Brake and Tire Wear Emissions from Onroad Vehicles in MOVES5

EPA United States Environmental Protection Agency

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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List of Acronyms

AMS	Auto Motor Sports magazine
CARB	California Air Resources Board
CBDC	California Brake Dynamometer Cycle
CMB	Chemical Mass Balance
CNG	Compressed Natural Gas
ELPI	Electrical Low Pressure Impactor
EMFAC	California Air Resources Board (CARB)'s on-road vehicle emissions model
EPA	U.S. Environmental Protection Agency
ERG	Eastern Research Group
ETW	Equivalent Test Weight
EV	Electric Vehicle
FTP	Federal Test Procedure
GHG	Greenhouse Gas
HD	Heavy-Duty
HHD	Heavy-Heavy-Duty
HDIUT	Heavy-Duty In-Use Testing
HLW	Heavily Loaded Weight
ICE	Internal Combustion Engine
LD	Light-Duty
LDT	Light-Duty Trucks
LDV	Light-Duty Vehicle
LHD	Light-Heavy-Duty
LM	Low-Metallic
MC	Motorcycle
MHD	Medium-Heavy-Duty
MOBILE	MOVES precursor
MOUDI	Micro-Orifice Uniform Deposition Impactor
MOVES	Motor Vehicle Emission Simulator Model

MY	Model Year
NAO	Non-Asbestos Organic
PART5	MOVES precursor for PM_{10} and $PM_{2.5}$ emissions
PERE	Physical Emission Rate Estimator
PM	Particulate Matter
$PM_{2.5}$	Particulate matter with mean aerodynamic diameter less than 2.5 µm
PM_{10}	Particulate matter with mean aerodynamic diameter less than 10 µm
RWD	Rear-wheel drive
SIP	State Implementation Plan
STP	Scaled Tractive Power
UDP	Urban Driving Program
VMT	Vehicle Miles Traveled
VSP	Vehicle Specific Power

1 Introduction

The United States Environmental Protection Agency's Motor Vehicle Emission Simulator—commonly referred to as MOVES—is a set of modeling tools for estimating air pollution emissions produced by onroad (highway) and nonroad mobile sources. MOVES estimates the emissions of greenhouse gases (GHGs), criteria pollutants and selected air toxics. The MOVES model is currently the official model for use for state implementation plan (SIP) submissions to EPA and for transportation conformity analyses outside of California. The model is also the primary modeling tool for estimating the impact of mobile source regulations on emission inventories.

The mobile source particulate matter inventory includes exhaust emissions and non-exhaust emissions. Exhaust emissions include particulate matter attributable to engine related processes such as fuel combustion, burnt oil, and other particles that exit the tailpipe. Non-exhaust processes include brake wear, tire wear, suspension or resuspension of road dust, and other sources. Particulate matter from brakes and tires is defined as the airborne portion of the "wear" that can be created by abrasion, corrosion, and turbulence. These wear processes can result in particles being suspended in the atmosphere. The size, chemical composition, and emission rate of particles arising from such sources contributes to atmospheric particle concentrations. However, these particles have different chemical composition and size than exhaust particulate matter.[1]

MOVES estimates $PM_{2.5}$ and PM_{10} emissions from brake and tire wear from onroad vehicles as documented in this report. MOVES does not speciate the $PM_{2.5}$ emissions from brake and tire wear. To provide estimates of speciated $PM_{2.5}$ emissions for the national emissions inventory and to provide input for air quality modeling, the EPA applies brake and tire wear SPECIATE profiles outside of MOVES as documented in the MOVES speciation report.[2] MOVES does not estimate emissions from road-dust. EPA estimates of road-dust emissions are in AP-42.[3]

This report was first drafted in 2008, based on a literature review conducted in 2006 and 2007. The algorithms and values discussed here were incorporated into MOVES2009 and carried over into later versions (MOVES2010a, MOVES2010b, MOVES2014) with little to no changes. The report was peer reviewed in 2014 as documented in the MOVES2014 report.[4]

In MOVES3, the brake and tire wear models remained essentially the same as MOVES2014 and earlier versions. However, there were two general updates worth noting with respect to brake wear and tire wear emissions.

> 1) In MOVES3, we consolidated the MOVES2014 vehicle regulatory classes LHD <= 10k and LHD <=14K into the MOVES3 LHD2b3 regulatory class (as discussed in the MOVES3 heavy-duty exhaust emission rate report[5]). We applied the brake and tire wear emission rates from the MOVES2014b LHD <= 10k regulatory class to represent the emission rates of the LHD2b3 regulatory class in MOVES3. MOVES3 also added the glider regulatory class, which are heavy heavy-duty (HHD) trucks with an old powertrain combined with a new chassis and cab assembly. Because the body of a glider truck is assumed to be the same as HHD vehicles, they are modeled with the same brake and tire wear emission rates. Additional details are discussed in Section 2.2.3.

2) MOVES3 also introduced modeling of “off-network idle,” accounting for the additional running emissions from vehicle idle operation occuring off the road network in areas such as parking lots, transit/distribution centers, etc. MOVES does not model off-network idle or extended idle emissions for brake or tire wear because the vehicle is completely stopped during this non-drive-cycle idle time. Additional details on brake wear during idling are discussed in Section 2.2.5.3.

No updates were made for MOVES4, but in MOVES5, we have updated the brake wear emission rates for both light and heavy-duty vehicles for model years 2011 and later. The new rates are developed using measurements from brake dynamometer emissions testing of brake systems representative of modern vehicles. The pre-2011 base rates remain unchanged, as they represent older generations of braking technology.

2 Brake Wear

There are two main types of brakes used in conventional (or non-hybrid electric) vehicles: disc brakes and drum brakes. In a drum brake, the components are housed in a round drum that rotates with the wheel. Inside the drum are “shoes” that press against the drum and slow the wheel. By contrast, disc brakes use an external rotor and caliper to halt wheel movement. Within the caliper are brake pads on either side of the rotor that clamp together when the brake pedal is pressed.[6] Both types of brakes use frictional processes to resist inertial vehicle motion. The action of braking results in wear and consequent release of a wide variety of materials (elemental, organic and inorganic compounds) into the environment.

Brake wear has multiple definitions in the literature. In this paper it refers to the mass of material lost from the brake pads. A fraction of that wear is airborne particulate matter (PM). MOVES models only PM <=10 µm, (PM_{10}). Some studies look at both wear and airborne PM, others look at one or the other. In brakes, the composition of the brake lining has an influence on the quantity and makeup of the released particles. Disc brakes are lined with brake pads while drum brakes use brake-shoes or friction linings. These materials differ in their rate of wear, the portion of wear particles that become airborne, and the size as well as composition of those particles.

