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Review

Assessing the Net Air Quality Impact of Electric Vehicle Adoption in California: A Comparative Analysis of Tailpipe Emission Reductions and Non-Exhaust Particulate Sources

Jihao Zhao [1,*]

[1] Minzu University of China, Beijing, China
* Correspondence: Jihao Zhao, Minzu University of China, Beijing, China

Abstract: California has treated electric vehicle adoption as a major strategy for improving transport-related air quality. The clearest benefit of electrification lies in the removal of operational tailpipe emissions, including nitrogen oxides, carbon monoxide, volatile organic compounds, and direct exhaust particulate matter. At the same time, traffic-related pollution does not end with the tailpipe. Tire wear, brake wear, road-surface abrasion, and dust resuspension remain relevant sources of particulate matter. This paper assesses the net air-quality implications of electric vehicle adoption in California by comparing the strong reduction of combustion-related pollutants with the persistence of non-exhaust particulate emissions. The analysis uses a policy-oriented and literature-based approach rather than original empirical measurement. It argues that the overall effect of electric vehicle adoption in California is positive for air quality, especially in relation to exhaust pollutants, but that the particulate benefits are more conditional than zero-tailpipe language may suggest. Brake wear is likely to decline because of regenerative braking, while tire wear and road dust effects may remain significant, particularly for heavier vehicles. The paper concludes that electric vehicle adoption should continue to be supported as a clean-air policy, but that California will need a broader regulatory approach if it seeks to reduce total traffic-related particulate exposure. In that sense, electrification is an important step in air-quality governance, but not a complete solution to the particulate burden associated with road transport.

Keywords: electric vehicles; air quality; particulate matter; non-exhaust emissions; transport policy

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1. Introduction

California has long been a leading jurisdiction in vehicle emissions regulation, transport environmental policy, and zero-emission vehicle promotion. Because the state combines heavy automobile dependence with persistent air-quality pressures, electric vehicle adoption has been framed as a means of improving both climate performance and public health. In operational terms, the logic is simple [1]. Battery electric vehicles do not produce tailpipe emissions while being driven, which means they can directly reduce exposure to combustion-related pollutants in traffic-intensive environments.

That benefit is important in the California context [1]. Ozone formation, particulate matter exposure, and near-road pollution remain central policy concerns across several regions of the state. Replacing internal combustion vehicles with electric vehicles can therefore improve local air quality, particularly in places where traffic density and population exposure overlap.

However, road traffic pollution is not limited to exhaust. Vehicles also produce particles through tire wear, brake wear, road-surface abrasion, and the resuspension of dust [2]. These non-exhaust emissions remain relevant even when tailpipe emissions fall.

As a result, the net air-quality impact of electric vehicle adoption should not be reduced to the phrase zero tailpipe emissions alone.

This paper examines that broader issue. It asks how electric vehicle adoption in California should be evaluated when the reduction of exhaust pollution is considered alongside the persistence of non-exhaust particulate sources [3]. The paper argues that the balance remains favorable to electrification, but that particulate reductions are more limited and more conditional than many simplified policy narratives suggest (As shown in Table 1).

Table 1. Comparative Pollutant Pathways under Vehicle Electrification

Pollutant or source	Internal combustion vehicle	Battery electric vehicle	Expected air-quality effect
Nitrogen oxides	Direct tailpipe emission	No operational tailpipe emission	Strong reduction
Carbon monoxide	Direct tailpipe emission	No operational tailpipe emission	Strong reduction
Volatile organic compounds	Tailpipe and fuel-related contribution	No operational tailpipe emission	Reduction
Brake wear particles	Present	Often reduced by regenerative braking	Partial reduction
Tire wear particles	Present	Still present	Limited change or conditional increase
Road dust resuspension	Present	Still present	Persists

California's air-quality governance also makes the issue analytically important because the state does not approach transport pollution through a single instrument. Instead, regulation is distributed across vehicle standards, fuel programs, regional planning, incentive structures, and public-health frameworks. Electric vehicle adoption therefore sits inside a broader environmental policy system rather than outside it. This matters for interpretation. When electrification is discussed in isolation, it can appear to offer a complete technological remedy. When it is located within California's wider regulatory setting, it is more accurately understood as one major component in a layered strategy for emission reduction and exposure control [4].

