to the lack of tailpipe emissions from EVs. As these pollutants decrease, hydroxyl radicals (OH) increase. The sea breeze carries these excess hydroxyl radicals to East LA, where they combine with VOCs to form SOA, categorized as $PM_{2.5}$. The FullE scenario led to a $PM_{2.5}$ increase of up to 0.67 µg/m³ (15.00%) in this region. This highlights the complex interplay between different pollutants and the need for region-specific strategies to manage air quality effectively.

This complex ozone chemistry and the observed increase in SOA and $PM_{2.5}$ underscore the need for tailored emission control strategies that consider the specific NOx and VOC dynamics of each region. Policymakers must carefully balance NOx and VOC reductions to optimize ozone and particulate matter mitigation efforts and avoid unintended consequences.

3. Well-to-Wheel (WTW) Analysis:

The study conducted a Well-to-Wheel (WTW) analysis to assess the environmental impact of various vehicle electrification scenarios by integrating the MOVES and Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) models. The GREET model, developed by Argonne National Laboratory, provided a comprehensive evaluation of both direct emissions from vehicle operations and indirect emissions from fuel production and distribution. Non-exhaust sources, such as tire and brake wear (TBW), along with tailpipe emissions, were included in the analysis through the MOVES model, with additional consideration of VOC emissions from refueling activities.

Across all scenarios, notable reductions were observed in key pollutants, particularly under the FullE scenario. For example, CO emissions were reduced by over 99% across all cities in the FullE scenario, reflecting the near elimination of tailpipe emissions. However, even the MedE and HighE scenarios demonstrated CO reductions, ranging from 15.4% to 27.1%. NOx emissions also exhibited notable decreases, with the FullE scenario achieving reductions of over 96% in all cities. In contrast, the MedE and HighE scenarios showed more moderate NOx reductions, with New York City experiencing the highest reductions in these scenarios (6.7% in MedE and 11.2% in HighE). SOx emissions presented an interesting regional variation. While the FullE scenario reduced SOx emissions by up to 89.4% in Los Angeles, New York City saw a reduction of 64.7%. The FullE scenario also resulted in substantial reductions in particulate matter emissions, with $PM_{2.5}$ decreasing by up to 84.2% in Houston and PM_{10} by 56.4% in the same city. However, even in the HighE scenario, $PM_{2.5}$ reductions reached up to 7.3% in New York City, indicating that indicative improvements are achievable even with partial electrification. The analysis highlighted the growing significance of non-exhaust emissions as tailpipe emissions decline. Under the FullE scenario, TBW contributions to PM_{10} and $PM_{2.5}$ emissions increased sharply, with TBW accounting for up to 97.4% of PM_{10} emissions and 84.3% of $PM_{2.5}$ emissions. This trend underscores the importance of addressing non-exhaust emissions in future air quality management strategies.

Greenhouse gas (GHG) emissions also showed notable reductions, particularly in the FullE scenario, where GHG-100 decreased by over 90% across all cities. However, even in the MedE and HighE scenarios, GHG-100 reductions were notable, particularly in New York City (12.1% and 20.2%, respectively). These findings illustrate that while full electrification offers the most significant environmental benefits, partial electrification scenarios still contribute to meaningful reductions in emissions. All other emission reduction results can be summarized in Table 3. The analysis underscores the need for modern TBW measurements to accurately assess the impact of electric vehicles on particle emissions. The current data, derived from older studies, may not fully capture the nuances of TBW emissions in modern and future vehicle fleets. Further research and updated data are critical for understanding the full environmental impact of electric vehicles, particularly as electrification progresses. This aspect is discussed in more detail in Section 4, which covers the limitations and uncertainties of the study.

Table 3. Summary of emissions reductions across scenarios (% Change relative to baseline)

	MedE				HighE				FullE			
	New York	Los Angeles	Chicago	Houston	New York	Los Angeles	Chicago	Houston	New York	Los Angeles	Chicago	Houston
CO	16.3%	15.6%	15.4%	16.0%	27.1%	26.0%	25.6%	26.7%	99.1%	99.2%	99.5%	99.4%
NO_X	6.7%	4.0%	4.0%	5.6%	11.2%	6.6%	6.6%	9.4%	96.1%	98.0%	98.3%	98.6%
SO_X	9.4%	7.9%	9.4%	3.2%	15.6%	13.2%	15.7%	5.3%	64.7%	89.4%	83.2%	24.0%
$PM_{2.5}$	4.4%	3.2%	2.7%	3.6%	7.3%	5.4%	4.5%	6.0%	77.1%	80.1%	81.8%	84.2%
PM_{10}	2.5%	1.1%	2.1%	2.4%	4.2%	1.9%	3.5%	4.1%	42.0%	42.1%	44.4%	56.4%
GHG-20	12.0%	7.6%	8.7%	9.8%	20.0%	12.7%	14.6%	16.3%	90.8%	90.5%	93.4%	94.5%
GHG-100	12.1%	7.7%	8.8%	9.8%	20.2%	12.8%	14.6%	16.4%	91.4%	90.9%	93.8%	94.7%

4. Limitations and Uncertainties

This study provides valuable insights into the potential air quality benefits of vehicle electrification, yet it is essential to recognize certain limitations and uncertainties that may impact the findings.

