TECHNICAL BRIEF

REVIEW OF CURRENT KNOWLEDGE ON NON-EXHAUST EMISSIONS FROM CONVENTIONAL AND ELECTRIC VEHICLES

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SUMMARY

There is an increasing recognition that regulation of exhaust particulate matter (PM) emissions from vehicles has been effective enough that they are now or will soon be lower in magnitude than PM from other non-exhaust vehicle sources such as tire wear and brake wear. For example, Figure 1 shows $PM_{2.5}$ data and projections for California on-road vehicles, showing that tire and brake $PM_{2.5}$ already exceeds exhaust $PM_{2.5}$. This has raised a concern that a shift to electric vehicles (EVs) may increase PM emissions since the increased mass of EVs relative to comparable conventional vehicles would lead to higher non-exhaust emissions that would not be offset by the elimination of exhaust emissions (Timmers and Achten, 2018). This paper reviews the literature on PM emissions from conventional vehicles and EVs, which indicates that although there are considerable uncertainties, EVs appear to provide a net benefit in PM emissions based on current vehicles and emissions levels. Future reductions in EV mass and grid emissions will increase these benefits.

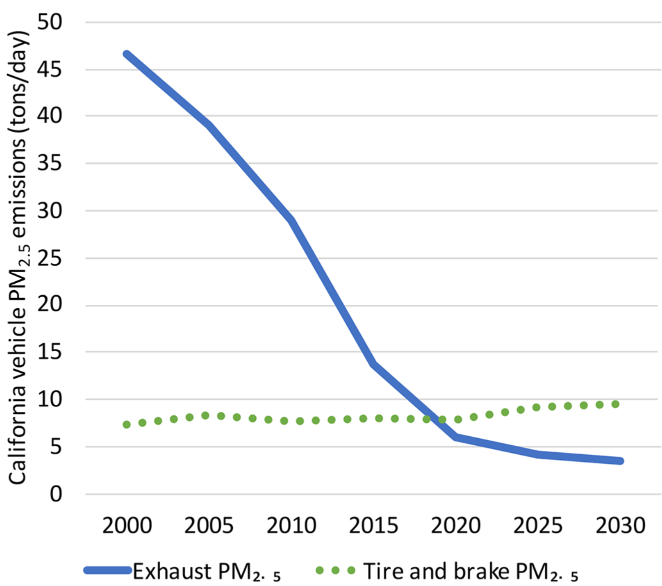


Figure 1. *Vehicle $PM_{2.5}$ emissions in California (source: California Air Resources Board modeled using the EMFAC2021 model (EMission FACtor))*

The measurement of non-exhaust PM emissions is a relatively nascent field and each source of emissions is affected by many factors, which are not always accounted for. This means that the numerical measurements of PM emissions considered in this paper have a variation of one or more orders of magnitude between studies depending on measurement or calculation methodology and specific composition or size fraction considered. Additionally, these emissions vary by location and their effects are affected by nearby pollution sources, so summary of or comparisons between these studies is difficult. Figure 2 shows the results of just one study, but one which was particularly comprehensive and which generally shows the trends seen in the review.

These results are from Woo, et al. (2022), which is the only study that performed detailed measurements of comparable gasoline vehicle and EV configurations. The figure shows $PM_{2.5}$ emissions for all primary and secondary sources, with red dots showing the sum of the non-exhaust emissions (each source and acronym will be described in more detail below).

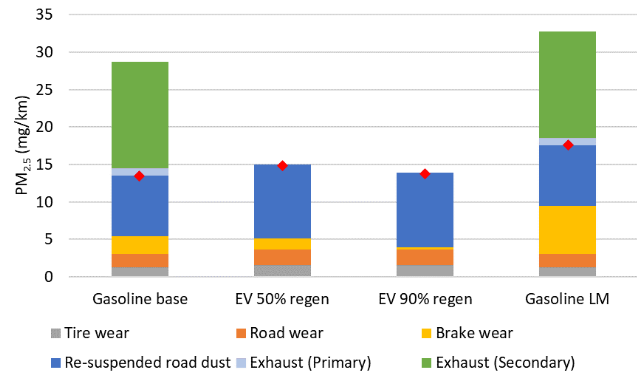


Figure 2. *Comparison of $PM_{2.5}$ emissions from a sample gasoline and EV for different assumptions (Source: Woo, et al. (2022))*