Another reason the topic deserves close examination is that the meaning of net benefit changes depending on scale. At the vehicle level, the operational advantage of an electric vehicle over a combustion vehicle appears straightforward because the tailpipe disappears. At the fleet level, however, the result depends on turnover speed, class composition, travel demand, and infrastructure conditions. At the exposure level, the issue becomes even more specific, because communities living near heavy traffic corridors are affected by the pollutants that remain closest to the road [5]. For this reason, the present analysis treats net air-quality benefit not as a single abstract outcome, but as a layered judgment that depends on pollutant type, spatial context, and policy objective.

The literature also suggests that public discussion often compresses several separate environmental questions into one. Climate mitigation, energy transition, urban air quality, and environmental justice are frequently bundled together under the banner of electric mobility. Although these agendas are linked, they are not identical. A transport system may become lower in carbon intensity while still producing substantial particulate exposure. Likewise, a policy that improves average urban air quality may still leave high local burdens in roadside communities. This paper therefore treats air quality as a distinct analytical issue that deserves separate assessment even when it overlaps with climate policy.

2. Literature Review

2.1. Electric Vehicles and Exhaust-Related Air-Quality Benefits

A large body of research and policy analysis supports the view that electric vehicles improve urban air quality by removing operational tailpipe emissions. Compared with internal combustion vehicles, battery electric vehicles avoid on-road emissions of nitrogen oxides, carbon monoxide, volatile organic compounds, and exhaust-generated particulate matter [6]. These reductions are especially relevant in congested urban corridors, where exposure to traffic pollution is spatially concentrated.

The literature also notes that tailpipe reductions matter beyond direct exposure alone. Nitrogen oxides and volatile organic compounds are important precursors in ozone formation, while combustion-related fine particles contribute directly to harmful ambient pollution [7]. In areas where photochemical smog and particulate matter remain policy priorities, electrification can therefore provide benefits through multiple pathways.

In California, this logic is strengthened by the state's regulatory structure and relatively cleaner electricity mix compared with more fossil-fuel-intensive systems. While full life-cycle environmental accounting has been examined in the literature, the main concern of this paper is operational air quality rather than the full life-cycle perspective. Within that scope, the literature generally supports the conclusion that electric vehicle adoption reduces a major share of traffic-related exhaust pollution [1].

2.2. Non-Exhaust Emissions as a Continuing Challenge

A second body of literature focuses on non-exhaust particulate emissions from road transport. These emissions arise from mechanical and road-surface processes rather than from fuel combustion. Tire wear, brake wear, road abrasion, and resuspended dust can all contribute to ambient particulate matter, and their relative importance increases as exhaust emissions are reduced by tighter standards and cleaner powertrains.

This literature complicates any assumption that electric vehicles solve traffic-related air pollution in a complete sense. Electric vehicles eliminate exhaust emissions during use, and regenerative braking may reduce brake wear, but tire wear and road dust processes remain [8]. Some research has also suggested that heavier vehicles may increase certain forms of non-exhaust particle generation under particular conditions.

At the same time, the literature does not support a simple reversal of the electrification argument. Non-exhaust emissions are significant, but that does not mean electric vehicles are equivalent to combustion vehicles in air-quality terms. The more accurate conclusion is that electric vehicles substantially reduce one set of important pollutants while leaving another set only partly affected.

2.3. California as a Policy Setting

California is an important case because it combines rapid electric vehicle growth, strict emissions policy, and well-documented air-quality challenges [9]. The state's institutions have invested heavily in zero-emission vehicle transition, while regional air agencies continue to address ozone and particulate matter problems. This creates a setting in which the air-quality implications of electrification are not abstract. They are directly connected to policy design, exposure reduction, and environmental governance.

The California case also highlights distributional concerns. Traffic-related air pollution is not evenly experienced across space [10]. Communities located near major roadways and freight corridors often face higher exposure burdens. In that setting, tailpipe reduction has clear public-health value, but persistent non-exhaust pollution means that electrification alone may not fully remove traffic-related particulate exposure.

An additional point in the literature concerns the composition of the vehicle fleet. Electric vehicle adoption does not proceed evenly across all classes [6]. Passenger cars, sport utility vehicles, buses, delivery fleets, and heavy-duty vehicles each have different implications for air quality. A discussion centered only on average electrification may therefore miss important variation. For example, the air-quality significance of replacing a high-mileage urban combustion fleet is not the same as replacing a low-use private vehicle. In California, where freight activity and long-distance goods movement matter greatly, the class composition of electrification has clear implications for both regional emissions and near-road exposure.