The overall size or mass of the brake pads also varies with vehicle type. Typically, trucks use larger brakes than passenger vehicles because their mass is greater. In 2004, most light duty vehicles used disc brakes in the front and drum brakes in the rear. Disc brakes tend to have improved braking performance compared to drum brakes and have correspondingly higher cost.

As a complicating issue, the particulate matter from brakes is dependent on the geometry of the brakes, wheels and rims. The air flow through the rims to cool the brakes and rotors play a key role in determining the wear characteristics. The emissions are also sensitive to driver activity patterns; more aggressive stop and go driving will naturally cause greater wear and emissions.

In MOVES, brake wear rates are stored in the EmissionRate table. As such, we assume that brake wear emissions do not change with vehicle age. In the EmissionRate table, brake wear is indicated by polProcessID = 11609 which refers to the Pollutant ID 116 (Primary $PM_{2.5}$ – Brakewear Particulate) and the process ID 9 (Brakewear). In the EmissionRate table, the meanBaseRate specifies the average mass-rate of emissions that are released per unit time in each operating mode (as explained in Section 2.2.5).

For brake wear, the meanBaseRateIM value is the same as meanBaseRate since I/M programs do not include brake wear. In MOVES, PM_{10} emissions are derived from $PM_{2.5}$ using the PM10PM25ratio value stored in the PM10EmissionRatio table.

2.1 Literature Review (2006-2007)

There are a very limited number of publications on brake wear PM emissions. There are even fewer publications discussing size distributions and speciation, and none quantifying emissions modally on which to directly base a model. This section summarizes the limited literature as of 2006. More details of the literature on brake and tire wear can be found in Appendix B. One of the earliest studies on brake wear emissions was done in 1983.[7] Particulate emissions from asbestos-based brakes from automobiles were measured under conditions simulating downtown city driving. The report presented a systematic approach to simulating brake applications and defining particulate emissions and was used in the development of the EPA PART5 model.[8] For PART5, EPA calculated PM_{10} emission factors for light-duty gasoline vehicles of 12.5 mg/mi for brake wear. Since 1985, the asbestos in brakes has been replaced by other materials, and newer studies have been conducted.

Garg et al. (2000)[9] conducted a study in which a brake dynamometer was used to generate wear particles under four wear conditions (much of the background information provided in the section introduction are from this paper). The study was performed using seven brake pad formulations that were in high volume use in 1998. Measurements were taken on both front disc as well as rear drum brakes. The study measured mass, size distribution, elemental composition, as well as fiber concentration at four temperature intervals. The report also estimated $PM_{2.5}$ and PM_{10} emissions for light-duty vehicles of 3.4 and 4.6 mg/mile, respectively for small vehicles, and $PM_{2.5}$ and PM_{10} emissions of 8.9 and 12.1 mg/mile, respectively for pickup trucks.

Sanders et al (2003)[10] looked at three more current (as of ~2003) classes of lining materials: low metallic, semi-metallic and non-asbestos organic (NAO) representing about 90 percent of automotive brakes at that time. In their dynamometer tests, three lining type/vehicle combinations (low metallic/mid-size car, semi-metallic/full-size truck, and non-asbestos organic/full-size car) were subject to two sets of braking conditions: the urban driving program (UDP) with a set of 24 stops which represent relatively mild braking (≤ 1.6 m/s^2) at relatively low speed (<90 km/h); and the Auto Motor and Sport magazine (AMS) test representing harsh braking conditions consisting of 10 consecutive 7.9 m/s^2 stops from 96 km/h. In addition to the dynamometer tests, the authors also reported two other testing scenarios: (a) a wind tunnel test where a series of 1.8 m/s^2 stops from 96 km/s of a full-size car with low metallic brakes were conducted; (b) test track testing of the same vehicle where stops from 60 mph at 0.15, 0.25 and 0.35 g-forces were conducted with low metallic and NAO brakes. The major findings from those tests were:

- The mean particle size and the shape of the mass distribution are very similar for each of the three linings.
- The wear rates are material dependent: the low metallic linings generate 3-4 times the number of wear particles compared to semi-metallic and NAO linings.
- 50-70 percent of the total wear material was released in the form of airborne particles.
- The wear (and portion of wear that is airborne PM emissions) increased non-linearly with higher levels of deceleration.

- The most abundant elements in brake wear debris composition were Fe, Cu, Si, Ba, K and Ti, although the relative composition varied significantly by brake type.

Table 2-1 contains the emission rates derived from the literature review conducted in support of MOVES2009. While there are emission rates presented from other papers, this paper largely relies on the Sanders et al. paper as it includes the widest array of materials in use at the time of analysis, measurement techniques, and deceleration ranges in a scientifically designed study. It is the only paper from which modal rates can be derived. It is also the most recent of the papers listed and improves on the measurement methods introduced in its predecessors. The other papers results are provided as a source of comparison. Note that the range of rates from Sanders et al. (2003) largely covers the range presented in the other papers as well. When determining the MOVES rates, the values from Garg et al. (2000), are also used.

Table 2-1 Non-Exhaust PM Emissions (per vehicle) from mobile sources literature values of emission factors from brake lining wear (largely cited in Luhana et al. (2004)'s literature review)

Literature Source	Vehicle Type	$PM_{2.5}$ [mg/km]	PM_{10} [mg/km]
Luhana et al. (2004)	Light Duty		0-79
	Heavy Duty		0-610
Sanders et al. (2003)	Light Duty		1.5 -7.0
Abu- Allaban et al. (2003)	Light Duty	0 - 5	0-80
	Heavy Duty	0-15	0-610
Westurland (2001)	Light Duty		6.9
	Heavy Duty		41.2
Garg et al (2000)	Passenger Cars*	3.4	4.6
	Large Pickup Trucks	8.9	12.1
Rauterberg-Wulff (1999)	Passenger Cars		1.0
	Heavy Duty Vehicles		24.5
Carbotech (1999)	Light Duty		1.8-4.9
	Heavy Duty		3.5
Cha et al. (1983) used in PART5	Cars and Trucks		7.8

* In this table, "passenger cars" are equivalent to light duty cars. "Light Duty" on its own includes all light-duty vehicles, including trucks though the studies are not all equivalent in their definitions.