This figure shows a number of points that are discussed below:

- Based on the analysis in Woo, et al. (2022), non-exhaust $PM_{2.5}$ emissions for the EV are higher than the gasoline vehicle. This is due to the increased mass of the EV in this sample, which was 20% heavier than the gasoline vehicle. Although the results from the review were more mixed, generally the differences between vehicles were relatively small.
- Increasing the contribution of regenerative braking from 50% to 90% still results in higher emissions for the EV, but decreases the difference considerably.
- If low-metallic (LM) brake pads are used on the gasoline vehicle instead of the default non-asbestos organic (NAO) brake pads, non-exhaust emissions will be significantly higher than those for the EV. Most new vehicles are supplied with NAO pads, but LM pads are less expensive so are often used in brake pad replacements (EPA, 2022). This shows one example of how a common change in equipment can significantly affect overall non-exhaust emissions.[1] Since non-exhaust emissions have few regulations, there is no emissions-based incentive to install NAO pads verses LM pads.
- Aside from brake emissions, the greatest source of variation in non-exhaust $PM_{2.5}$ is re-suspended road dust. Modeling of resuspension has a particularly high degree of disagreement between studies, and it is not clear how much these emissions are affected by mass or whether they should be included in vehicle emissions comparisons. In particular, these emissions are likely also affected by vehicle

1 Although LM brakes could also be used in EVs, regenerative braking significantly reduces brake wear, meaning that the original brake pads will last much longer and may last the full vehicle life (Liu, et al., 2021).

aerodynamic turbulence and they can include emissions from tire, brake, and road wear that were previously counted as emissions, raising concerns about double counting. Without resuspension, the EV would have had 25% lower non-exhaust emissions than the gasoline vehicle in this analysis.

- When exhaust $PM_{2.5}$ emissions are included, the EV has much lower overall emissions than the gasoline vehicle in all cases. These can be classified as "primary," which are those particles emitted directly from the tailpipe, and "secondary," which are those particles formed from the reaction of exhaust gases in the atmosphere. The contribution of secondary $PM_{2.5}$ can have a large emissions impact.

Finally, although EVs show significant benefits when all emissions sources are included, the reduction is not as great as may be anticipated based on tailpipe emissions only. This paper focuses on a narrow comparison of current conventional and electric automobiles but suggests that there could be significant additional benefits in moving towards radically lighter automobiles or non-automotive alternatives such a mass transit, bicycles, and urban design to reduce the need for travel.

PARTICULATE MATTER BASICS

Particulate matter (PM) consists of collections of solid or liquid particles suspended in air. These pollutants are of concern since they can be inhaled and are linked to adverse health effects.

Sizes and Characteristics of PM

PM can be categorized based on its size. $PM_{2.5}$ and PM_{10} represent particles that are smaller than 2.5 μm and 10 μm, respectively. Ultrafine particles (UFPs) refer to particles smaller than 0.1 μm. It should be noted that UFP comprises a portion of $PM_{2.5}$ and PM_{10}, and $PM_{2.5}$ also makes up a portion of PM_{10}. Mass-based measurements (μg/m^3) are often used for $PM_{2.5}$ and PM_{10}, while particle number concentration (number of particles/cm^3) is used for UFP. $PM_{2.5}$ and PM_{10} are currently regulated by the U.S. EPA, while UFPs are not currently regulated due to the limited causal evidence between UFPs and health.

PM can be generated from fuel combustion in internal combustion engine vehicles (ICEVs), which is referred as tailpipe emissions, while no tailpipe emissions are generated from electric vehicles (EVs). In addition, because no PM precursor pollutants (e.g., nitrogen oxides, NOx, and volatile organic compounds, VOCs) are emitted from EVs, reductions in secondary formation of PM are expected. On the other hand, both ICEVs and EVs generate non-exhaust particle emissions from brake, tire, and road wear as well as resuspended road dust. Mobile source regulations are contributing to decreases in exhaust emissions, which leads to increased relative contribution of non-exhaust emissions, especially for near road exposure.