The literature also highlights the importance of measurement difficulty. Tailpipe emissions can be linked to engine operation and emissions standards with relative conceptual clarity. Non-exhaust emissions are harder to model because they depend on friction, road condition, speed, weather, driving style, and the chemical composition of materials [11]. This has two consequences. First, the evidence base for non-exhaust emissions is often more variable and more sensitive to assumptions. Second, policy tends to lag behind the science because regulation was historically organized around fuels, engines, and exhaust-control technologies. The result is not a lack of relevance, but a governance gap between what is easy to regulate and what is increasingly important for particulate exposure.

A further strand of scholarship considers the interaction between pollution reduction and urban development patterns. In highly motorized regions, cleaner vehicles can reduce per-vehicle emissions while total traffic volumes remain large. This means that improvements in technology do not necessarily eliminate the environmental pressures associated with automobile dependence itself [12]. Electric vehicles improve the emissions profile of mobility, but they do not erase congestion, land-use fragmentation, or road-dominated urban form. For air-quality analysis, the practical implication is that electrification should be studied alongside broader mobility systems rather than as a self-sufficient intervention detached from travel demand.

3. Theoretical Framework

This paper uses a net-impact framework. The central idea is that the air-quality value of electric vehicle adoption should be understood through the interaction of two processes: the removal of tailpipe emissions and the persistence or modification of non-exhaust particulate sources.

The first process is substitution [13]. When an electric vehicle replaces an internal combustion vehicle, operational exhaust emissions fall. The strongest benefits appear in relation to nitrogen oxides, carbon monoxide, volatile organic compounds, and direct combustion particles.

The second process is persistence. Non-exhaust particulate emissions continue because they are generated by vehicle motion, braking, tire-road contact, and road conditions rather than by fuel combustion itself [14].

The third process is modification [15]. Electrification can change some non-exhaust sources in different directions. Regenerative braking may reduce brake wear, while heavier vehicle mass may increase tire wear or dust resuspension in some circumstances. Because these effects do not all move in the same direction, the net particulate outcome is more conditional than the exhaust outcome.

This framework leads to a practical conclusion: the net air-quality effect of electric vehicle adoption is positive, but the size and composition of that benefit vary across pollutant categories (As shown in Table 2).

Table 2. Net-impact Framework for California Electric Vehicle Air-Quality Assessment

Analytical layer	Main mechanism	Direction of change after electrification	Policy significance

Substitution	Removal of tailpipe combustion	Clearly favorable	Improves exhaust-related air quality
Persistence	Continuation of non-exhaust sources	Residual burden remains	Limits total particulate gains
Modification	Brake, tire, and weight-related changes	Mixed and conditional	Requires targeted regulation
Net result	Balance of all effects	Positive overall but uneven across pollutants	Supports complementary policy design

The framework can also be interpreted through the difference between absolute and relative improvement. In absolute terms, removing tailpipe emissions is a major gain because it directly eliminates a class of harmful pollutants from vehicle operation. In relative terms, however, the residual importance of non-exhaust particles rises because the denominator changes. Once exhaust declines, the sources that remain account for a larger share of traffic-related particulate matter. This does not mean those sources suddenly become new problems out of nowhere. Rather, it means they become more visible within an increasingly electrified transport system [16].

Another useful distinction is between emissions and exposure [17]. Two sources may not be equal in terms of mass, composition, or health significance. Tailpipe pollutants often include gases and fine particles with strong implications for respiratory and cardiovascular health, especially at roadside locations. Non-exhaust particles are also important, but their impacts vary according to size fraction, chemical composition, and atmospheric behavior. The present framework therefore does not assume that all particles or pollutants carry identical health implications. Instead, it recognizes that the policy meaning of net benefit depends not just on whether emissions continue, but on what those emissions are and where people encounter them.

4. Analysis

4.1. Why the Overall Balance Remains Positive

The strongest aspect of the case for electric vehicle adoption in California is the elimination of operational tailpipe emissions. This results in a direct reduction in traffic-related exhaust pollution at the point of use. In densely populated or heavily trafficked areas, this reduction is particularly significant as it directly impacts locations where human exposure is concentrated [8].