2.2 Developing Rates for MOVES

Prior to MOVES5, brake wear rates for all MOVES regulatory classes did not vary by model year. MOVES now estimates brake wear emission rates for two ranges of model years. For model years up to and including 2010, the base brake wear rates remain the same as those used in MOVES4. The analysis for these braking emission rates accounts for:

(1) Composition of brake pads
(2) Number (and type) of brakes
(3) Front vs rear braking
(4) Airborne fraction
(5) Particle mass size distribution ($PM_{2.5}$ vs PM_{10})
(6) Braking intensity
(7) Vehicle class: Light-Duty vs Heavy-Duty

For model years 2011 and later, a separate set of rates has been developed for MOVES5 based on testing of brake configurations representing a more modern fleet. Because the rates for the two model year ranges were developed using different methodologies, some underlying assumptions used to derive emission rates differ as well. In addition to the seven parameters listed above, the base emission rates for model years 2011 and later account for differences by fuel type to account for electric vehicles (EVs) that occupy an increasing share of the vehicle fleet and use regenerative braking.

Finally, because the new data sets do not cover motorcycle brakes, the base motorcycle brake wear emission rates in MOVES remain unchanged for all model years.

2.2.1 Emission Rates for Light-Duty Vehicles for Model Years Prior to 2011

As discussed in Sanders et al. (2003) which covers brake wear emissions from light-duty vehicles, most brake pads (at the time of the publication of that paper) are either low-metallic (mid-size car), semi-metallic (full-size light duty truck), or non-asbestos organic (full-size car). Using the results from this study, we make the following assumptions which are consistent with those used in the paper.

- equal mix of the three brake types
- four brakes per light duty vehicle, including two front disc brakes, and two rear drum brakes
- 2/3 of braking power (and thus emissions) in front brakes (1/3 rear)[a]
- the fraction of total PM below 2.5 µm is ~ 10 percent (+/-5 percent)[b]
- 60 percent of brake wear is airborne PM (+/- 10 percent).

[a] Based on discussions with Matti Mariq at Ford Motor Company (co-author of Sanders (2003)) and consistent with the Garg et al. (2000) paper, which used 70%. Some of the other assumptions in this list is also from these discussions.

[b] More will be discussed below.

We also do not compensate for the different average weights of the vehicles (though the MOVES VSP bins scale emissions with mass). We assume there is an equal mix of the three brake types because the market share penetration is not known.

2.2.1.1 Base Rates by Braking Intensity

For each test cycle from Sanders et al. (2003) and Garg et al. (2000), the following figures show how we went from the measured results to emission rates of g/hour (for deceleration times only) at various deceleration speeds. Sanders et al. (2003) used three measurement techniques, a filter, an Electrical Low Pressure Impactor (ELPI), and a Micro-Orifice Uniform Deposition Impactor (MOUDI). While all three measurement techniques produced similar results, we show all here. In Table 2-2 through Table 2-5, test results are shown for the UDP and wind tunnel tests from Sanders et al. (2003), as well as the Garg et al. (2000) analysis. The latter paper adds another deceleration point for comparison. The Auto Motor and Sport magazine (AMS) results are not presented in the Sanders paper; however, the authors provided the data for the purposes of this study.

Table 2-2 – Brake Dynamometer (UDP) results[c]

Test	brake lining	PM_{10} emiss.	(mg/stop/brake)	
UDP		filter	ELPI	
	low metallic	6.9[d]	7.0	
	semi-metallic	1.7	1.7	
	Non-asbestos	1.1	1.5	
Average/stop/brake		3.2	3.4	
Avg. /veh		9.7	10.2	
deceleration =			0.0012	km/s^2
avg. brake time in secs =			13.5	secs
avg. emissions in mg/stop =			9.95	Mg/stop
emission rate for the UDP test =			2.65	g/hr

[c] As these are intermediate values, the number of significant digits may exceed the precision known. However, they are kept in this presentation, and rounded for the final results. The UDP decelerations are the average decelerations from those measured in the Sanders paper. The average brake times were determined with the assistance of one of the original authors of the paper (Matti Mariq) who supplied the second by second trace. The filter PM_{10} were determined by multiplying the total PM reported in Table 5 of the paper with the PM_{10} to total PM ratio determined from the ELPI measurement.

[d] Sanders et al, reports the total filter PM to be 8.2 mg/brake/stop. In order to get PM_{10} equivalent, we applied the ELPI ratio from table 5 in the reference. So, 6.9 = 8.2* (7/8.3). The other numbers were calculated in a similar fashion. Also, the avg per vehicle emissions is the avg stop/veh/brake emissions multiplied by 3. This is based on the assumption made earlier that 2/3 of braking comes from the front brakes (one was measured) and 1/3 from the rear brakes.

Table 2-3 – Wind Tunnel results

Test	brake lining	PM_{10} emiss.	(mg/stop/brake)	
Tunnel		filter	ELPI	MOUDI
	low metallic	44	45	40

deceleration=	0.0018	km/s^2
Initial Velocity V(0) =	0.0267	km/s
avg. brake time in sec =V(0)/dec	14.8	s
avg. emissions in mg/stop =	129.0	mg/stop
emision rate for the wind tunnel test=	31.4	g/hr

Table 2-4 – AMS Test results

Test	brake lining	PM_{10} emiss.	(mg/stop/brake)
AMS		filter	ELPI
	low metallic	800	70
	semi-metallic	510	63
	Non-asbestos	550	92
	Average=	620	75
	Avg/veh rate =	1116	135

deceleration =	0.0079	km/s^2
Initial Velocity V(0) =	0.0278	km/s
avg. brake time in sec =V(0)/dec	3.5	s
avg. emissions in mg/stop for PM_{10}=	1116	mg/stop
emision rate for PM_{10} for the AMS test=	1143	g/hr
avg. emissions in mg/stop for $PM_{2.5}$=	135.0	mg/stop
emision rate for $PM_{2.5}$ for the AMS test=	138.2	g/hr

Table 2-5 – Garg et al. (2000) Brake Dynamometer results

Test	brake lining	PM_{10} emiss.*	$PM_{2.5}$**	(mg/stop/brake)
avg. over all temp.	semi-metallic #1	1.85	1.35	
	semi-metallic #5	0.82	0.60	
	NAOS #2	2.14	1.57	
	NAOS #3	0.89	0.66	
	NAOS#7	1.41	1.03	
	Grand Avg. =	1.42	1.04	mg/stop
deceleration =			0.00294	km/s^2
Initial Velocity V(0) =			0.0139	km/s
avg. brake time in sec =V(0)/dec			4.7	s
avg. emissions in mg/stop for PM_{10} =			1.42	mg/stop
emision rate for PM_{10} for the GM test=			1.08	g/hr
avg. emissions in mg/stop for $PM_{2.5}$ =			1.04	mg/stop
emision rate for $PM_{2.5}$ for the test=			0.79	g/hr

We used these four data points to fit an exponential function to determine the emission rate at different deceleration levels as shown in Figure 2-1. The AMS test, at higher decelerations, clearly has a significant influence on results of the curve fit. Additional test data at higher deceleration levels could be used for future refinement of this data.

