



Brake Wear Emissions in Particulate Matter

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Executive Summary

Background

The Federal Clean Air Act (FCAA) sets nationwide air quality standards called National Ambient Air Quality Standards (NAAQS) to protect public health and quality of life (i.e., well-being). The U.S Environmental Protection Agency (EPA) administers the FCAA, and sets and updates NAAQS for six criteria pollutants:

- Ozone (O₃)
- Carbon Monoxide (CO)
- Particulate Matter (PM₁₀ and PM_{2.5})
- Nitrogen Dioxide (NO₂)
- Sulfur Dioxide (SO₂)
- Lead (Pb)

In addition to those listed above, California has four extra pollutants for California Ambient Air Quality Standards (CAAQS) administered by the California Air Resource Board (ARB):

- Visibility Reducing Particles
- Sulfates
- Hydrogen Sulfide
- Vinyl Chloride

More information on the National/California state criteria pollutants and their corresponding standard values can be found at <https://www.arb.ca.gov/research/aaqs/aaqs2.pdf>

Addressing the potential impact of Caltrans' transportation projects on air quality in environmental documents is required for NEPA (National Environmental Policy Act), CEQA (California Environmental Quality Act), and transportation conformity¹ under the FCAA. Of the National/California criteria pollutants that need to be considered in environmental documents, PM (i.e., PM₁₀ and PM_{2.5}) has been of particular interest in transportation air quality analyses due to its unique characteristics and environmental circumstances:

- PM emissions from a typical transportation project consist of
 - Exhaust emissions (i.e., tailpipe emissions)
 - Break wear emissions
 - Tire wear emissions
 - Road dust

Whereas other transportation project related pollutants (e.g., CO and NO₂) are emitted from tailpipe (i.e., exhaust emissions).

¹ The information on transportation conformity can be found at <https://www.epa.gov/state-and-local-transportation/transportation-conformity> and https://www.fhwa.dot.gov/Environment/air_quality/conformity/con_broc.cfm

- As vehicles have been becoming cleaner due to increasingly stringent emission standards, PM exhaust emission, once the dominant PM emission component in the past, has been substantially reduced. As a result, PM exhaust emissions are becoming a small component of overall PM₁₀ and PM_{2.5} emissions. On the contrary, other PM emissions (i.e., brake wear, tire wear, and road dust) have not been regulated. Therefore, PM non-exhaust emission has become increasingly important.
- Compared to the National/California standard values, the ambient PM concentrations in California are generally high, especially in Southern California. Therefore, Caltrans has had a very hard time meeting conformity requirements in Southern California.
- Currently, no feasible project-level mitigation measures² for PM exists.

Figure 1 shows the estimated PM emissions by source type using (1) EMFAC³ and (2) ARB's road dust data source⁴ for the eight fleet age modeling scenarios (i.e., 2015, 2020, 2025, 2030, 2035, 2040, 2045, and 2050) in a hypothetical project.

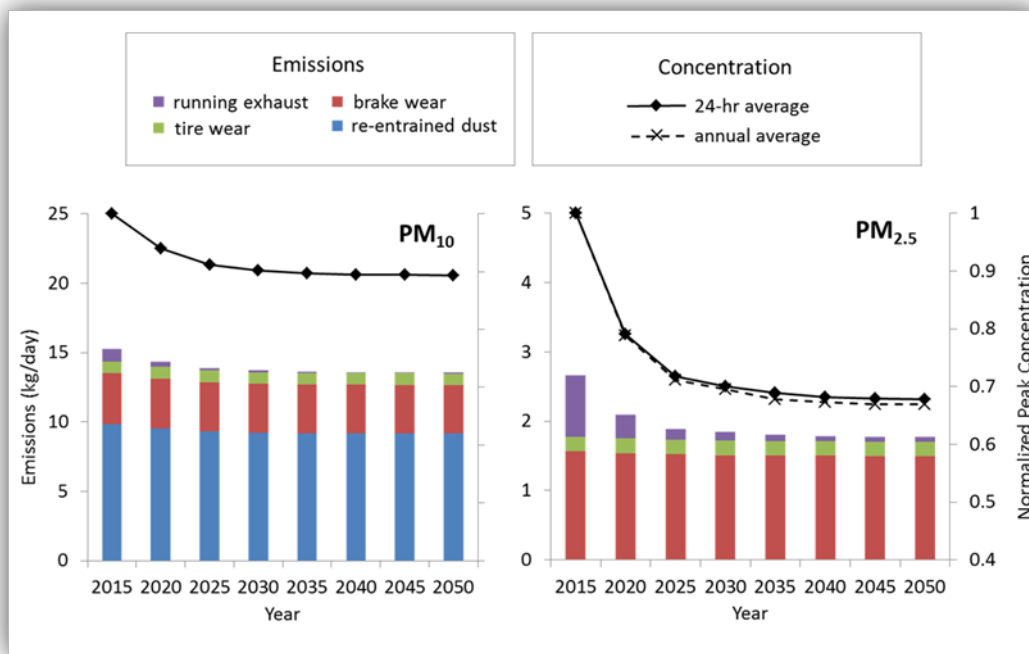


Figure 1: A PM sensitivity study to fleet turnover for a hypothetical project with 125,000 total Annual Average Daily Traffic (AADT). (Source: Modified from Figure 9 of Quantitative Particulate Matter Hot-Spot Analysis Best Practices Guidebook by Caltrans (2016).)

² Roadside barriers (i.e., soundwalls) are considered as a good candidate for mitigation. However, currently there is no EPA approved method to quantify the effect of roadside barriers on near-road air quality.

³ Unlike other states where MOVES, an emission modeling tool developed by EPA, must be used for their emissions calculations, Caltrans must use EMFAC, an emissions modeling tool developed by ARB, for exhaust, brake wear, and tire wear emissions calculations on Caltrans' projects.

⁴ EMFAC does not provide road dust emissions. ARB's road dust data source is recommended for use for road dust emissions calculations in California.

The following can be found and/or inferred from Figure 1:

- As newer and cleaner vehicles have lower emissions rates, fleet turnover results in substantial decreases of PM exhaust emissions between 2015 and 2020.
- However, the trend of PM exhaust decrease becomes relatively unnoticeable after 2025. In other words, fleet turnover (i.e., fleet age) will have a minimal impact on PM exhaust emissions after 2025.
- The exhaust emissions component of PM₁₀ becomes almost negligible after 2025, and the exhaust emissions component of PM_{2.5} becomes very small after 2025.
- Road dust is and will continue to be the major contributor to PM₁₀.
- Brake wear is the major contributor to PM_{2.5}. Moreover, brake wear also plays an important role in PM₁₀ emissions.

Summary of Findings

Caltrans Division of Environmental Analysis (DEA) conducted a brake wear/tire wear emissions modeling study in 2016, and a technical memorandum, *Assessment of Brake Wear and Tire Wear in Particulate Matter Emissions Modeling* (hereinafter *Technical Memorandum*) was produced. The Technical Memorandum is attached in Appendix.

The following is a summary of the major findings and recommendations from the *Technical Memorandum*. Please note that Figure 1 of the *Technical Memorandum* is presented in Figure 4:

The two official models used to estimate on-road emissions—MOVES and EMFAC—treat brake and tire wear differently, and apportion different amounts of brake and tire wear PM₁₀ to the PM_{2.5} size category. In general, for future analysis years, EMFAC-based brake and tire wear estimates are higher than those produced by MOVES, especially for brake wear emissions and for PM_{2.5}.

Current brake and tire wear data are based on a limited number of studies, many of which were completed more than a decade ago prior to technology and regulatory changes affecting current and future vehicle fleets. As a result, modern vehicle, brake, and tire technologies are not effectively represented in the data used to develop MOVES and EMFAC brake and tire wear PM emissions.

As a general observation, EMFAC produces brake wear emissions that are far greater than tire wear emissions, and produces PM_{2.5} emissions which are far greater than emissions produced by MOVES. Therefore it is a high priority to assess and improve EMFAC-based brake-related emissions estimates. Major findings and recommendations include

- ***MOVES varies brake and tire wear emissions by travel speed; EMFAC does not.*** *EMFAC brake and tire wear emission factors were developed primarily to support regional emissions inventory development, for which average travel speeds were considered sufficient to characterize regionally-averaged conditions. At the project level, speed-based emission factors offer the opportunity to assess emissions differences among various project alternatives that modify forecasted travel volumes, fleet mix, and speeds. For example, assume a build-project alternative reduced peak-period congestion and improved traffic flow from 10-15 mph to 30-35 mph. As shown in Figures 2 and 3, use of MOVES-based emission factors, which adjust for speed changes, would result in build-scenario brake-wear g/mi PM emission rates about 50% less than no-build rates; EMFAC-based results would show no change in g/mi emissions. Note that speed-based emission factor differences included in MOVES apply to all analysis years. Thus, the most important recommendation emerging from our assessment is to examine whether EMFAC-based emissions can be speed-adjusted using the technical information employed by EPA to develop MOVES speed-varying emissions factors. Given the overwhelming importance of brake wear compared to tire wear emissions (see Figure 1), this examination should focus on brake wear emissions.*
- ***Electric and hybrid-electric vehicles employ regenerative braking systems to recharge batteries; qualitatively, these systems are expected to reduce the wear-rate of brake pads.*** *Neither MOVES nor EMFAC takes into consideration how regenerative braking affects brake wear emissions. The importance of this issue increases over time, since the vehicle fleet is forecasted to include a greater fraction of advanced technology vehicles in coming years. The CEC, for example, forecasts that up to 17% of the truck fleet and up to 30% of the light-duty fleet will be electric or hybrid vehicles by 2050. The impact of this issue is relatively small for current and near-term analysis years, and larger over time with fleet turnover. Thus, there is an important need to quantitatively adjust EMFAC-based brake-wear emissions rates to account for forecasted regenerative braking systems use.*