Several important factors must be considered when thinking about the potential health implications of non-exhaust PM emissions from EVs. Toxicity of particles are known to vary by particle size, surface area, chemical composition, and physical characteristics of the particles (Schraufnagel, 2020; Park et al. 2018).

PM sizes are important as it determines how deep into the human body the particles can penetrate. Once inhaled, these particles can be deposited throughout the airways, and where they get deposited depend on their size. PM_{10} can be inhaled into the lungs then are most likely deposited on the surfaces of the larger airways in the upper region of the lung, while $PM_{2.5}$ can travel further into the lungs and are deposited on the surface of the deeper parts of the lung (Seinfeld and Pandis, 2016). UFPs are able to enter the bloodstream and translocate to essentially all organs. Additionally, studies have shown that UFPs can cross the blood-brain barrier (Schraufnagel, 2020).

The chemical composition of PM is another important factor to consider. Research efforts have been made to identify specific PM components and/or sources of PM that would be more strongly associated with specific health outcomes, so that future regulations can be more targeted and effective in protecting public health. Several studies have identified PM from traffic sources as a main contributor to observed health effects (Adams et al., 2015; Peterson et al., 2020). However, the current knowledge is insufficient to precisely quantify or rank the health effects of PM from different sources or of individual PM components (Adams, et al., 2015; Hime, Marks, and Cowie, 2018; Kelly and Fussell, 2012).

Major PM components can vary by location (urban vs. rural), nearby sources (traffic vs. power plants vs. restaurants) as well as nearby soil characteristics (Dominici et al., 2015; Adams et al. 2015; Park et al. 2018). Distinctive PM composition from non-exhaust emissions compared to PM from exhaust emissions, particularly metal tracers, may be associated with both toxicity and resultant health effects. PM composition of brake wear (high metal components) and tire wear (high rubber components) also differ. Zinc is often considered to be a marker for tire wear, while copper and iron are markers for brake wear. In addition, both the component types and concentrations vary by brand and product for tires and brakes.

Another important factor to consider is the dispersion pattern in the environment of non-exhaust PM emissions. Generally, PM from traffic is shown to decrease down to background levels within 500–600 meters from a roadway. A study showed that non-exhaust PM had a stronger spatial gradient than exhaust PM (Koutrakis et al. 2017). However, there is only limited data available, often collected over a short time period, to accurately characterize whether and how dispersion patterns of non-exhaust PM emissions may differ from exhaust emissions to investigate the potentially varying health effects associated with each. In addition, mass-based measurements for different PM fractions do not consider other factors such as composition and particle number that are valuable in evaluating the health effects associated with PM. More systematic approaches that collect long-term data and consider meteorology as well as traffic patterns (total vehicle miles, vehicle characteristics, road type, etc) is required to develop accurate exposure estimates that can be used in epidemiological analyses.

Sources of Vehicle PM

Although exhaust emissions have historically been the focus of regulation and analysis for vehicle emissions there are a variety of sources of PM emissions:

- **Tire wear:** Tire wear results from the friction interface between the tire and the road. A large set of factors affect tire wear rates, including tire composition, road type, driving style, and suspension alignment, but for comparisons of similar vehicles the main consideration is vehicle mass, which linearly increases wear rates (OECD, 2020). Approximately 8% of tire wear becomes PM_{10} or below (EPA, 2020).
- **Road wear:** The interaction between tires and roads also wears the road. Although the contributors to road wear are less clear than for tire wear, road wear is generally assumed to be linearly related to vehicle mass.
- **Brake wear:** The operation of brakes involves friction between the pads and rotors, which results in wear from both surfaces. Brake wear is affected by pad and rotor composition, component temperature due to previous braking, driving style, and other factors, but for comparisons of similar vehicles the main consideration is vehicle mass, which causes a linear increase in wear rates. However, EVs and other vehicles with electric drive motors can also use the motor to slow the vehicle through "regenerative" braking, which decreases wear from the friction braking system.
- **Resuspension:** As a vehicle moves along a road, the tires lift dust that was previously deposited on the road and reintroduces it into the air. The inclusion of resuspension is controversial since some amount of the re-emitted particles were previously emitted from vehicles and are being double counted (OECD, 2020). Further, the scaling of resuspension is uncertain since there has been little study on the relative emissions of similar vehicles. Although resuspension is often assumed to scale with vehicle mass, the datasets used to estimate these factors often include dissimilar vehicles such as motorcycles, passenger cars, and trucks (AQEG, 2005). Although mass is one factor which may affect resuspension, other vehicle characteristics such as vehicle aerodynamic turbulence are likely to also affect these resuspension rates (Venkatram, 2000).
- **Primary Exhaust Particles:** Primary or direct emissions of PM from vehicle exhaust has been well-studied and regulated for decades, resulting in the greatly decreased levels discussed previously.
- **Secondary Formation of particles:** In addition to the PM emitted in vehicle exhaust, other exhaust components such as VOC (i.e., unburnt hydrocarbons), NOx, ammonia (NH_3), SO_2 and others can react with themselves and with emissions from other sources in the atmosphere to create PM. The rate of these reactions is highly dependent on atmospheric conditions, concentrations of other precursors and photochemical oxidants, and can occur at various distances from the point of emissions.