One significant limitation arises from the use of average power plant emissions rather than marginal emissions during high electricity demand days. High-demand days often coincide with high ozone days, where power plants operate at higher capacities and emissions rates and higher emitting marginal generation assets are brought online. By relying on average emissions data, our study does not fully capture the peak emissions and their impact on air quality during these critical periods. This could lead to an underestimation of the impact of air quality from charging and the potential overestimation of the benefits of vehicle electrification on such high-demand, high-ozone days.

Additionally, the study focuses on a single month during the warm season, which is effective for examining ozone patterns but might not comprehensively capture the source contributions and chemical processes influencing $PM_{2.5}$ and ozone throughout the year. The selected period represents a high-ozone episode with elevated $PM_{2.5}$ concentrations, offering an opportunity to investigate potential impacts that surpass those of a typical month. However, distinct seasonal variations and diverse source origins are not fully accounted for.

Interannual changes in meteorology and emission sources, excluding on-road vehicles and power plants, might also affect the outcomes. While the study mitigated possible errors by concentrating on scenario comparisons and holding other variables steady, future research could integrate meteorological data corresponding to various climate change scenarios to deepen the analysis of the long-term impacts of vehicle electrification.

Another limitation is the regional emphasis on applied power plant scenarios, which might not capture the complete range of effects that could emerge beyond these boundaries. Given the interconnected nature of the electricity grid, the benefits of vehicle electrification might extend to areas outside where the measures are implemented.

It is important to acknowledge that numerical modeling, such as that used in this study, inherently carries uncertainties due to the limitations in input data accuracy and the various parameterizations within the models. Therefore, caution should be exercised when using and interpreting the model outputs, and these uncertainties should be considered in any conclusions or applications of the results. These limitations suggest that while the results indicate potential for air quality improvement through vehicle electrification, the actual outcomes could vary, particularly during peak emission periods. Further research incorporating these factors would provide a more comprehensive assessment of the impacts of widespread electric vehicle adoption.

5. Opportunities for Future Research

While this study provides a robust analysis of the potential air quality benefits of vehicle electrification, several areas warrant further investigation to enhance our understanding and address remaining uncertainties.

a) **Sensitivity of ozone to electricity generation profiles:** Future research should explore the sensitivity of ozone formation to different electricity generation profiles, particularly focusing on marginal emissions during high-demand days. High electricity demand days often align with high ozone days, and power plants operating at higher capacities may emit more pollutants and higher emitting marginal power plants are brought online to meet peak demand. Investigating marginal emissions rather than average emissions will provide a more accurate assessment of peak emissions and their impact on air quality, leading to more precise evaluations of the benefits of vehicle electrification.

b) **Sensitivity of GHG and ozone to renewable electricity availability:** The availability of grid-stable, reliable renewable, zero-carbon electricity is critical for maximizing the environmental benefits of vehicle electrification. Future studies should assess how the integration of renewable energy sources impacts GHG and ozone levels – particularly on high-demand days. when higher-emitting back-up and peaking generation is needed. Understanding the sensitivity of GHG and ozone reductions to the proportion of renewable energy in the electricity mix will help in formulating effective policies that promote cleaner energy sources, thus enhancing the overall benefits of electrification.

c) **Sensitivity to recent research on tire and brake wear emission factors:** TBW emissions are a significant source of non-exhaust particulate matter, and recent research suggests that current models like MOVES may not fully capture these emissions. While total PM emissions, including both exhaust and non-exhaust PM, from ICE vehicles and EVs have been compared using emission factors from NEI and MOVES, recent studies have made comparisons based on experimental data. For example, Woo et al. (2022) found that when only primary exhaust PM emissions were considered, and vehicles were equipped with non-asbestos organic brake pads, the total PM_{10} emissions from EVs were 10-17% higher than those from ICEVs. Additionally, a recent study suggests that non-exhaust particle emissions from

EVs may exceed the total particle emissions from ICE passenger cars, including exhaust emissions, depending on factors like regenerative braking, road type, and vehicle type (Liu et al., 2021). Future research must incorporate the latest findings on TBW emission factors to refine emission inventories and improve the accuracy of air quality models. This will help in understanding the full impact of vehicle electrification on particulate matter pollution and in developing robust strategies and policies to mitigate non-exhaust emissions.

These areas of future research will build on the current study, providing deeper insights into the complexities of vehicle electrification and its environmental impacts. By addressing these topics, researchers can contribute to more comprehensive and effective strategies for improving air quality and reducing greenhouse gas emissions.

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