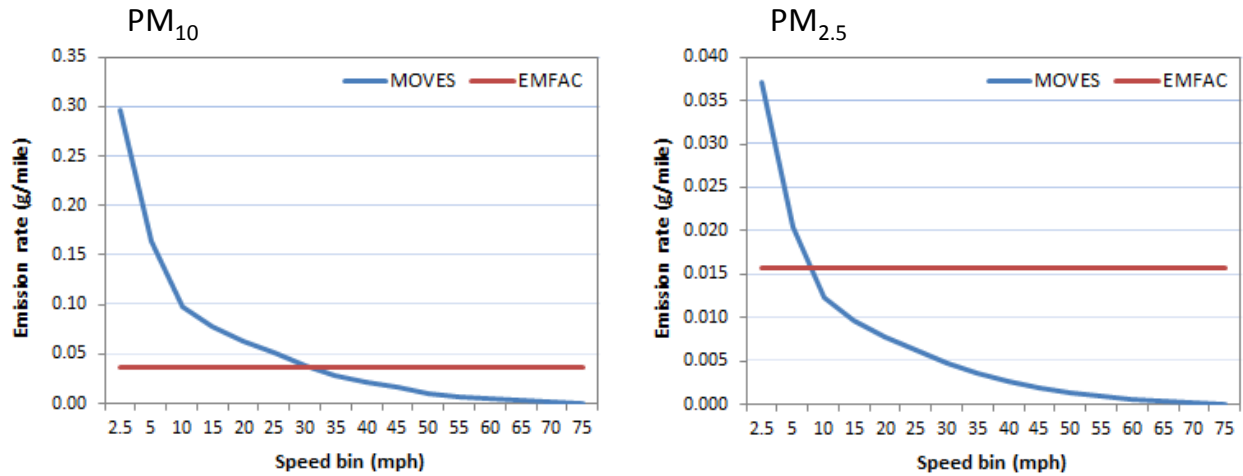


Figure 2. MOVES and EMFAC brake wear PM10 and PM2.5 emission rates for light-duty vehicles for a hypothetical project (Source: Figure 2 of *Technical Memorandum*)⁵

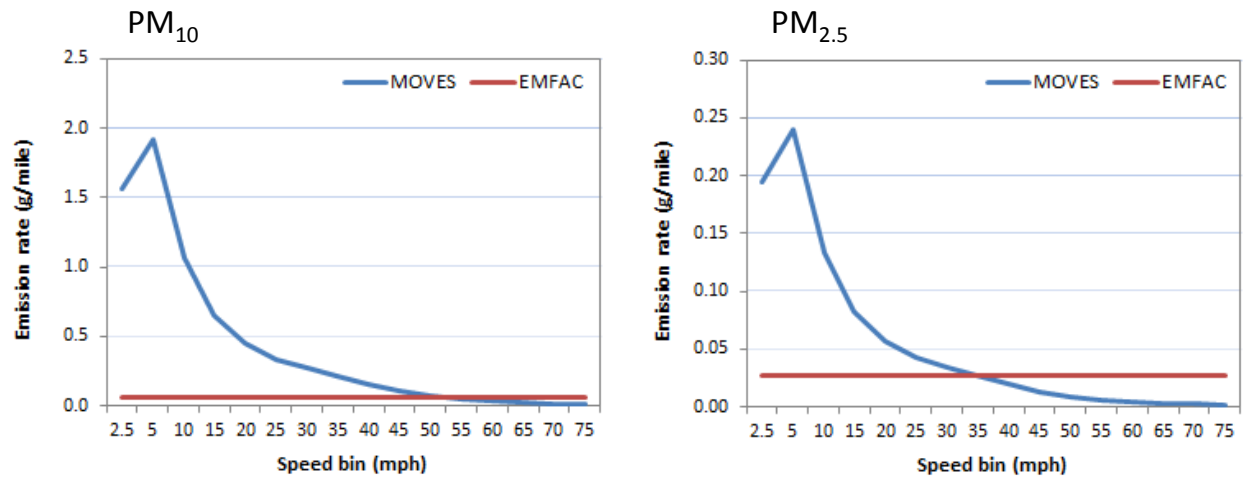


Figure 3. MOVES and EMFAC brake wear PM10 and PM2.5 emission rates for heavy heavy-duty trucks for a hypothetical project (Source: Figure 3 of *Technical Memorandum*)⁶

⁵ Note that MOVES brake wear emission rates vary by speed. In effect, the MOVES model embeds assumptions that per-mile brake wear emissions are lower when vehicle speed is higher, due to some combination of fewer braking and/or deceleration mode activities at higher speeds. In contrast, EMFAC brake wear emission rates are constant across all speeds for a specific vehicle type.

⁶ Please see Footnote 5 for additional information.

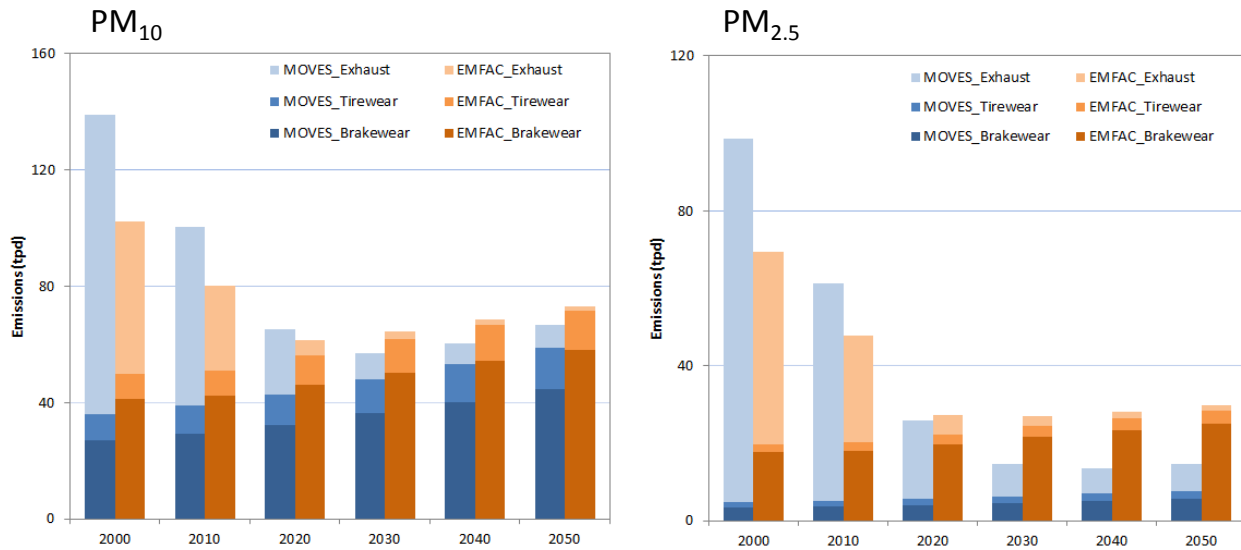


Figure 4. Comparison of MOVES and EMFAC emissions models for California statewide annual average daily emissions for PM₁₀ and PM_{2.5} (Source: Figure 1 of *Technical Memorandum*)

Gaps in Findings

Considering that PM emission calculation using EMFAC is a critical step in air quality analyses on Caltrans projects (e.g., emissions modeling and dispersion modeling), more realistic non-exhaust PM emission factors are needed to be implemented in EMFAC for proper disclosure of air quality impacts and for informed decision-making:

- Non-exhaust PM emission factors, especially brake wear, used in the current version of EMFAC need to be re-evaluated.
- More importantly, non-exhaust PM emission factors used in the current version of EMFAC are not speed-dependent. In order to improve EMFAC reliability, it is crucial to develop and implement speed-dependent non-exhaust PM emission factors in EMFAC.
- In addition, it is becoming increasingly important to account for effect of regenerative braking system in non-exhaust PM emission calculation. Therefore, EMFAC-based brake wear emissions rates need to be updated and adjusted for forecasted regenerative braking systems use.

Next Steps

Caltrans DEA will explore an opportunity to collaborate with ARB to fill the gap identified above.

Detailed Findings

Please see the attached *Technical Memorandum* in Appendix.

Consultation with State DOTs

As mentioned above, EMFAC is an emission modeling tool developed and maintained by ARB, and is required to be used only in California; other State DOTs are required to use MOVES, an emission modeling tool developed and maintained by EPA. Accordingly, other DOTs do not have a strong knowledge in EMFAC, and are not interested in improving EMFAC-based brake wear/tire wear emissions factors. Therefore, no consultation with other State DOTs has been conducted.

Related Research and Resources

Assessment of Brake Wear and Tire Wear in particulate Matter Emissions Modeling, Caltrans, 2016. (See Appendix)

Brake and Tire Wear Emissions from On-road Vehicles in MOVES2014, EPA, 2014.
https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=525701

Quantitative Particulate Matter Hot-Spot Analysis Best Practices Guidebook, Caltrans (2016)

Contacts

As stated above, no consultation with other State DOTs has been conducted for this information.

Appendix

Assessment of Brake Wear and Tire Wear in particulate Matter Emissions Modeling.

Assessment of Brake Wear and Tire Wear in Particulate Matter Emissions Modeling



Technical Memorandum
May 11, 2016

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Summary

With fleet turnover, exhaust particulate matter (PM) emissions are declining substantially; brake wear and, to a lesser extent, tire wear PM emissions are becoming a larger fraction of total on-road PM emissions. However, modeling of brake and tire wear emissions is based on limited literature, and much of it is old in comparison to recent work done to evaluate exhaust emissions. The two official models used to estimate on-road emissions—MOVES and EMFAC—treat brake and tire wear differently, with the result being that future-year EMFAC-based brake and tire wear estimates are higher than those produced by MOVES, especially for brake wear and for PM_{2.5}. Additionally, the vehicle fleet is evolving to include advanced technology vehicles (e.g., electric or hybrid vehicles with regenerative braking), and these vehicles are not represented in the data used to develop the brake and tire wear emissions factors included in current models. This memorandum explains brake and tire wear emission factors in MOVES and EMFAC, and prioritizes steps that can be taken to improve emissions modeling. As a general observation, EMFAC brake wear emissions are far greater than tire wear emissions; therefore, it is a high priority to assess and improve brake-related emissions estimates. The work summarized here was motivated by the U.S. Environmental Protection Agency (EPA) mandate to model PM hot-spots; EPA's mandate requires quantification of brake and tire wear PM emissions. Major findings and recommendations include:

- **MOVES varies brake and tire wear emissions by travel speed; EMFAC does not.** At the project level, speed-based emission factors offer the opportunity to assess emissions differences among various project alternatives that modify forecasted travel volumes, fleet mix, and speeds. *Thus, the most important recommendation emerging from our assessment is to examine whether EMFAC-based emissions can be speed-adjusted using the technical information employed by EPA to develop MOVES speed-varying emissions factors.*
- **Electric and hybrid-electric vehicles employ regenerative braking systems to recharge batteries; qualitatively, these systems are expected to reduce the wear rate of brake pads.** Neither MOVES nor EMFAC takes into consideration how regenerative braking affects brake wear emissions. The importance of this issue increases over time, since the vehicle fleet is forecasted to include a greater fraction of advanced technology vehicles in coming years. *Thus, there is an important need to quantitatively adjust EMFAC-based brake-wear emissions rates to account for forecasted regenerative braking systems use.*