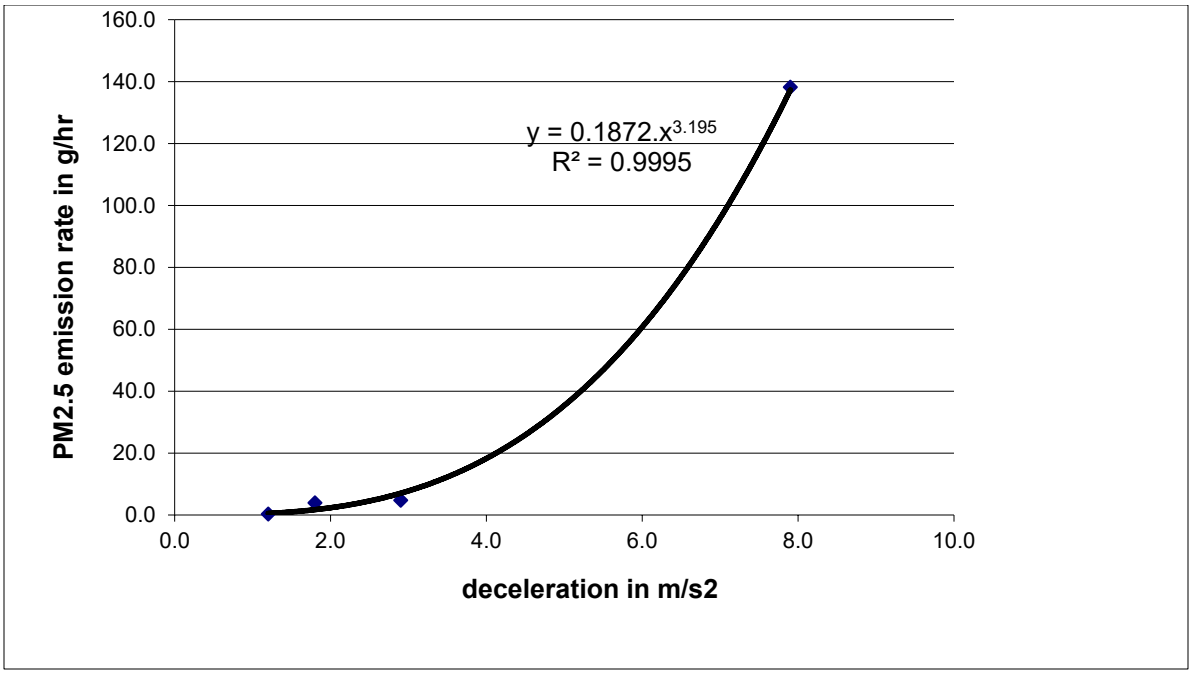


Figure 2-1 Brake wear $PM_{2.5}$ emission rates in units of grams per hour for light-duty vehicles as a function of deceleration rate based on Sanders et al. (2003) and Garg et al. (2000)

2.2.1.2 Average Braking Intensity

In the previous section, we determined the rate of particulate matter emissions during braking in units of grams per hour (per vehicle) as a function of deceleration level for a light-duty vehicle. MOVES, on the other hand, estimates brake wear from a variety of onroad vehicles over the full range of driving conditions, and classifies driving into operating modes that are quite different than the deceleration levels used in brake wear testing. This section describes how the above rates are combined to derive an average braking rate that is applied to the braking operating mode (opModeID 0). There are two major steps in this analysis.

1. Estimate the amount of braking (as opposed to coasting to a slower speed) at different deceleration levels for a light-duty vehicle.
2. Use real-world driving data on the frequency of different deceleration levels to define an average braking deceleration level, and hence an average brake wear emission rate for typical braking for a light-duty vehicle.

First**,** we needed to distinguish the deceleration episodes caused by braking from those that were merely coasting to a lower speed. We estimated the fraction of activity that is braking within each of the MOVES coasting operating modes (opModeID 11, 21 and 33) by first determining the coastdown curve.

A coastdown curve represents the expected deceleration rate of a vehicle across a range of vehicle speeds when no tractive power is applied. The coastdown curves were generated using the coastdown equations from the Physical Emission Rate Estimator (PERE)[11] and calculating the deceleration at each speed when the forward tractive power is zero. We assumed all deceleration below coastdown is braking and all activity above the curve is low throttle deceleration. Figure 2-2 shows coastdown curves for cars

of a variety of weights and coastdown coefficients. The dotted curve is a typical coastdown curve for this class of vehicle, where 1,497 kg was defined as the typical mass of a light-duty vehicle (passenger car). More information about the PERE coastdown calculation process is described in Appendix A.