Figure 3 shows the relative levels of the non-exhaust emissions sources across a variety of studies, as reviewed in Piscitello, et al. (2021). There is significant variation between different estimates due to different sampling methods, environments, and vehicle types.

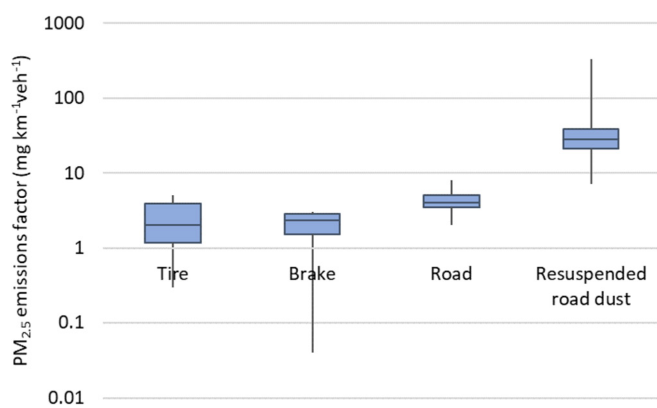


Figure 3. Variation in different sources of emission (source: Piscitello, et al., 2021)

Vehicle PM Health Effects

Generally speaking, there are few studies that directly examine the health effects associated with EV emissions. The limited health studies available for vehicle emissions are often focused on exhaust emissions and/or do not differentiate exhaust and non-exhaust emissions (Choma, et al., 2020). The available studies that examine the health benefits associated with EVs often use projections or estimations for both EV adoption rate and health effects rather than real-world data. Studies that specifically investigate health effects or differential toxicity associated with individual non-exhaust emission sources (e.g., brake wear vs. tire wear) are also rare. There is recent interest in the potentially increasing relative contribution of non-exhaust PM emissions from EVs given the known health effects associated with PM. However, it also needs to be recognized that reductions in other exhaust emissions (e.g., NOx, VOC) will lead to health benefits following a greater EV adoption (Carey, 2023).

There now seems to be a greater interest and efforts to better understand the potential implications of increasing the relative contribution of non-exhaust emissions from EV adoption. More studies are likely to be published, including a study that is currently underway funded by Health Effects Institute (HEI) assessing the effects of metals from non-exhaust emissions on asthma and lung function in the Children's Health Study in a Southern California cohort. Two new studies have also been launched to measure and disentangle non-exhaust and exhaust emissions to better understand their effects on human health (Health Effects Institute, 2021; Green Car Congress, 2023).

A selection of studies performed to date shows the significant health implications of PM emissions. Gerlofs-Nijland, et al. (2019) examined the toxicity of $PM_{2.5}$ from brake pads and tires by exposing $PM_{2.5}$ emissions from various sources to mice by inhalation. The study showed that $PM_{2.5}$ from non-asbestos organic (NAO) brake pads and ECE-NAO hybrid brake pads possess a higher toxic potential (based on inflammatory responses and hematological parameters) than ECE low-metallic brake pads, semi-metallic brake pads, and tire/road wear (Figure 4).[2] Their results suggest PM with lower metal content is likely to be least potent in causing adverse health effects. It is also worth noting that other sources of $PM_{2.5}$ (e.g., stove, poultry farm) also exhibit higher potency than some of the non-exhaust $PM_{2.5}$.