- **Numerous other factors can affect brake or tire wear emissions that are not fully characterized by either MOVES or EMFAC.** However, collectively these factors are lower priority issues because they are likely to account for only a small fraction of overall PM emissions or have minimal impact on build vs. no-build project comparisons. Examples include federal requirements to reduce the stopping distance of trucks and the growing use of lower rolling resistance tires. *Although various factors introduce uncertainty into the emissions modeling process, they are less important to address than brake wear emissions variation by travel speed and the impact from regenerative braking systems.*

Introduction

This purpose of this technical memorandum is to prioritize ways to improve how brake and tire wear PM emissions are estimated in California. This work was motivated by the EPA requirement to complete quantitative PM hot-spot analyses for selected transportation projects. PM hot-spot analysis results, particularly for analysis years of 2020 and beyond, reflect the growing importance of brake and tire wear as a fraction of total on-road vehicle PM emissions. However, there are important shortcomings in the way that brake wear and tire wear emissions are currently estimated, due in part to issues such as the introduction of advanced technology vehicles and the use of outdated emissions data. In addition, brake wear and tire wear modeling techniques were originally developed to support regional emissions analysis work and have important limitations (e.g., they are not sufficiently sensitive to reflect emissions variations by vehicle type and travel speed) when applied to transportation project-level assessment. Given these shortcomings, we developed this document to help Caltrans better understand how brake and tire wear emissions are estimated, and what steps can be taken to improve those estimates.

Following this introduction, the remainder of this document is organized to include

- Statewide on-road PM emissions over time, by emissions source
- An overview of brake and tire wear modeling by MOVES and EMFAC, focused on
 - Data sources used to create emission factors
 - Assumptions embedded in each model regarding brake and tire wear emissions
 - An illustration of MOVES and EMFAC output differences, using hypothetical cases
- Anticipated changes in future brake and tire wear emissions due to regulations and advances in vehicle technology
- Overall findings and recommendations to assess and improve emissions estimations

Statewide On-road PM Emissions Over Time, by Emissions Source

On-road mobile source emissions are a major contributor to PM emissions in urban areas. Motor vehicles emit PM through combustion exhaust, brake wear, tire wear, and the suspension or resuspension of road dust. PM exhaust emissions have historically dominated mobile source

inventories. However, federal emissions standards have dramatically reduced exhaust emissions over time, while other forms of PM emissions have remained largely unregulated. **Figure 1** illustrates these changes for two regulatory models: MOVES2014a and EMFAC2014 v1.0.7 (hereafter referred to as MOVES and EMFAC). As shown in Figure 1, in 2020 and beyond, brake wear and tire wear emissions will account for a much larger proportion than exhaust emissions in the California statewide on-road vehicle-based PM emissions; the modeled statewide total brake wear and tire wear emissions increase by year due to projected continuous growth in travel activities (i.e., vehicle miles traveled).

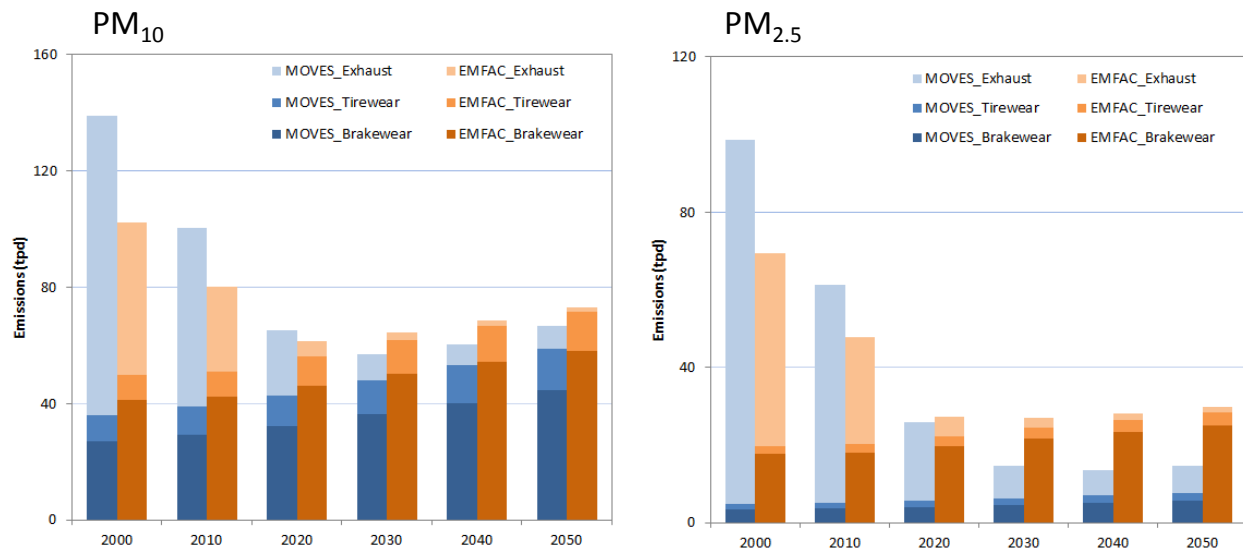


Figure 1. Comparison of MOVES and EMFAC emissions models for California statewide annual average daily emissions for PM₁₀ and PM_{2.5}.

At the project level, quantitative PM hot-spot analyses rely on detailed PM modeling that includes brake wear and tire wear emissions as well as exhaust emissions (U.S. Environmental Protection Agency, 2015). However, the modeling approaches and data used for estimating brake wear and tire wear emissions have not been as extensively researched and refined as exhaust emissions, especially in EMFAC. A recent study with modeled running exhaust, brake wear, and tire wear emissions for a hypothetical highway project suggested that brake wear and tire wear emissions from EMFAC were higher than those generated by MOVES; fleet turnover effects were found to sharply reduce project-level exhaust emissions with limited variation in brake wear and tire wear emissions by analysis year (Reid et al., 2016). There is a growing need to assess brake wear and tire wear emissions modeling, evaluate how brake wear and tire wear emissions may change with future changes to the vehicle fleet, and identify and prioritize opportunities to improve brake wear and tire wear estimation.

Brake Wear and Tire Wear Modeling: MOVES vs. EMFAC

Both MOVES and EMFAC model brake wear and tire wear as two separate PM emission processes. However, MOVES and EMFAC emission rates for brake wear and tire wear are different, since they are

based on different data sources, modeling assumptions, and calculation methods. Using light-duty vehicles (LDVs) and heavy-duty trucks (HDTs) as examples, this section illustrates MOVES and EMFAC differences. The discussion separately addresses brake and tire wear. In both discussions, the text refers to “base” emission rates. Base emission rates are specific to vehicle types and operations in MOVES, and only to vehicle types in EMFAC. For example, MOVES includes base brake wear emissions rates specific to LDVs operating in a moderate speed coasting mode with speed ranging from 25 mph to 50 mph. Overall, or composite emissions rates, are derived by weighting and aggregating base rates to appropriately reflect the fraction of vehicle types and operating modes that make up overall fleet travel activities.

Brake Wear Modeling Differences Between MOVES and EMFAC

1. Data Sources

The data sources used for developing the base brake wear emission rates in MOVES and EMFAC are limited in comparison to the many studies used to support exhaust emissions rate development.

Table 1 summarizes the studies used to support brake wear emissions development; these studies derived data in several ways, such as through the use of dynamometers or wind tunnels to obtain PM measurements. Virtually all of these studies date from 1999 to 2004 (U.S. Environmental Protection Agency, 2014; California Air Resources Board, 2011).

Two studies in particular were used to develop brake wear emissions for both MOVES and EMFAC: work completed by Garg et al. (2000) and Sanders et al. (2003). Although MOVES and EMFAC relied on the same studies, the two models produce different base brake wear emission rates (see sample data in **Tables 2 and 3**). Differences are due to varying assumptions and calculation methods. In MOVES, base brake wear emission rates are quantified as grams per hour and vary by vehicle type (i.e., regulatory class) and vehicle operating mode (e.g., vehicle speed, acceleration/deceleration modes). In EMFAC, base brake wear emission rates are quantified at the per-mile level and vary only by vehicle type and do not change by vehicle speed. Note that the lack of a speed-adjusted emission rate in EMFAC poses significant challenges for project-level PM hot-spot analysis, since EMFAC lacks the ability to assess emissions changes due to changes in congestion (travel speed). In both MOVES and EMFAC, the base brake wear emission rates are independent of fuel type, road type, calendar year, model year, and meteorology (e.g., temperature and relative humidity). One exception is urban buses in EMFAC; their base rates vary by fuel type as shown in Table 3. Both models suggest that the highest brake wear emission rates are associated with buses and heavy duty vehicles, based on the assumption that use of these vehicles typically involves more braking applications and requires more brake friction to stop.¹

¹ An interesting difference between MOVES and EMFAC involves medium heavy-duty trucks (MDHTs) vs. heavy heavy-duty trucks (HHDTs). Unlike MOVES, where emission rates of MDHTs are lower than the rates for HHDTs, EMFAC brake wear emission rates for MDHTs are higher than the rates for HHDTs. This is because EMFAC includes an assumption of more per-mile brake applications for MDHTs than for HHDTs (i.e., 3 vs. 1.2).

Table 1. Data sources for brake wear emission rates in MOVES and EMFAC.

Data Source	MOVES	EMFAC
(Garg et al., 2000)	Used to scale LDV emission factors to produce brake wear emission rates for heavy-duty vehicles.	Not used.
(Sanders et al., 2003)		
(Luhana et al., 2004)		
(Abu-Allaban et al., 2003)		
(Westerlund, 2001)		
(Rauterberg-Wulff, 1999)		
(Carbotech, 1999)	Used for developing base PM _{2.5} brake wear emission rates (grams per hour) for LDV only.	Used for developing base total PM emission rates (grams per brake application) for all vehicle types.
(California Air Resources Board, 2011)		

Table 2. Examples of MOVES base brake wear emission rates (g/hr) for PM_{2.5} (U.S. Environmental Protection Agency, 2014).