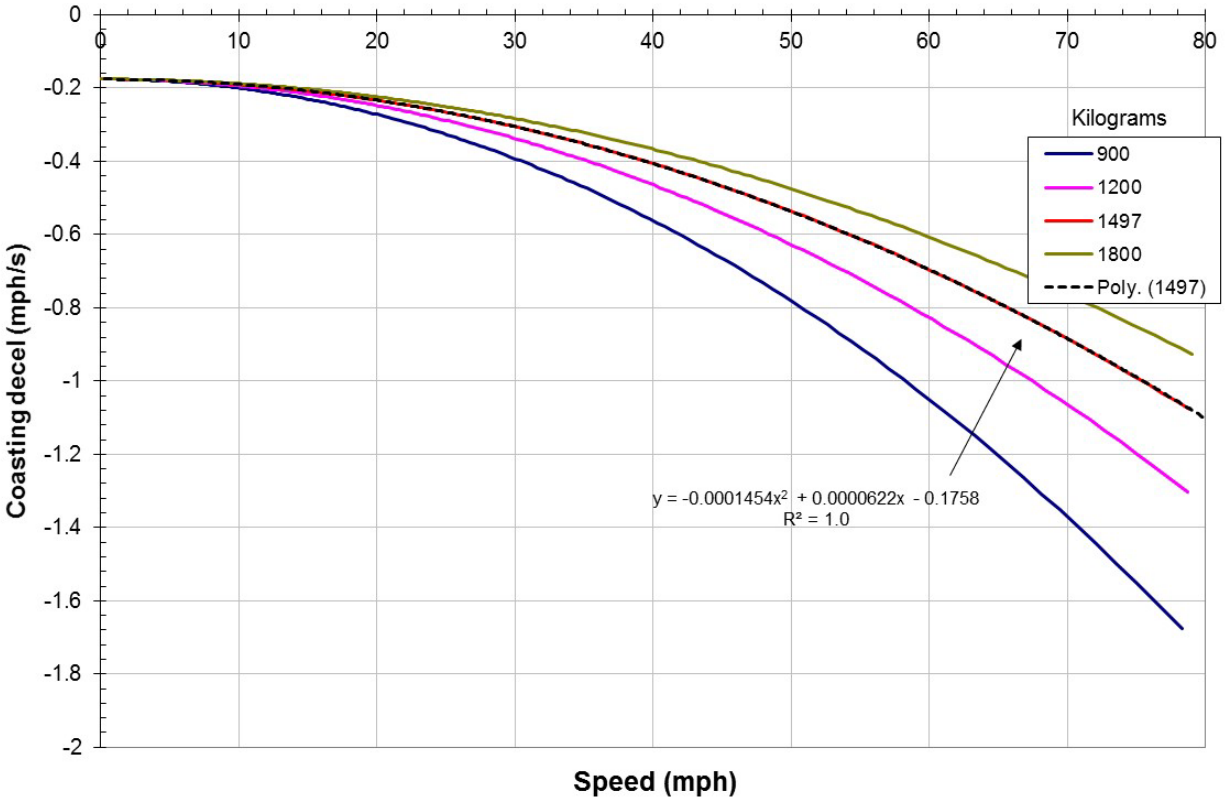


Figure 2-2 Modeled Coastdown curves using the PERE model for a variety of light-duty vehicles masses

Second**,** we used real-world driving data on the frequency of different deceleration levels to define an "average" braking deceleration level, and hence an average brake-wear emission rate for typical braking. For light-duty vehicles, the deceleration activity was determined from two real-world instrumented vehicle studies: one from Kansas City and the other in Los Angeles. The Kansas City study was conducted by EPA and Eastern Research Group (ERG) in 2005 to study real world driving activity and fuel economy of conventional and hybrid electric vehicles.[12] Over 200 vehicles were recruited, though for the current analysis, only the activity data from the conventional, or non-hybrid, population were examined. The Los Angeles activity data was conducted by Sierra Research for the California Department of Transportation (Caltrans) with both instrumented vehicles as well as chase car data.[13,14,15] The deceleration data was analyzed for both studies.

Table 2-6 shows the distribution of braking activity across deceleration levels from the Kansas City and Los Angeles studies. As expected, the majority of braking occurs during mild decelerations rather than full, high-deceleration stops.

Table 2-6 Distribution of braking activity in the LA and Kansas City studies for each deceleration bin

Decel (mph/s)	LA urban	LA rural	KC	AVG
1	37.1%	27.1%	54.5%	39.5%
2	26.3%	27.9%	26.3%	26.9%
3	17.9%	20.2%	12.8%	17.0%
4	10.2%	12.2%	4.6%	9.0%
5	5.6%	8.2%	1.3%	5.0%
6	1.6%	2.4%	0.30%	1.4%
7	0.64%	0.98%	0.07%	0.6%
8	0.28%	0.41%	0.02%	0.2%
9	0.17%	0.26%	0.02%	0.2%
10	0.10%	0.13%	0.01%	0.08%
11	0.05%	0.09%	0.01%	0.05%
12	0.03%	0.05%	0%	0.03%
13	0.01%	0.01%	0%	0.01%
14	0%	0.01%	0%	0%
sum	100.0%	99.9%	99.9%	100.0%

The emission rate curve from Figure 2-1 was combined with the average activity in Table 3-6 (using a sum of the product) to calculate an average MOVES braking emission rate for light-duty vehicles. This gives an average light-duty vehicle $PM_{2.5}$ emission rate of 0.557 g/hr for a braking event.

2.2.1.3 MOVES Rates

The MOVES pre-2011 light-duty brake wear $PM_{2.5}$ base emission rates (operating mode 0) in g/hr are shown in Table 2-7. The rates are calculated per the methodology described above. They are the same for all pre-2011 model years and are independent of fuel type. Brake wear rates for operating modes 11, 21, and 33 are ratioed from these base rates using the braking fractions derived in Section 2.2.5.1. A summary of effective g/mile emission rates is given in Section 2.4

Table 2-7 Pre-2011 light-duty brake wear $PM_{2.5}$ base emission rates (operating mode 0) in g/hr

Regulatory class	$PM_{2.5}$ (g.hr)
Passenger Cars (20)	0.557
Passenger Trucks (30)	0.627

The average passenger car PM_{10} brake wear emission rates of 24.84 mg/mi (output from MOVES5) is compared to the previous studies (in the literature) in Table 2-1. Carbotech (1999), Sanders et al. (2003), Garg et al. (2000), are all laboratory measurements and have significantly lower reported emission rates than MOVES. On the other hand, Luhana et al. (2004), Abu-Allaban et al. (2003), Westurland (2001), and Rauteberg-Wulff (1999) are roadside measurements or tunnel measurements. These studies generally

have higher emissions than laboratory measurements. The MOVES rates are also considerably higher than the publication cites. This is largely due to the fact that the MOVES primary source, Sanders et al. (2003), cites results primarily from the UDP braking events which are significantly milder than the AMS decelerations. Through the modeling described in this paper, the AMS deceleration rates are weighted in with the milder deceleration emission rates to give higher rates comparable to some of the results achieved from the tunnel and roadside studies. The light duty rates are thus calibrated to laboratory measurements adjusted to real-world factors, and "validated" to be within the range of roadside and tunnel measurements.

2.2.2 Emission Rates for Light-Duty Vehicles for Model Years 2011 and Later

The data from this analysis comes from a light-duty brake dynamometer test campaign jointly led by EPA and the California Air Resources Board (CARB), along with a companion data set from a study led by the California Department of Transportation (Caltrans).[16,17] The studies covered a range of common vehicle and brake configurations, including different brake pad materials, and employed a variety of instruments to characterize brake wear PM, including measurements of particle mass, number, and size distribution.

Because brake wear emissions in MOVES are modeled in terms of $PM_{2.5}$ and PM_{10} mass, this analysis uses the mass measurements captured by a TSI 100S4 MOUDI, with 10, 2.5 and 1 µm cut points.

2.2.2.1 Brake Dynamometer Drive Cycle

Both studies used a new test cycle, the California Brake Dynamometer Cycle (CBDC), which was developed as part of the EPA-CARB study to represent average real-world braking activity for light-duty vehicles.[16] The CBDC is based on micro-trip braking events sampled from the 2010-2012 California Household Travel Survey and contains segments with a range of braking intensities that together are intended to be representative of real world driving.[18] The test cycle development also accounted for brake heating and cooling during braking operation to ensure that the cycle's brake temperature profiles would also be representative of real-world driving. However, the addition of these cooling segments means that the total distance of the CBDC exceeds the summed distance of the representative micro-trips it is composed of.