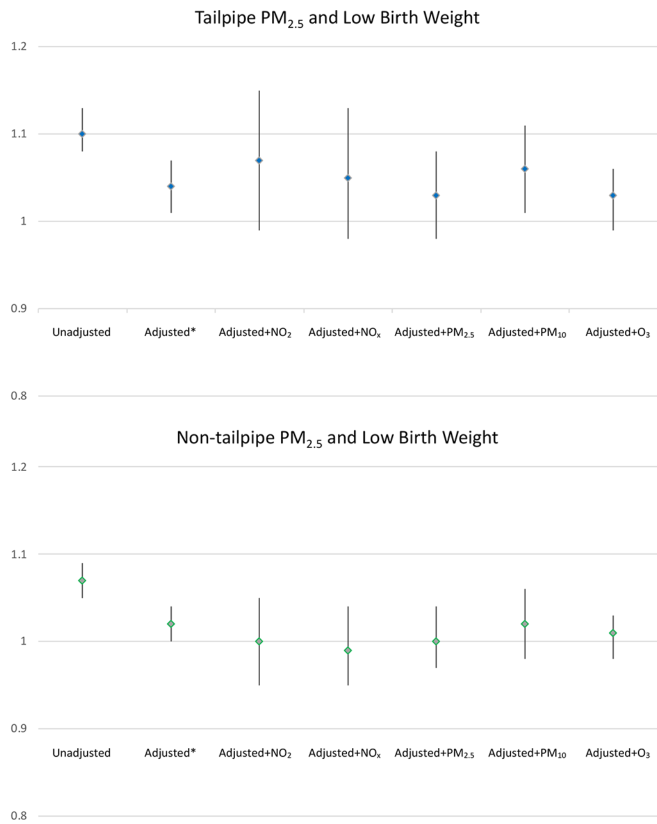
2 ECE brake pads use a low steel formulation of brake pads for the Economic Commission for Europe.

Smith, et al. (2017) conducted an epidemiological analysis using a population-based cohort in greater London to investigate the association between traffic-related exposures (air pollutants and noise) and birth weight. The study showed that non-exhaust $PM_{2.5}$ emissions were associated with low birth weight in this study population, although they found that the magnitude of association between exhaust $PM_{2.5}$ was consistently stronger than non-exhaust $PM_{2.5}$. However, they could not look at their independent effects due to multicollinearity (high correlation between these two measures – exhaust and non-exhaust $PM_{2.5}$). The two-pollutant analyses showed insignificant association between non-exhaust $PM_{2.5}$ and low birth weight, while the multipollutant results for exhaust $PM_{2.5}$ were suggestive of positive, although still not statistically significant, association (Figure 5). It should be noted that individuals are exposed to multiple air pollutants at once, thus single-pollutant analyses are not adequate in evaluating health risks associated with air pollution.

Choma, et al. (2020) was a health benefits assessment that calculated Metropolitan Statistical Area (MSA)-specific mortality considering NOx, SO_2, NH_3, volatile organic compounds (VOCs) and primary $PM_{2.5}$ from ICEV exhaust emissions, and power plant emissions of NOx, SO_2, and primary $PM_{2.5}$ as a consequence of EV electricity consumption. Figure 6 shows that the number of deaths associated with ICEV emissions are substantially higher than the deaths attributable to EVs in all 53 MSAs. Number of deaths attributable to $PM_{2.5}$ are also higher for ICEVs in most MSAs, though not all. This analysis did not focus on tire and brake wear, so assumed they were the same for ICEVs and BEVs.