Operating Mode ^a	Braking	Idling	Low Speed Coasting	Moderate Speed Coasting	Cruise/ Acceleration
Light-duty vehicle (LDV), g/hr	0.55846	0.02447	0.54600	0.35896	0.06440
Medium heavy-duty truck (MHDT), g/hr	2.09000	0.06604	1.90190	1.51525	0.25289
Heavy heavy-duty truck (HHDT), g/hr	4.16000	0.06656	4.16000	2.66656	0.28288

^aMOVES assumes some brake use in each of the operating modes listed; for example, the "idling" mode is assumed to include some fraction of time that involves brake use, and therefore idling results in 0.02447 g/hr of brake wear PM_{2.5} emissions for light-duty vehicles.

Table 3. Examples of base brake wear PM_{2.5} emission rates in EMFAC (California Air Resources Board, 2015a).

Vehicle Type	Emission Rate (g/mile)
Light-duty vehicle (LDV), light-duty truck 1 (LDT1 or T1) and 2 (LDT2 or T2), medium-duty vehicle (MDV or T3)	0.01575
Light heavy-duty truck 1 (LHD1 or T4)	0.03276
Light heavy-duty truck 2 (LHD2 or T5)	0.03822
Medium heavy-duty truck (MHDT or T6), motor home, urban bus - gasoline, and other buses	0.05586
Heavy heavy-duty truck (HHDT or T7)	0.02646
Urban bus (UBUS) - diesel/natural gas	0.36078
School bus (SBUS)	0.31920
Motorcycle (MCY)	0.00504

2. Modeling Assumptions

A side-by-side comparison of key modeling assumptions between MOVES and EMFAC is presented in [Table 4](#). The MOVES calculation approach for brake wear emissions is based on PM_{2.5} measurements for LDVs for specific vehicle operations; these are then adjusted to estimate brake wear emissions for other vehicle types and for PM₁₀. In contrast, the EMFAC approach is based on total PM brake wear data (representing PM₃₀) that are associated with an overall average trip; the PM₃₀ data are then scaled to estimate brake wear emissions for PM₁₀ and PM_{2.5}. MOVES and EMFAC involve different assumptions regarding brake pad materials, braking activities per vehicle, and brake types.

Table 4. MOVES and EMFAC modeling assumptions for base brake wear emission rates.

Components	MOVES	EMFAC
Base pollutant	PM _{2.5}	PM ₃₀
Unit	Gram per hour	Gram per mile
Variation	By vehicle type and operating mode	By vehicle type
Testing drive cycles for braking activity	A single Federal Test Procedure (FTP) cycle	Multiple drive cycles for different vehicle types (e.g., for light-duty vehicles, heavy-duty trucks, and buses)
Brake pad materials	Assumed equal mix of three brake types (low-metallic, semi-metallic, non-asbestos organic)	Assumed vehicle type-specific mix of three brake types
Brake number & type	Assumed two front disc brakes and two rear drum brakes for LDVs	Varies by vehicle type: four disc brakes for LDVs and MDVs; two front discs, four tractor drums, and four trailer drums for HHDTs; two discs for motorcycles; and two front discs and two rear drums for other vehicle types
Airborne dust fraction	60%	50%
PM ₁₀ to PM _{2.5} ratio ^a	8	2.333
Basic modeling method	Regression model between PM _{2.5} rates and vehicle deceleration rates; distribution of braking activity for each deceleration bin based on real-world instrumented vehicle studies conducted in Los Angeles and Kansas City	Regression model between brake emission rates and wheel loads (varies by wheel type and vehicle gross weight) for different brake materials, brake types, and initial braking speeds (assumed one average speed specific to each vehicle type).
Aggregation of emission rates	Average brake emission rates (per hour) for different operating modes for LDVs; adjusted for other vehicle types (with different numbers of brakes and braking events) using scaling factors and linear interpolation	Average brake emission rates (per mile) based on different braking attributes (e.g., type of brake application, number of brakes, and braking frequency) for each vehicle type

^aThe MOVES PM₁₀ to PM_{2.5} ratio is based on more recent information (2003 data) than the information used to support the ratio in EMFAC (pre-2000 data) (Sanders et al., 2003; California Air Resources Board, 2010).

3. Illustration of Brake Wear Modeling Differences with a Hypothetical Case

To compare brake wear emissions generated from MOVES and EMFAC, we conducted a series of modeling scenarios based on a hypothetical road in Fresno, California. The test case included the following parameters:

- Geographic area: Fresno County, California
- Analysis years: 2000, 2005, 2010, 2015, 2020, 2025, 2030, 2035, 2040, 2045, and 2050
- Modeling period: January weekday
- Brake wear emissions unit: gram per mile (by average speed bin)
- Vehicle age distribution: EMFAC2014 default for Fresno County
- Vehicle type: different vehicle types in MOVES and EMFAC, mapped using vehicle class definition and weight information (see [Table 5](#))

Table 5. MOVES and EMFAC vehicle types mapping.

EMFAC			MOVES		
Vehicle Type	Definition	Weight Class (lb)	Vehicle Type	Definition	Weight Class (lb)
LDV	Passenger cars	All	LDV	Light-duty Vehicles	All
LDT1	Light-duty trucks	0-3750	LDT	Light-duty Trucks	All
LDT2	Light-duty trucks	3751-5750			
MDV	Medium-duty trucks	5751-8500			
LHDT1	Light heavy-duty trucks	8501-10000	LHD1	Class 2b trucks with two axles and four tires	8501-10000
LHDT2	Light heavy-duty trucks	10001-14000	LHD2	Class 2b trucks with two axles and at least six tires or Class 3 trucks	8501-14000
MHDT	Medium heavy-duty trucks	14001-33000	LHD3	Class 4 and 5 trucks	14000-19500
			MHD	Class 6 and 7 trucks	19500-33000
HHDT	Heavy heavy-duty trucks	33001+	HHD	Class 8a and 8b trucks	33001+
OBUS	Other buses	All	N/A	N/A	N/A
UBUS	Urban buses	All	UB	Urban bus	All
MCY	Motorcycles	All	MC	Motorcycles	All
SBUS	School buses	All	N/A	N/A	N/A
MH	Motor homes	All	N/A	N/A	N/A

Using light-duty vehicles and heavy heavy-duty trucks as examples, [Figures 2 and 3](#) present the PM_{10} and $PM_{2.5}$ brake wear emission rates from MOVES and EMFAC. Note that MOVES brake wear emission rates vary by speed. In effect, the MOVES model embeds assumptions that per-mile brake wear emissions are lower when vehicle speed is higher, due to some combination of fewer braking and/or deceleration mode activities at higher speeds.² In contrast, EMFAC brake wear emission rates are constant across all speeds for a specific vehicle type. The EMFAC speed-constant rate is within the range of the speed-variable rates from MOVES. For example, the EMFAC LDVs brake wear emission rates are similar to the MOVES rates associated with the 30 mph bin and 10 mph bin for PM_{10} and $PM_{2.5}$, respectively. Both MOVES and EMFAC show that heavy-duty vehicles have much larger g/mi brake wear emissions than light-duty vehicles.

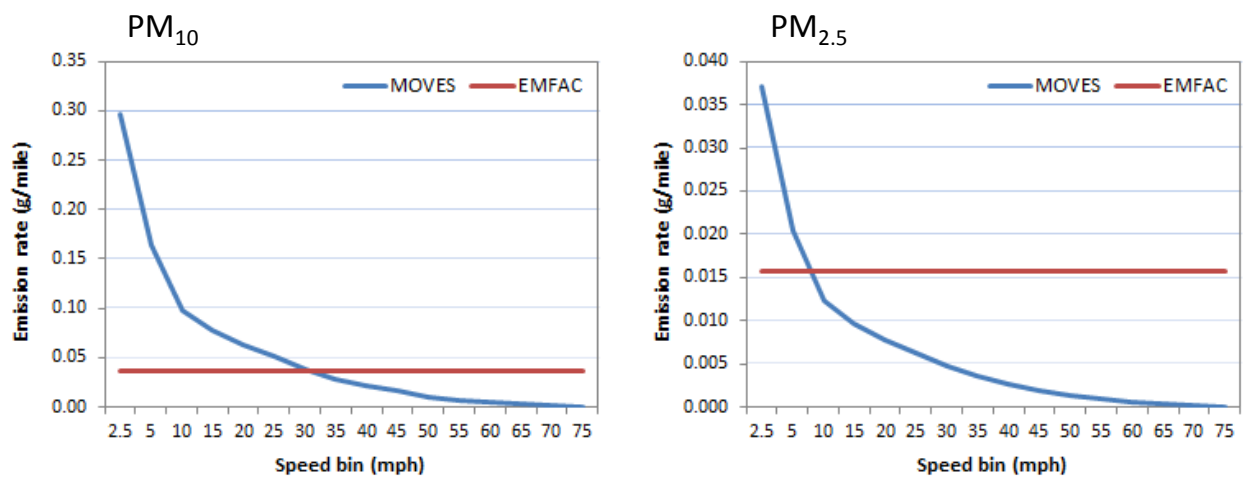


Figure 2. MOVES and EMFAC brake wear PM_{10} and $PM_{2.5}$ emission rates for light-duty vehicles.

² In general, MOVES brake wear emission rates decrease with increased vehicle speeds. However, for HHDTs, MOVES g/mi brake wear emission rates for the 2.5 mph speed bin appear lower than those for the 5 mph bin. EPA's technical staff confirmed that, for heavy-duty vehicles, MOVES incorporated idling activities (with lower brake wear emissions) within the 2.5 mph bin, which result in the lower average brake wear emission rates observed for this speed bin (personal communication with EPA's MOVES Team on February 9, 2016).