For nitrogen oxides, carbon monoxide, and exhaust-derived fine particles, the direction of change is evident [18]. These pollutants decrease when combustion is removed from vehicle operation. Since California has spent decades addressing transport-related air pollution through standards and planning, electrification aligns with a longer regulatory trajectory that prioritizes on-road emissions as a central target.

From an air-quality perspective, electric vehicles should still be considered beneficial [6]. Any evaluation focusing solely on what remains after electrification, without acknowledging the scale of avoided exhaust pollution, would be incomplete.

Another reason the overall balance remains positive is that electric vehicle adoption transforms the regulatory opportunity structure. Exhaust control in combustion vehicles eventually faces diminishing returns as standards tighten and the removal of remaining emissions becomes increasingly costly. Electrification circumvents this incremental approach by eliminating operational combustion entirely. Even if non-exhaust emissions persist, the removal of tailpipe pollutants represents a qualitative shift in the composition of urban traffic pollution. This is particularly valuable in policy contexts where near-road exposure continues to pose significant public health challenges.

The practical implications of this shift are most apparent in urban corridors where traffic density, pedestrian activity, schools, housing, and commercial spaces intersect. In such areas, reducing exhaust emissions at the point of use helps lower direct human exposure in spaces where people spend significant time. This is one reason the air-quality argument for electric vehicles remains compelling, even when broader discussions about life-cycle impact or electricity generation are set aside [2]. For the operational urban environment, the elimination of the tailpipe constitutes a substantial environmental improvement.

4.2. Why Particulate Conclusions Must Be More Cautious

The particulate story is less straightforward [7]. Traffic-generated particulate matter originates from multiple sources, and electric vehicles do not eliminate all of them. Tire wear persists. Road dust resuspension continues. Brake wear may decrease but does not vanish entirely.

This means the term zero emission can be misleading if interpreted as zero particulate impact in a broader air-quality context. A more precise interpretation is that electric vehicles are zero-tailpipe vehicles during operation, not zero-particle vehicles in all traffic-related aspects [7].

Vehicle mass is one reason for caution. Many battery electric vehicles are heavier than comparable internal combustion vehicles, primarily due to their battery systems. Increased weight can amplify the forces involved in tire-road interaction, potentially affecting tire wear and suspended dust. However, these effects vary depending on vehicle class, road conditions, speed, tire design, and driving patterns. It would therefore be an overstatement to claim that electric vehicles necessarily worsen particulate pollution, but it would also be inaccurate to assert that all traffic-related particles decline significantly with expanded electrification [15].

This caution also has a methodological dimension. Public and policy discussions often seek a definitive answer to whether electric vehicles are cleaner. However, the answer depends on the indicator being evaluated. If the focus is operational exhaust gases, the conclusion is strongly affirmative. If the focus is total roadside particulate burden, the answer becomes more nuanced [7]. If the focus is broader transport-system sustainability, additional considerations such as material use, infrastructure, and travel demand arise. A robust analytical framework should therefore avoid binary conclusions and instead identify the dimensions along which electrification is most and least effective.

California's unique geography reinforces this point. Different regions experience varying pollutant mixes, atmospheric conditions, and traffic patterns. The air-quality impact of vehicle electrification in a dense urban basin differs from its impact in suburban or freight-dominated areas. This variation does not undermine the general argument of the paper but suggests that policy design should be context-sensitive rather than assuming uniform outcomes across the state.

4.3. Brake Wear as a Meaningful Partial Advantage

Brake wear is the clearest non-exhaust category in which electric vehicles may provide an additional benefit. Regenerative braking enables many deceleration events to be managed partly through energy recovery rather than friction braking [2, 8]. Consequently, brake-pad abrasion can be reduced under numerous ordinary driving conditions.

This does not eliminate brake wear entirely, as friction braking still occurs in specific situations. Nevertheless, the brake-wear effect is significant because it demonstrates that electrification alters non-exhaust emissions in varied rather than uniform ways. The outcome is not a simple continuation of all particulate sources but a mixed pattern of substantial reduction, partial reduction, and residual burden.

4.4. Implications for California Policy

For California, the main policy implication is that electric vehicle adoption should continue to be regarded as a positive air-quality strategy, but it cannot serve as a stand-alone solution to total traffic particulate exposure. The state's next phase of air-quality governance will need to increasingly address the sources that persist after exhaust emissions are reduced.