	Pulmonary inflammation effect potency as assessed by polymorph nuclear neutrophils (PMN)	**Hematological parameter effect potency as assessed by Lymphocytes**
Most potent	Poultry farm	Non-asbestos organic (NAO) brake pads
	ECE-NAO hybrid brake pads	ECE-NAO hybrid brake pads
	Non-asbestos organic (NAO) brake pads	Tire/road wear
	Modern stove	Modern stove
	Diesel engine exhaust	Semi-metallic brake pads without copper
	Old-fashioned stove	ECE low-metallic brake pads including copper
	Tire/road wear	Poultry farm
	Semi-metallic brake pads without copper	Old-fashioned stove
Least potent	ECE low-metallic brake pads including copper	Diesel engine exhaust

Figure 4: *Ranking of PM toxicity for pulmonary inflammation and hematological parameter effects (source: Gerlof-Nijland et al., 2019).*



** Adjusted models are adjusted for sex, maternal age, ethnicity, birth registration type, birth season, birth year, Carstairs quintile (census output area level), tabacco expenditure (census output area level), gestational age as linear and quadratic terms, and random intercept for middle layer superoutput areas, in addition to including the air pollutant shown above.*

Figure 5. *Odds of term low birth weight (LBW), associated with interquartile range (IQR) increases in air pollutants, in single and two air pollutant models (Source: Smith et al., 2017).*

NON-EXHAUST PM FROM EVs

A literature review was conducted in order to survey the current understanding of a number of key questions surrounding non-exhaust PM. Around 100 studies were reviewed in total, of which 23 were included in a quantitative review (these studies are identified in the reference list with an asterisk (*)). The following subsections discuss each of the key questions addressed quantitatively.

Are non-exhaust PM currently higher than exhaust PM?

66% of the 18 studies that addressed this question found that non-exhaust PM were higher, while 22% were mixed (it depended on the location, time of the study, or reviewed studies with different answers). There was also a consistent finding that exhaust PM tended to be fine or ultrafine ($PM_{2.5}$ and below) while non-exhaust PM tended to be coarse (the fraction of PM_{10} above $PM_{2.5}$, i.e., $PM_{2.5\text{-}10}$) (for example, Habre, et al., 2022).

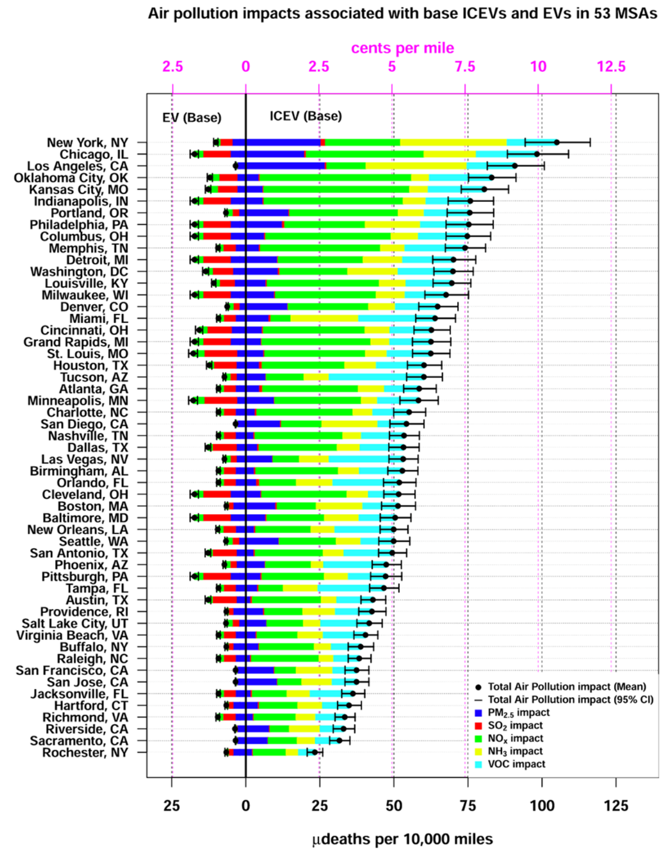


Figure 6. *Estimated air pollution mortality for base ICEVs (right) and EVs (left) in each MSA, by pollutant. 1 µdeath = 10^{-6} deaths (source: "Assessing the health impacts of electric vehicles through air pollution in the United States" by Choma et al. (2020) is licensed under CC BY 4.0).*

Do EVs have higher non-exhaust PM emissions than conventional vehicles?