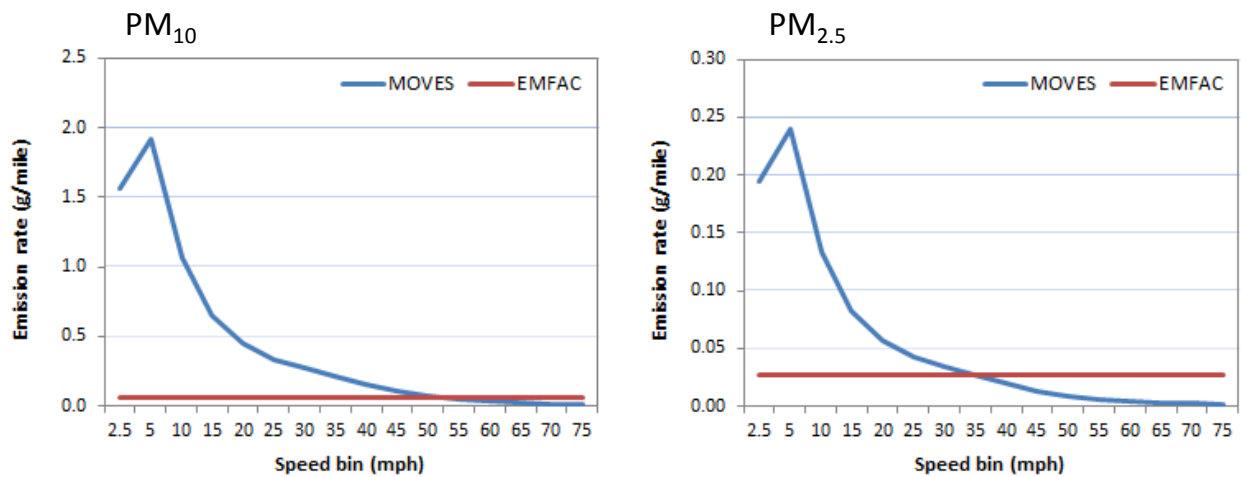


Figure 3. MOVES and EMFAC brake wear PM_{10} and $PM_{2.5}$ emission rates for heavy heavy-duty trucks.

For project-level emissions assessment, base emission rates have to be aggregated to high-level vehicle categories (such as non-trucks and trucks) typically used in project-level PM hot-spot work. Therefore, using MOVES and EMFAC brake wear emissions rates, we also calculated g/mi brake emission factors for three vehicle categories defined in EMFAC and CT-EMFAC: Non-Truck, Truck 1 (light heavy-duty trucks) and Truck 2 (medium heavy-duty trucks and heavy heavy-duty trucks), as well as for fleet average. Also, to make the case study more appropriate for PM hot-spot assessments, we assumed the vehicle fleet to be comprised of 8% trucks (consistent with the sample EPA benchmark of 8% trucks and 125,000 AADT for a PM Project of Air Quality Concern). The resulting case study brake wear emission factors are shown in [Figures 4 and 5](#).

Major findings from this case study include:

- EMFAC g/mi brake wear emissions do not vary by speed; therefore project-level brake wear emissions are proportional to vehicle miles. Project analyses that involve congestion relief and travel speed changes (given that fleet mix is not changed) will not result in varying g/mi brake wear emission rates.
- At the per-mile level, EMFAC brake wear emissions are lower in low-speed bins but higher in high-speed bins than MOVES brake wear emissions.
- EMFAC brake wear emissions rate differences among the three vehicle categories are less substantial than the differences embedded in MOVES; for low-speed bins, MOVES Truck 2 brake wear emissions are much higher than Truck 1 and Non-Truck brake wear emissions.

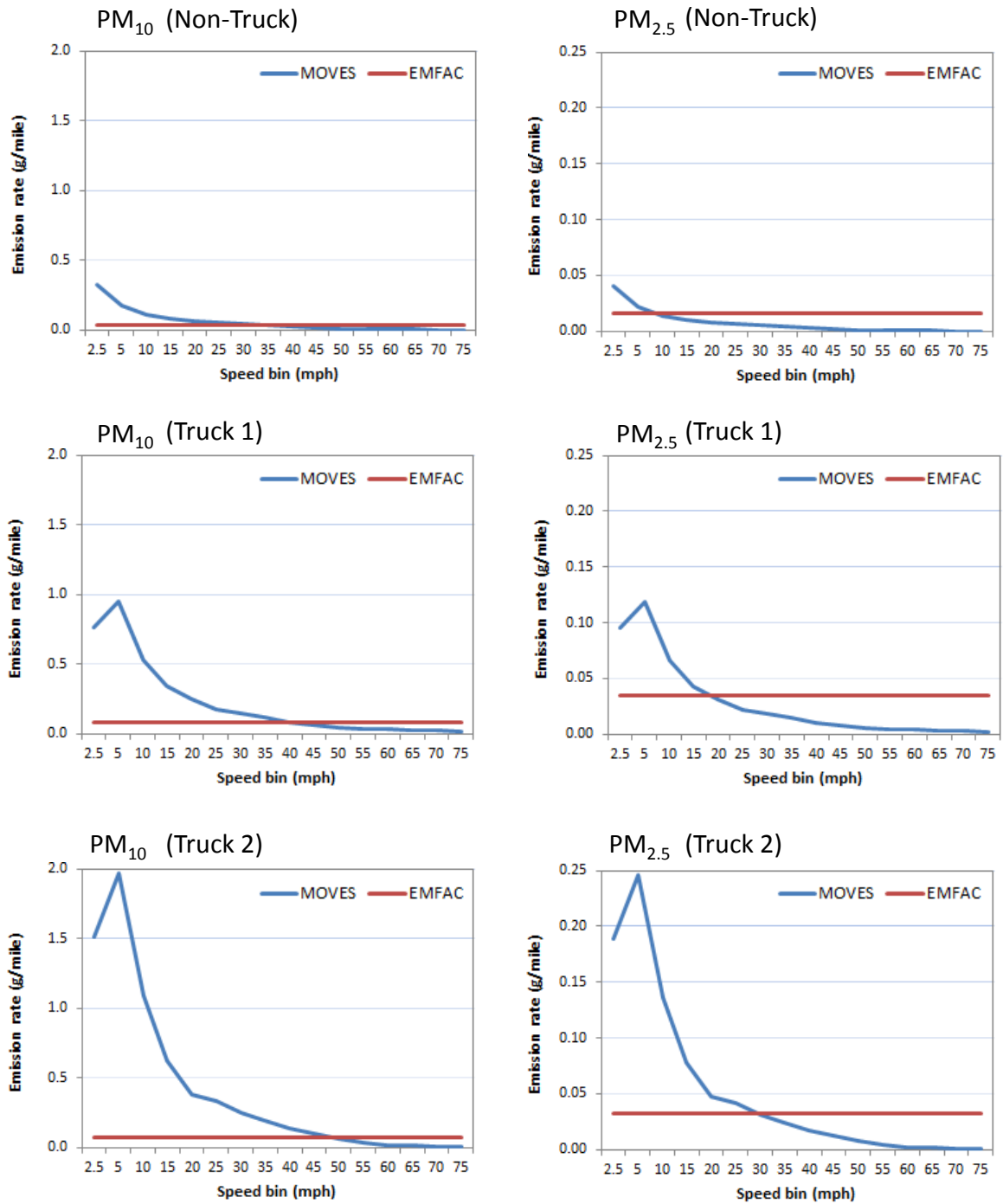


Figure 4. MOVES and EMFAC brake wear PM₁₀ and PM_{2.5} emission rates for Non-Truck, Truck 1 (light heavy-duty trucks) and Truck 2 (medium and heavy heavy-duty trucks).

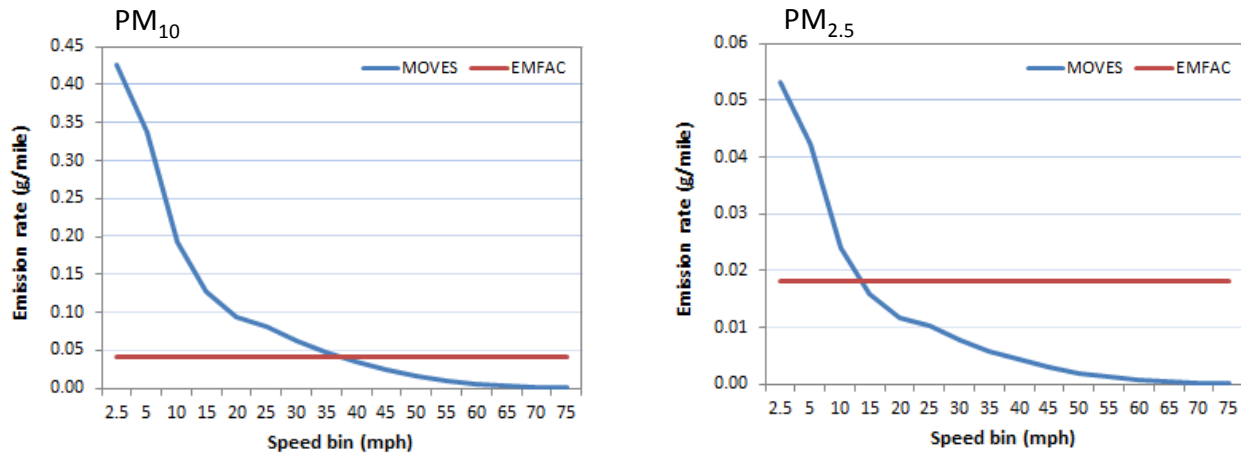


Figure 5. MOVES and EMFAC fleet-average brake wear PM₁₀ and PM_{2.5} emissions (assumes a hypothetical vehicle fleet with 8% trucks).

Tire Wear Modeling Differences Between MOVES and EMFAC

1. Data Sources

MOVES and EMFAC base emission rates for tire wear were derived from limited data sources. MOVES tire wear data is primarily from two studies that measured tire weight loss (Luhana et al., 2004; Kupiainen et al., 2005). EMFAC tire wear data is from a study published in 2000 based on data adopted from EPA's 1995 particulate emission factors model (PART5). Note that PART5 is an outdated model originally distributed by the Office of Transportation and Air Quality (OTAQ) of EPA in August 1995; to estimate PM emissions from highway vehicles, EPA replaced the PART5 model with the MOBILE model, which was later replaced with the MOVES model. Due to their different data sources, the base tire wear emission rates in MOVES and EMFAC are different, as illustrated by the sample data for LDVs and HHDTs shown in [Tables 6 and 7](#). In both models, base tire wear emission rates are independent of road type, model year, and meteorology (e.g., temperature and relative humidity). In MOVES, base tire wear emission rates are quantified in units of g/hr and, as with brake wear emissions, tire wear emissions vary by vehicle speed. In EMFAC, base tire wear emission rates vary only by vehicle and fuel type. In both models, heavy-duty vehicles have higher per-mile tire wear emission rates than light-duty vehicles (mainly due to the assumptions that heavy-duty vehicles have more tires than light-duty vehicles).

Table 6. Base tire wear PM_{2.5} emission rates (g/hr and g/mi) for LDVs and HHDTs in MOVES (U.S. Environmental Protection Agency, 2014).