This indicates the need for a broader policy portfolio. In addition to promoting zero-emission vehicle adoption, regulators may need to focus more on vehicle weight, tire material performance, brake technologies, road maintenance, and street cleaning in areas with high exposure. Public transit, walking, and cycling also remain important, as reducing overall vehicle activity can help lower both exhaust and non-exhaust pollution (As shown in Table 3).

Table 3. Policy Directions for Reducing Remaining Traffic-Related Particulate Burdens in California

Policy area	Primary target	Expected relation to non-exhaust emissions	Relevance to California
Vehicle weight management	Heavier vehicle classes	Can help limit tire and dust effects	High
Low-wear tire standards	Tire material and design	May reduce particle generation	High
Brake technology improvement	Residual brake abrasion	Supports further reduction	Medium to high
Street cleaning and road maintenance	Dust loading and resuspension	Can reduce roadside particle burden	High
Public transit and active travel	Total vehicle activity	Reduces both exhaust and non-exhaust traffic burden	High

5. Discussion

The broader significance of this analysis lies in the distinction between technological transition and pollution elimination. Electric vehicle adoption changes the composition of traffic-related air pollution, but it does not eliminate it entirely [7]. The transition removes a major class of harmful emissions, especially those linked to combustion, while leaving non-exhaust particles as a residual issue that remains visible.

This has implications for how clean transport is addressed in public policy. A narrow focus on zero tailpipe emissions is beneficial, but it can obscure the fact that traffic systems continue to generate particulate matter through material wear and road interaction. Electrification should therefore be understood as a significant improvement in urban air quality rather than a complete solution to transport-related pollution [13].

The California case is particularly useful as it demonstrates the outcomes when a jurisdiction progresses further along the electrification pathway. As tailpipe emissions decline, the policy significance of non-exhaust particulate matter becomes more apparent. This does not diminish the rationale for electrification but instead shifts the focus to the next set of regulatory questions that need to be addressed [5].

The discussion also highlights a communication challenge in transport policy. Electric vehicles are often promoted with slogans that are technically accurate within a specific domain but can be misunderstood by broader audiences. The claim of zero tailpipe emissions is valid, yet it may be interpreted by non-specialist audiences as implying zero pollution overall. The issue is not the accuracy of the claim within its proper scope but the tendency for its scope to be overlooked in public interpretation [10, 11]. Consequently, policy communication may unintentionally oversimplify the environmental profile of electric mobility, potentially leading to confusion or backlash later.

A more robust public narrative would acknowledge both the advantages and limitations of electrification. Electric vehicles are undeniably cleaner than combustion vehicles in terms of operational exhaust emissions, which justifies continued policy support. However, cleaner does not equate to pollution-free in all respects. Recognizing residual particulate sources does not undermine the case for electrification; rather, it strengthens it by aligning policy language with the actual structure of transport emissions.

The present study also has implications for environmental justice analysis. Communities located near highways, logistics corridors, and major arterials are likely to benefit from reduced exhaust exposure as electric vehicle adoption increases. However, if non-exhaust particles remain significant, these communities may continue to face substantial roadside particulate burdens even after major shifts in fleet technology [15]. Achieving a just transition in transport requires more than electrification targets alone; it necessitates ongoing attention to where pollution persists, which communities are most affected, and the regulatory tools employed to address these issues.

6. Conclusion

This paper assessed the net air-quality impact of electric vehicle adoption in California by comparing the reduction of tailpipe emissions with the persistence of non-exhaust particulate sources. The analysis found that electric vehicles provide clear operational air-quality benefits by removing combustion-related pollutants during use. These benefits are especially important for nitrogen oxides, carbon monoxide, volatile organic compounds, and exhaust-derived particulate matter.

At the same time, the paper showed that electrification does not eliminate all traffic-related particle emissions. Tire wear, road abrasion, and dust resuspension remain relevant, while brake wear is reduced but not removed entirely. For that reason, the net effect of electric vehicle adoption remains positive, but particulate benefits are more limited and conditional than zero-tailpipe language might imply.

The main conclusion is that electric vehicle adoption improves air quality in California on balance, but the quality of that improvement depends on which pollutants are being considered. Electrification is a major part of cleaner transport policy, yet the long-term reduction of traffic-related particulate exposure will also require attention to the non-exhaust sources that remain after the tailpipe disappears.

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