MOVES has only one primary braking operating mode (opModeID 0) and therefore, cannot differentiate braking by intensity. The opMode 0 rate in MOVES represents a fleetwide average emission rate for braking across all conditions. Therefore, brake wear emission rates derived from the entire CBDC are suitable for use in MOVES because they provide an approximation for average braking behavior. Because of the greater total distance in the CBDC relative to its component micro-trips, distance-based emission rates (g/mile) use the summed distance of the selected micro-trips. Time-based emission rates (g/hr), like those used in MOVES, use the total time during the CBDC where the brakes are applied as opposed to the full drive cycle duration, which includes periods of acceleration and steady-state speed operation. For this analysis, the break wear rates for each test were calculated as the total measured PM emissions for the test cycle divided by the total braking time of the CBDC.

2.2.2.2 Brake Dynamometer and PM Measurement

The PM sampling was conducted on a brake dynamometer test bench enclosed within a constant volume sampling system. High efficiency particulate air (HEPA) filtered air was directed through the front of the brake enclosure, passed through and around the braking system, and ducted out towards a set of isokinetic sampling probes. Figure 2-3 shows a schematic of the sampling system.[17] The four sampling probes were situated at a 90-degree elbow in the ducting system at least eight diameters from the brake enclosure to ensure isokinetic sampling from a laminar flow. Figure 2-4 shows a velocity contour map from a computational fluid dynamics (CFD) simulation of the sampling system from the air inlet to the sampling probes.[16] The sampling probes fed a variety of instruments used to characterize PM emissions. Because brake wear emissions in MOVES are modeled in terms of $PM_{2.5}$ and PM_{10} mass, this analysis uses the mass measurements captured by a TSI 100S4 MOUDI, with 10, 2.5 and 1 µm cut points. Because the sampling system was fully enclosed and samples were collected continuously through the CBDC, any condensed particle emissions during the test cycle were measured, including fugitive emissions from heating and cooling of the braking system, and particulates released between braking events.

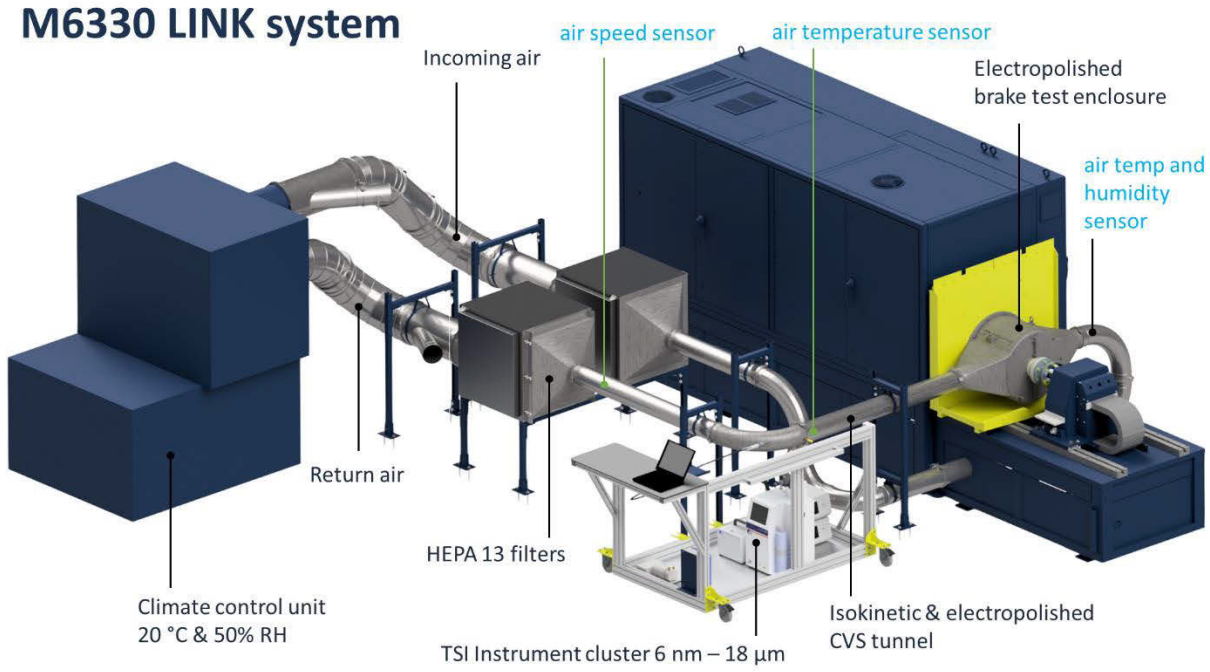


Figure 2-3 Schematic of brake wear PM testing system

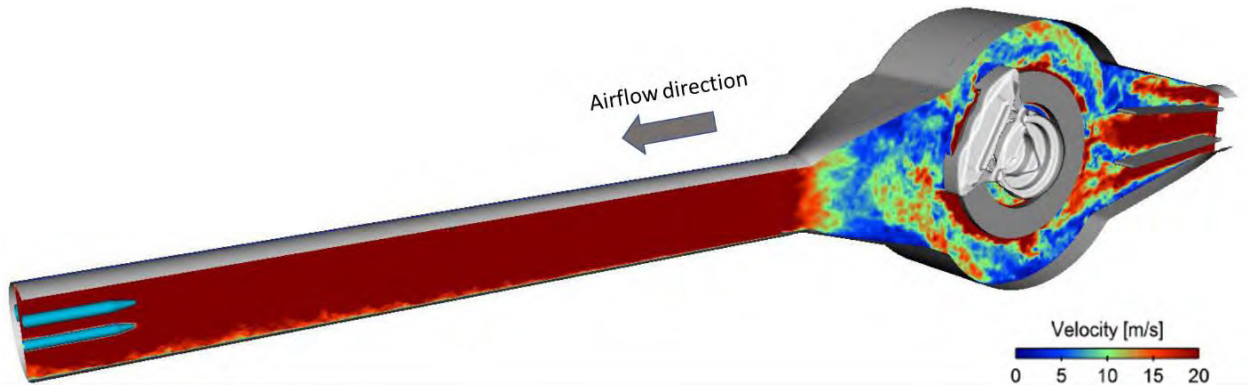


Figure 2-4 Velocity contour of cooling air resulting from CFD simulation

New brake components undergo a "bedding in" process when they are first exposed to braking forces and temperatures. During this process, the surfaces of the friction components are altered and eventually reach an equilibrium state. In this transition period, particulate emissions may change and not be representative of normal braking emissions. For this reason, each brake configuration was run through a burnishing cycle prior to sampling on the CBDC.[16]

2.2.2.3 Test Configurations and Vehicle-Level Results

The studies included testing of both front and rear brake configurations for several popular light-duty vehicle models. The vehicles were selected to be a representative sample of typical vehicles in the national fleet, and to include a representative range of brake technologies. They also included a variety of brake pads including both original equipment supplier (OES) and aftermarket brake pads. In the study, all OES pad materials were non-asbestos organic (NAO). The aftermarket pads included both NAO and low-metallic (LM) pad compositions. The joint EPA and CARB study included six vehicles, including one hybrid. Three of the vehicles in the study were tested for both an equivalent test weight (ETW) and a heavily loaded weight (HLW). For this analysis, we have also included testing results from one electric vehicle (EV), the Tesla Model 3, that comes from the Caltrans study. Two replicate tests were conducted for each configuration. The full scope of the combined data sets used in this analysis is summarized in Table 2-8 below.