Speed Bin (mph)	LDV (g/hr)	LDV (g/mi)	HHDT (g/hr)	HHDT (g/mi)
2.5	0.006355	0.005084	0.023655	0.018924
5	0.012020	0.002404	0.044740	0.008948
10	0.022310	0.002231	0.083050	0.008305
15	0.031065	0.002071	0.115635	0.007709
20	0.038440	0.001922	0.143120	0.007156
25	0.044600	0.001784	0.166050	0.006642
30	0.049680	0.001656	0.184950	0.006165
35	0.053795	0.001537	0.200305	0.005723
40	0.057080	0.001427	0.212480	0.005312
45	0.059580	0.001324	0.221850	0.00493
50	0.061450	0.001229	0.228800	0.004576
55	0.062755	0.001141	0.233640	0.004248
60	0.063540	0.001059	0.236580	0.003943
65	0.063895	0.000983	0.237900	0.00366
70	0.063910	0.000913	0.237790	0.003397
75	0.063525	0.000847	0.236475	0.003153

Table 7. Base tire wear PM_{2.5} emission rates in EMFAC (California Air Resources Board, 2015a).

Vehicle Type	Emission Rate (g/mi)
LDVs, LDTs, and MDVs	0.002
LHDT (Gas)	0.002
LHDT (Diesel)	0.003
MHDT (Gas)	0.003
MHDT, MH, OBUS (Diesel)	0.004
HHDT (Gas)	0.005
HHDT (Diesel & Natural Gas)	0.009
Urban Buses (Diesel)	0.003
School Buses (Gas)	0.002
Motorcycles	0.001

2. Modeling Assumptions

Table 8 summarizes the key assumptions made in MOVES and EMFAC for developing the base tire wear emission rates. The MOVES calculation approach for tire wear emissions is based on a regression model fitted with LDV tire weight loss rates (g/mile) against average vehicle speed (mph). MOVES also assumes zero tire wear emissions for vehicle idling. Tire wear emissions for other vehicle types are adjusted from LDV emission rates using scaling factors. The EMFAC approach is based on a simplified calculation of multiplying a constant per-wheel airborne PM emission rate by the average number of wheels.

Table 8. Comparison of modeling assumptions for base tire wear emission rates.

Components	MOVES	EMFAC
Base pollutant	PM _{2.5}	PM ₃₀
Unit	Gram per hour	Gram per mile
Variation	Varies by vehicle type and operating mode (speed)	Varies by vehicle type and fuel type
Number of wheels	Assumed for different vehicle types	Assumed for different vehicle types and fuel types
PM ₁₀ to PM _{2.5} factor ^a	6.667	4
Basic modeling method	Regression curve fitted with tire weight loss rates (g/mile) against average speed (mph) for LDVs; scaling factors applied for other vehicle types; assuming total tire wear per vehicle is a function of the number of tires per vehicle	Multiplying a constant per-wheel airborne PM emission rate (0.002 g/mile/wheel) by the average number of wheels for each vehicle/fuel type

^aThe MOVES PM₁₀ to PM_{2.5} ratio is based on more recent information (2005 data) than the information used to support the ratio in EMFAC (pre-2000 data) (Kupiainen et al., 2005) (California Air Resources Board, 2010).

Comparisons of MOVES and EMFAC LDV and HHDT base PM₁₀ and PM_{2.5} tire wear emission rates are presented in **Figures 6 and 7**. Similar to what was shown earlier regarding brake wear emissions, g/mi MOVES base tire wear emission rates decrease by speed, while EMFAC base tire wear emission rates are constant across all travel speeds for specific vehicles and fuel types. EMFAC rates include higher tire wear emissions from diesel vehicles than gasoline vehicles (with the assumption that diesel vehicles typically have more tires than gasoline vehicles).

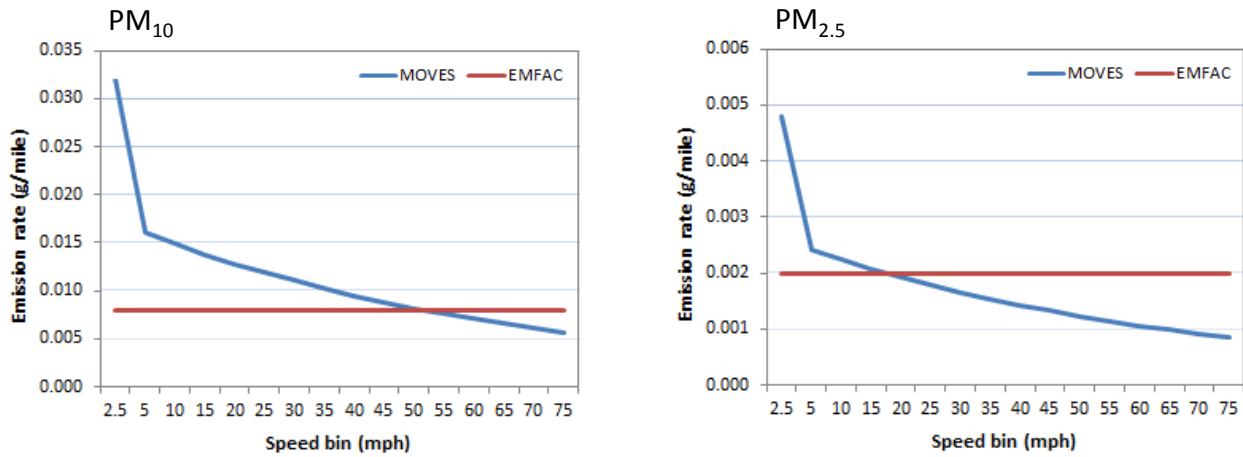


Figure 6. MOVES and EMFAC base tire wear PM₁₀ and PM_{2.5} emission rates for LDVs.

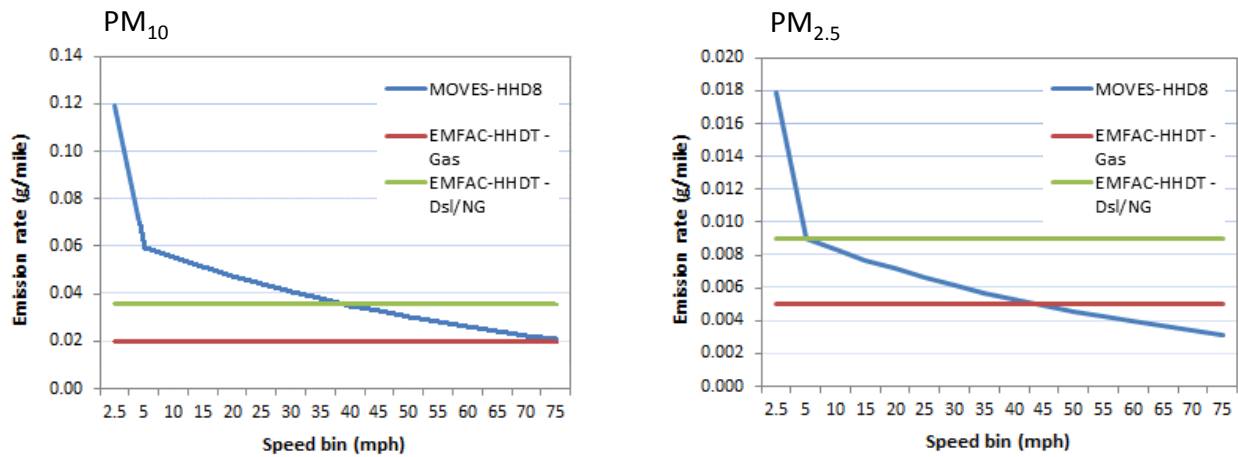


Figure 7. MOVES and EMFAC base tire wear PM₁₀ and PM_{2.5} emission rates for HHDTs.

3. Illustration of Tire Wear Modeling Differences with a Hypothetical Case

Average g/mi tire wear emission factors for three vehicle categories and a hypothetical fleet with 8% trucks are presented in Figures 8 and 9. Main findings include:

- EMFAC g/mi tire wear emissions do not vary by speed; therefore project-level tire wear emissions are proportional to vehicle miles. As with brake wear emissions, and absent changes to the fleet mix, project analyses that involve congestion relief and travel speed changes will not result in varying g/mi tire wear emission rates.
- Compared to MOVES emission rates, EMFAC g/mi tire wear emissions are lower in low-speed bins but higher in high-speed bins.

- The EMFAC fleet average tire wear PM₁₀ emission factor (for the 8% fleet scenario) is similar to MOVES factors associated with 50-55 mph vehicle speeds; however, for PM_{2.5}, the EMFAC tire wear emissions factor is similar to MOVES factors for 15-20 mph vehicle speeds.