75% of the 8 studies that addressed this question found that EVs did ***not*** have higher non-exhaust PM emissions than conventional vehicles, while 25% were mixed. This is likely surprising since there is a narrative that studies have consistently found that EVs have higher emissions, but this was not actually the case, even among studies that have been associated with this message. Instead, the findings can be more correctly characterized as "the increased popularity of electric vehicles will likely not have a great effect on PM levels" (Timmers and Achten, 2016). The results in 38% of these studies also varied significantly with the amount of regenerative braking assumed, which ranged from 100% to 0%. For example, Beddows and Harrison (2021) found that whether or not EVs provided a benefit depending on level of regenerative braking assumeds. Most studies that included regenerative braking assumed more than 2/3 of braking needs were met by regenerative braking, but none of the studies reviewed had strong justification for the specific assumption used.

How should resuspension emissions from individual vehicles be modeled?

This is a complex question that couldn't be addressed quantitatively since resuspension emissions are affected by a large number of factors, such as time since precipitation, temperature, pavement porosity, local dust levels, use of salt and other traction materials, traffic volume, street cleaning, and other factors (TER, 2020). As shown above, different estimates of resuspension emissions vary by orders of magnitude. There is also the potential for double-counting since the origin of the particles that are resuspended may be brake, tire, and road wear emissions that were previously counted. If these sources of emissions were eliminated, for example by using regenerative braking to substantially eliminate brake wear emissions, then these particles would no longer be available to be resuspended. Understanding resuspension is also a measurement challenge since these resuspended brake, tire, and road wear PM are chemically identical to new emissions. As an example of how resuspension is currently handled in inventories, the U.S. Environmental Protection Agency does not model resuspension emissions as vehicle-specific mobile emissions, but instead separately models dust emissions as a general emissions source dependent on local conditions such as ambient dust and frequency of precipitation (EPA, 2011).

CONCLUSION AND FUTURE DIRECTION

An overarching finding from this review is that non-exhaust PM is increasing in importance but understudied and generally unregulated. In fact, regulation would currently be impossible since there are no standardized tests for measuring non-exhaust PM, so no way of determining compliance. The review also suggests some opportunity in this area: since little attention has been focused on these emissions sources, there are likely opportunities for significant reductions in at least brake and tire PM. For example, silicon and zinc concentrations in a Cooper-brand tire were shown to be 10 and 2 times those in a Michelin-brand tire, respectively (Wang et al. 2023). EPA (2022) found that brake PM from aftermarket low metallic brake pads were 2–4 times higher than non-asbestos organic pads. In both cases relatively simple changes in component composition could have significant effects on emissions. Additionally, hybrid vehicles are a close replacement for conventional gasoline vehicles and can benefit from regenerative braking.

The increasing importance of non-exhaust PM also has significant implications for EV adoption. Although EVs do appear to be a net positive when considering the full range of emissions impacts they may not improve air quality as much as is hoped, particularly in areas that are near roads or are otherwise particularly affected by non-exhaust PM. The mass of electric vehicles should decrease in the future as technology improves, but as the modeling study shown in Figure 7 indicates, EV mass will have a high sensitivity to driving range.[3] This means that a movement towards longer vehicle ranges could allow tire PM in particular to continue to be higher. This suggests that continued attention to mass reductions will be valuable. Additionally, although this is outside of the scope of this report, non-automotive transportation alternatives such as bicycles, mass transit, increased urban density, and trip reduction would all be important in achieving large reductions in non-exhaust PM.

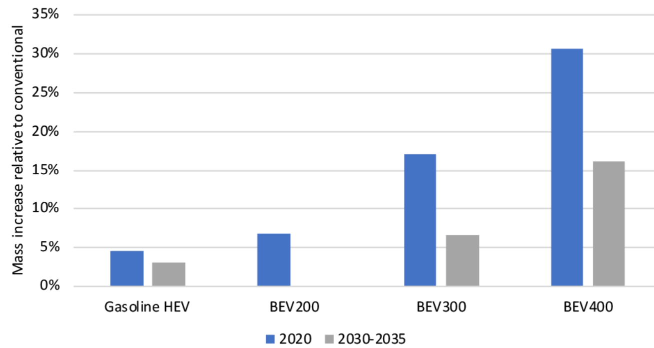


Figure 7. Modeled mass increase of current and future hybrid and electric vehicles relative to a conventional vehicle (source: Kelly, et al., 2022)

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3 Vehicle masses are from Kelly, et al. (2022); the BEV with 200 miles of range had a slightly negative mass increase relative to the conventional vehicle.

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