Table 2-8 Light-duty brake dyno test configurations

Vehicle	Model Year	Front/Rear Type	Regenerative Braking	Pad Materials	Wheel Load
Toyota Camry	2011	disk/disk	no	OES-NAO, Aftermarket-NAO, Aftermarket-LM	ETW
Honda Civic	2013	disk/drum	no	OES-NAO, After-NAO	ETW
Ford F-150	2015	disk/disk	no	OES-NAO, Aftermarket-NAO, Aftermarket-LM	ETW, HLW
Toyota Sienna	2013	disk/disk	no	OES-NAO, Aftermarket-NAO	ETW, HLW
Toyota Prius	2016	disk/disk	yes	OES-NAO, Aftermarket-NAO	ETW
Nissan Rogue	2016	disk/disk	no	OES-NAO, Aftermarket-NAO	ETW, HLW
Tesla Model 3	2019	disk/disk	yes	OES-NAO	ETW

2.2.2.4 Brake Wear Rates by Vehicle Mass and Technology

The raw measured brake wear rates from the dynamometer testing were combined for each vehicle configuration to generate per-vehicle brake wear emission rates in units used by MOVES (grams per braking hour). The per-vehicle weights were determined by adding the average of the measured rates for the front wheel to the average of the measured weights for the rear wheel and multiplying the result by two. The resulting rates are summarized in Figure 2-5. Generally, for each vehicle, all NAO pads produced similar emissions. The low-metallic pads produced the highest emission rates. Because the OES and aftermarket NAO pads produce similar emissions, and because the testing report did not include relative population fractions for OES NAO vs aftermarket NAO pads, we have combined the results for all NAO pads for the rest of this analysis.

In addition to using a variety of brake pad materials, the current light-duty vehicles fleet includes a mix of onboard deceleration technologies. Most notably, some electric and hybrid-electric vehicles use regenerative braking to decelerate, which significantly reduces friction brake usage. Particulate emissions from brakes are generated by the force of friction used to dissipate vehicle energy at the brake surface. However, when a vehicle is using regenerative brakes, some of the kinetic energy from slowing the vehicle is used to recharge the battery instead of being dissipated entirely by the friction applied by the brakes. Thus, there is less material wear via friction and less particulate emissions.[19]

As seen in Figure 2-5, the two vehicles equipped with regenerative braking systems (the 2016 Toyota Prius and the 2019 Tesla Model 3) have much lower brake wear emission rates than comparable vehicles without regenerative braking systems. This is consistent with other studies on the topic. For example, a study on non-exhaust emissions from electric vehicles found that regenerative braking reduced brake wear emissions by 68%.[20]

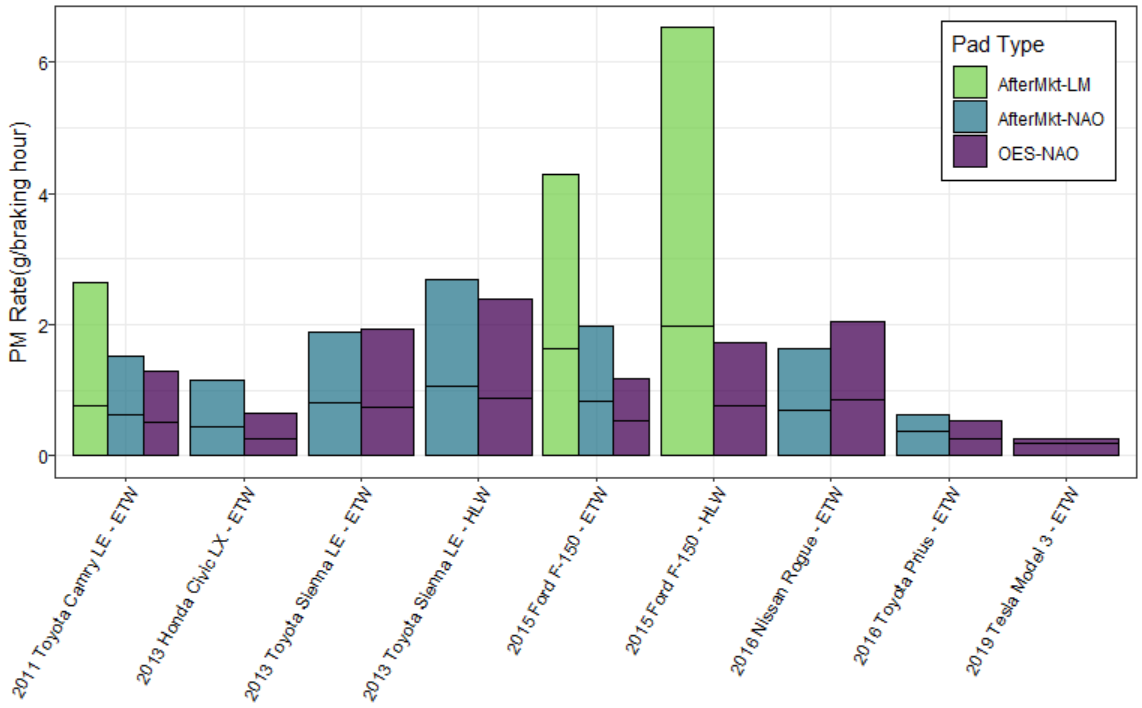


Figure 2-5 Vehicle-level emission rates for each vehicle and pad configuration tested. Each bar represents the PM_{10} rate for the test configuration. The horizontal lines within each bar indicate the $PM_{2.5}$ rate.