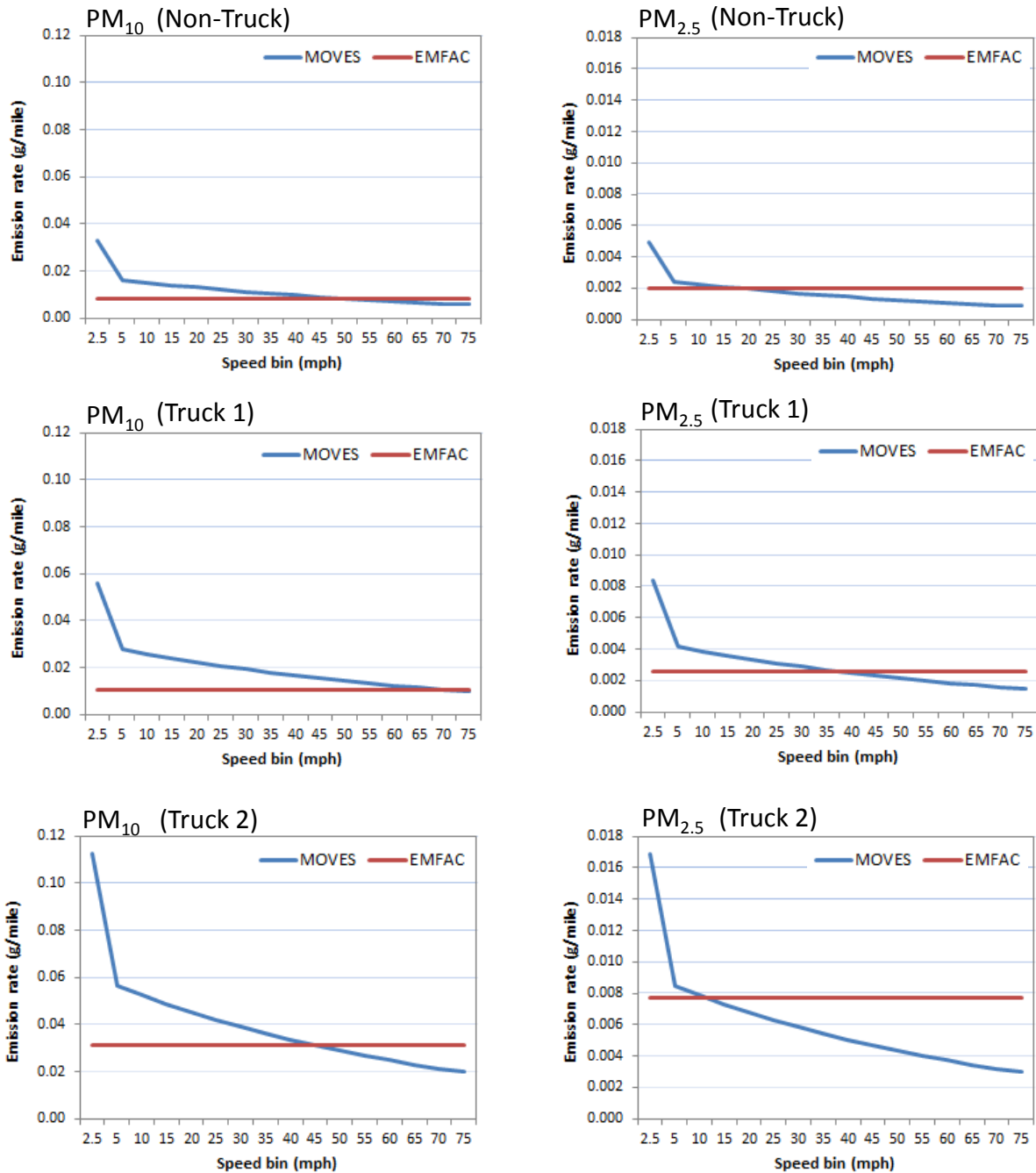


Figure 8. MOVES and EMFAC tire wear PM₁₀ and PM_{2.5} emission factors for Non-Truck, Truck 1 (light heavy-duty trucks) and Truck 2 (medium and heavy heavy-duty trucks).

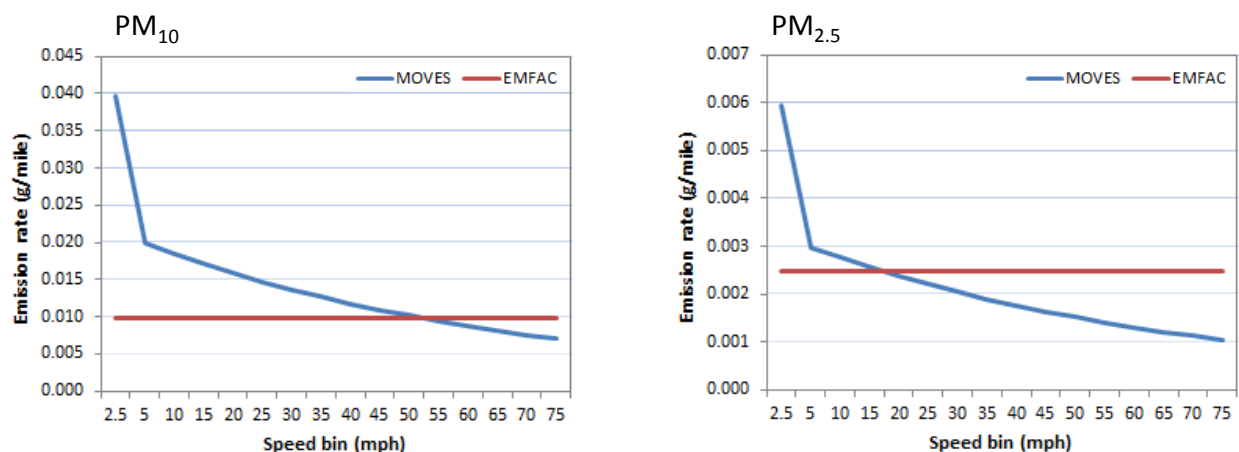


Figure 9. MOVES and EMFAC fleet-average tire wear PM_{10} and $PM_{2.5}$ emission factors.

Brake Wear and Tire Wear Data: Future Potential Changes

In this section, we discuss potential future changes in brake wear and tire wear emissions due to anticipated penetration of advanced technology vehicles and changes in response to recent regulations.

Brake Wear

1. Regenerative Braking

In recent years, alternative braking systems have been applied to advanced technology vehicles such as electric and hybrid light-duty vehicles and trucks. An important example of an alternative braking system (different from the traditional disc or drum braking) is regenerative braking. The regenerative brake is an energy recovery mechanism which slows a vehicle by converting kinetic energy into electricity and storing the power for later use (for example, in batteries). This contrasts with conventional braking systems, where the excess kinetic energy is converted to heat by friction in the brakes which causes brake wear dust emissions (California Air Resources Board, 2015b).³

Currently, neither EMFAC nor MOVES provides estimates of brake wear emissions from vehicles with regenerative braking. To evaluate the emission impacts from regenerative braking, we designed a set of test case scenarios and estimated fleet average emission rates with and without regenerative braking. For the test scenarios, the following assumptions were made.

³As noted by the California Air Resources Board (CARB) in a November 2015 report on heavy-duty hybrid vehicles, "Regenerative braking also extends the life of the brakes therefore reducing the operating and maintenance costs of the vehicle. Many fleets are reporting greatly extended brake maintenance intervals, especially in severe-duty, stop-and-go vocations such as refuse haulers and inner-city transit buses, which result in much fewer brake replacements over the hybrid vehicle's life. *Reduced brake wear also contributes to reduction of near-road exposure to brake dust emissions.*" [emphasis added]. See pp II-1 to II-2 in: http://www.arb.ca.gov/msprog/tech/techreport/hybrid_tech_report.pdf.

- Fresno, California was selected as the modeling area and 2015 and 2050 were selected as the modeling years.
- For the “Base” scenarios, no regenerative braking system was assumed in the fleet. In other words, the penetration rate of regenerative braking was assumed to be zero. For the scenarios called “EV30,” we assumed 30% of the light-duty fleet to be electric or hybrid vehicles equipped with a regenerative braking system (i.e., a penetration rate of 30% for regenerative braking). The EV30 scenarios were based on a forecast by the California Energy Commission (CEC) that by 2050 up to 30% of the LDV California fleet will be electric or hybrid vehicles (Bahreinian, 2013).⁴ We used a 30% regenerative braking penetration rate in both the 2015 and 2050 analysis years to test whether the analysis results were influenced by fleet composition shifts over time (meaning shifts in the percentage of the total vehicle fleet assumed to be LDVs).
- To test for the maximum impact of LDV regenerative braking use, the brake wear emission rate for the 30% of LDVs with regenerative braking was set to zero in both MOVES and EMFAC. One exception in MOVES involved emission rates at speeds lower than 10 mph. For the MOVES-based emissions, we applied gasoline-powered LDV emission rates for travel under 10 mph; this is because some literature indicates that conventional braking is still required during very low speed conditions (Cody et al., 2009).

Analysis results are shown in [Figure 10](#). With 30% regenerative braking penetration, EMFAC estimated an emission benefit of approximately 30% in both 2015 and 2050, while MOVES estimated emission benefits ranging from 13% to 30% in 2015 and 10% to 28% in 2050 (MOVES results vary with varying speeds). MOVES data suggest that the largest absolute brake wear emission reduction benefits of regenerative braking occur at lower speeds of less than 30 mph.

⁴ The CEC also forecasted that up to 17% of the heavy-duty fleet would be diesel-electric hybrids by 2050 (McBride, 2015); in this analysis, we did not evaluate scenarios with heavy-duty vehicles equipped with regenerative braking. For analysis purposes other than assessing brake wear, current versions of MOVES and EMFAC assume penetration into the vehicle fleet of light-duty electric and hybrid vehicles; neither model currently includes heavy-duty electric and hybrid vehicles in future-year default vehicle fleets.

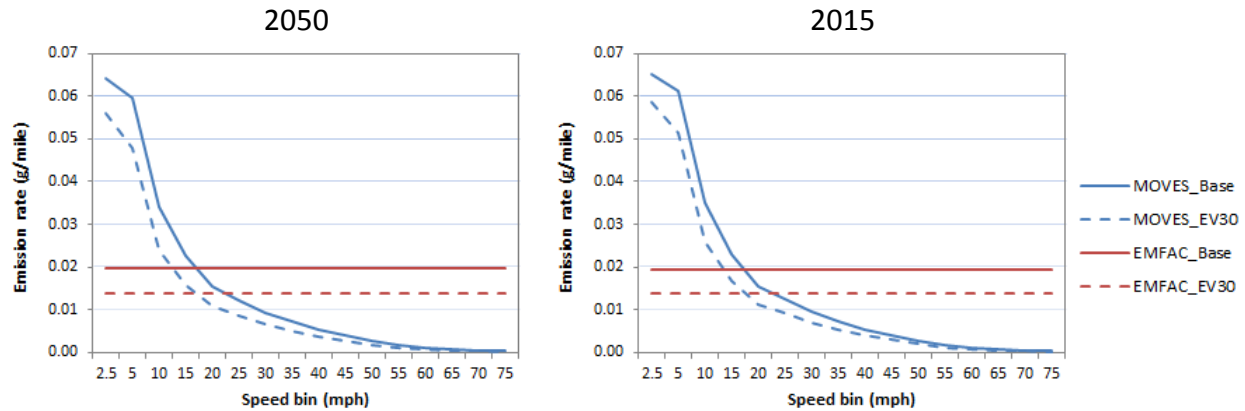


Figure 10. MOVES and EMFAC fleet-average brake wear $PM_{2.5}$ emission rates with and without considering regenerative braking technology for a Fresno, CA hypothetical case.

2. Reduced Stopping Distance Regulation

In 2009, the National Highway Traffic Safety Administration (NHTSA) announced Federal Motor Vehicle Safety Standard (FMVSS) 121, to require Reduced Stopping Distance (RSD) for heavy-duty trucks. The RSD regulation requires a 30 percent reduction in the maximum stopping distance for the vast majority of new heavy truck tractors—from 355 feet to 250 feet—phased-in over the 2011 to 2013 model years.⁵ The RSD requirements have encouraged development of different brake materials and front axle brake configurations, as described below, that may influence brake wear emissions.

- **Brake materials:** Among some manufacturers, there is a trend to shift brake linings to semi-metallic materials to obtain better stopping power at high temperature (NUCAP Brakes, 2011). In the aftermarket sales of brake parts, increased use of semi-metallic brakes has also been observed for parts sales related to higher-end vehicles (Global Industry Analysts Inc., 2015). Use of semi-metallic brakes has been shown to result in the release of more airborne dust than other brake types such as metallic and ceramic brakes. Therefore if semi-metallic brake use increases in response to the RSD requirement, it is likely that brake wear emissions will increase for at least some vehicles. Further research is needed for quantifying the impact of brake materials on brake wear emissions at both regional and project levels.
- **Brake size:** In response to the RSD requirements, larger-sized brakes with more brake lining surface area have been phased into some of the truck fleet (e.g., 16.5x5-in. and 16.5x7-in. brakes, in comparison to 15x4-in. brakes). The PM emissions impact from a shift to larger brake sizes is uncertain. Larger brakes likely mean larger brake pad surfaces that, when worn, may generate more brake wear PM than smaller brake pads; however, larger brake surfaces may also help dissipate heat generated from friction, and reduced heat might reduce brake pad wear (Sturgess, 2010; Skydel, 2014).

⁵ See: <http://www.nhtsa.gov/Laws+&+Regulations/Brakes>.

- *Hazardous material restrictions:* Effective January 1, 2014, California legislation (SB 346) regulated the hazardous material content in brake pads. The goal was to reduce the copper weight content of brake pads to 5% by 2021 and 0.5% by 2025. Other states are currently considering similar legislation (Centric Parts, 2012).⁶ Potentially, the new requirement could change the chemical composition and size distribution of brake wear PM emissions (e.g., the PM_{2.5} to PM₁₀ mass ratio), although as of this writing there was no definitive data or information to help forecast the brake wear emissions implications.

Tire Wear

This discussion highlights technology and regulatory issues that likely have an impact on tire wear PM emissions. However, there is insufficient information to indicate the overall effect of these issues on fleet-average tire wear PM emissions.

1. Advanced Technology

A portion of tires sold either separately or as original vehicle equipment are designed to reduce rolling resistance and improve fuel economy. However, there is some evidence that low rolling resistance tires may wear more quickly, resulting in increased tire wear emissions rates. Rolling resistance consumes about 4% to 7% of the energy expended by a vehicle (Transportation Research Board, 2006). For passenger vehicles, a 10% reduction in rolling resistance has been estimated to lead to a 1% to 2% increase in fuel economy; this approximation has been included in studies of tire rolling resistance that date from the 1980s (Sandberg, 1997) to more recent work by NHTSA (Evans et al., 2009). A 2003 CEC study estimated that adoption of low rolling resistance tires could reduce gasoline consumption 1.5 to 4.5% (Larson et al., 2003). A 2009 NHTSA study found that if 2% of replacement tires reduced rolling resistance by 5%, there would be 7.9 million gallons of fuel and 76,000 metric tons of CO₂ saved annually (National Highway Traffic Safety Administration, 2009). Federal requirements to achieve higher Corporate Average Fuel Economy (CAFE) standards have led to greater use of reduced rolling resistance tires; low rolling resistance tires are frequently standard equipment for electric and hybrid vehicles. California mandates the use of low rolling resistance tires on heavy-duty trucks (California Air Resources Board, 2014). Notwithstanding their fuel economy and CO₂ emissions benefits, some studies have observed that low rolling resistance tires wear out more quickly (Witzenburg, 2014; Campbell, 2015), although earlier work by NHTSA found mixed results (Evans et al., 2009; National Highway Traffic Safety Administration, 2010). If all or some subset of low rolling resistance tires wear out more rapidly than conventional tires, then it would follow that their tire wear PM emission rates would be greater. The impact, if any, on fleet-average tire wear PM emissions would be a function of the penetration rate of low rolling resistance tires into the vehicle fleet.

In addition to changes in rolling resistance, tire size changes may be affecting PM emissions. Some industry professionals have observed that demand for larger wheel sizes is increasing for both cars and trucks (Campbell, 2014). This suggests the surface areas of tires might be increasing as well,

⁶ Similar legislation took effect January 1, 2015, in the state of Washington.

although the impact on tire wear emissions would depend on several factors, such as rolling resistance. Overall, changes in tire technology and potential shifts in tire purchasing trends may be having an impact on tire wear PM emissions. However, these impacts are too uncertain to quantify at this time.

2. Standards/Regulations

Tire under-inflation results in more tread wear loss. For example, statistics from Firestone Tire and Rubber Company indicate that under-inflation of 25% could cause 40% more tread wear loss.⁷ Various studies have shown that greater than 25% of in-use vehicles have underinflated tires (e.g., Waddell, 2008; Pearce and Hanlon, 2007; Ratrout, 2005; Thiriez and Boudy, 2001). However, neither EMFAC nor MOVES considers impacts from tire under-inflation on tire wear PM emissions. NHTSA's FMVSS Tire Pressure Monitoring Systems (TPMS) Rule required installation of a TPMS capable of detecting when one or more of the vehicle's tires is 25 percent or more below the manufacturer's recommended inflation pressure, or when a minimum activation pressure specified in the standard is reached, whichever is higher.⁸ As of this writing, insufficient data were available to quantify to what extent fleet penetration of TPMS-equipped vehicles has reduced under-inflation, and how that relates, if at all, to actual and modeled fleet-average tire wear PM emissions.

Brake Wear and Tire Wear Modeling: Major Findings and Recommendations

The two official models used to estimate on-road emissions—MOVES and EMFAC—treat brake and tire wear differently, and apportion different amounts of brake and tire wear PM₁₀ to the PM_{2.5} size category. In general, for future analysis years EMFAC-based brake and tire wear estimates are higher than those produced by MOVES, especially for brake wear emissions and for PM_{2.5}.

Current brake and tire wear data are based on a limited number of studies, many of which were completed more than a decade ago prior to technology and regulatory changes affecting current and future vehicle fleets. As a result, modern vehicle, brake, and tire technologies are not effectively represented in the data used to develop MOVES and EMFAC brake and tire wear PM emissions.

As a general observation, EMFAC produces brake wear emissions that are far greater than tire wear emissions, and produces PM_{2.5} emissions which are far greater than emissions produced by MOVES. Therefore it is a high priority to assess and improve EMFAC-based brake-related emissions estimates. Major findings and recommendations include

- **MOVES varies brake and tire wear emissions by travel speed; EMFAC does not.** EMFAC brake and tire wear emission factors were developed primarily to support regional emissions inventory development, for which average travel speeds were considered sufficient to

⁷ See: <http://www.tireqp.com/nahitrsaadn.html>

⁸ The requirement affects 2007 and later vehicles; see: <http://www.nhtsa.gov/cars/rules/rulings/tpmsfinalrule.6/tpmsfinalrule.6.html>.

characterize regionally-averaged conditions. At the project level, speed-based emission factors offer the opportunity to assess emissions differences among various project alternatives that modify forecasted travel volumes, fleet mix, and speeds. For example, assume a build-project alternative reduced peak-period congestion and improved traffic flow from 10-15 mph to 30-35 mph. As shown in Figures 2 and 3, use of MOVES-based emission factors, which adjust for speed changes, would result in build-scenario brake-wear g/mi PM emission rates about 50% less than no-build rates; EMFAC-based results would show no change in g/mi emissions. Note that speed-based emission factor differences included in MOVES apply to all analysis years. *Thus, the most important recommendation emerging from our assessment is to examine whether EMFAC-based emissions can be speed-adjusted using the technical information employed by EPA to develop MOVES speed-varying emissions factors. Given the overwhelming importance of brake wear compared to tire wear emissions (see Figure 1), this examination should focus on brake wear emissions.*

- **Electric and hybrid-electric vehicles employ regenerative braking systems to recharge batteries; qualitatively, these systems are expected to reduce the wear-rate of brake pads.** Neither MOVES nor EMFAC takes into consideration how regenerative braking affects brake wear emissions. The importance of this issue increases over time, since the vehicle fleet is forecasted to include a greater fraction of advanced technology vehicles in coming years. The CEC, for example, forecasts that up to 17% of the truck fleet and up to 30% of the light-duty fleet will be electric or hybrid vehicles by 2050. The impact of this issue is relatively small for current and near-term analysis years, and larger over time with fleet turnover. *Thus, there is an important need to quantitatively adjust EMFAC-based brake-wear emissions rates to account for forecasted regenerative braking systems use.*
- **Numerous other factors can affect brake or tire wear emissions that are not fully characterized by either MOVES or EMFAC.** However, collectively they are likely to account for only a small fraction of overall PM emissions, or are likely to have minimal impact on build vs. no-build project comparisons, and are therefore lower priority issues. For brake wear, factors include the federal requirements to reduce the stopping distance of trucks. For tire wear, factors include the growing use of lower rolling resistance tires, efforts to reduce under-inflation of tires in-use, and potential increase in the use of larger-sized tires over time. For both brake and tire wear, factors include the differences between the EPA and CARB assumptions about the fraction of PM_{10} that is $PM_{2.5}$ (EPA ratios are based on more recent data and result in reduced $PM_{2.5}$ values as a fraction of PM_{10}). *Although all of the factors discussed introduce uncertainty into the emissions modeling process, they are less important to address than brake wear emissions variation by travel speed and the emissions impact on brake wear from regenerative braking systems. It may be possible to update PM_{10} to $PM_{2.5}$ ratios rather easily to reflect more recent information; such an update may assist project analyses in build vs. no-build situations where background PM concentrations are not already above the PM NAAQS.*

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15. Abstract Exhaust particulate matter (PM) emissions are declining substantially; brake and tire wear PM emissions are becoming a larger fraction of on-road PM. However, modeling of brake and tire wear is based on limited literature, and the official models—MOVES and EMFAC—treat brake and tire wear differently. Future-year EMFAC-based brake and tire wear estimates are higher than those produced by MOVES, especially for brake wear and for PM _{2.5} . MOVES varies brake and tire wear emissions by travel speed; EMFAC does not. It is important to examine whether EMFAC-based emissions can be speed-adjusted. Given the overwhelming importance of brake wear compared to tire wear emissions, future examinations should focus on brake wear emissions.			
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