Prior to MOVES5, the MOVES model assumed that brake wear rates scale linearly with vehicle mass, because the power needed to slow a vehicle at a given rate of deceleration is directly proportional to its mass.[21] Figure 2-6 and Figure 2-7 show the measured $PM_{2.5}$ and PM_{10} brake wear emission rates as a function of vehicle mass and pad material. Because the Tesla utilized aggressive regenerative braking as well as conventional friction braking, we omitted it from these regressions, but included it in the figures as a point of comparison. Both figures show strong linear correlation between vehicle mass and brake wear emissions, confirming the previous assumptions used in MOVES. Based on this result, it is possible to construct population-weighted regressions based on brake pad composition that represent fleet-average emission rates by vehicle weight. From these regressions, representative emission rates can be calculated for each light-duty regulatory class in MOVES using the appropriate average vehicle masses. Because the dataset only contains data for a single EV, an equivalent regression was calculated through the Tesla's $PM_{2.5}$ and PM_{10} emissions and the origin. The slopes of these lines were used to estimate the mass-based emission factors for light-duty EVs in MOVES.

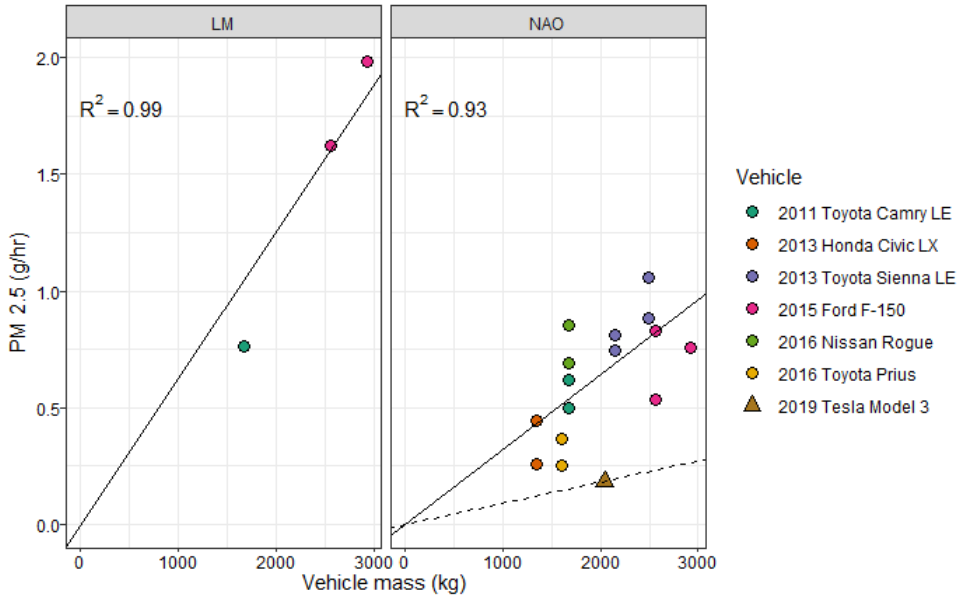


Figure 2-6 Vehicle-level brake wear $PM_{2.5}$ emission rates by vehicle mass and brake pad material

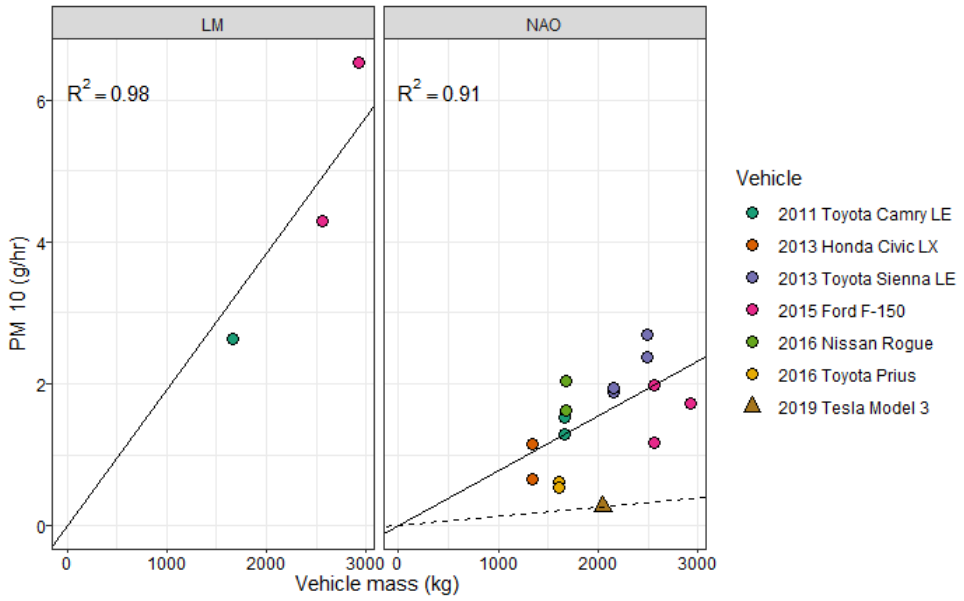


Figure 2-7 Vehicle-level brake wear PM_{10} emission rates by vehicle mass and brake pad material

The EPA report includes estimated proportions of NAO and LM pads in the national fleet for each of the tested vehicle models. Because the test vehicles were selected to represent common vehicles in the national fleet, and because the pad material fractions are similar across the range of vehicle models, we used the average of the pad fractions from these vehicles to represent the national fleet in MOVES.

Table 2-9 summarizes the estimated pad fractions reported for each vehicle model.[16] The table also includes the average of these values. Assuming that the test vehicles are representative, of the national fleet, 82 percent of the fleet is equipped with NAO pads. This is a higher rate of NAO usage than used for

the pre-2011 rates, which, lacking additional data, assumed that a third of pads were organic, and two-thirds were either low-metallic or semi-metallic. Population fractions of pad materials were not reported for the Tesla which is equipped with NAO brake pads from the factory. Lacking additional data on EV pad fractions, in MOVES, we have assumed that 100 percent of EV pads are NAO for the purposes of defining base brake wear emission rates.

Table 2-9 Estimated fleet-level pad material fractions for each vehicle model

Vehicle	NAO Fraction	LM Fraction
2013 Honda Civic LX	0.77	0.23
2016 Toyota Prius	0.82	0.18
2016 Nissan Rogue	0.88	0.12
2011 Toyota Camry LE	0.82	0.18
2013 Toyota Sienna LE	0.77	0.23
2015 Ford F-150	0.87	0.13
Average	0.82	0.18

The brake wear PM rates discussed above represent rates measured on a brake dynamometer under optimized sampling conditions. The measurements did not account for particle deposition on the surface of the wheel, the undercarriage of the vehicle, or the roadway. Sanders et al estimated that deposition onto these surfaces reduces the emitted brake wear PM by about a third.[10] To account for this, we multiply the slopes of the fit lines illustrated in Figure 2-6 and Figure 2-7 by 0.66 to get an estimated brake wear airborne emission rate as a function of vehicle mass: $E=0.66\alpha m$, where α is the fitted slope, and m is the vehicle mass.

Figure 2-8 shows the final weighted $PM_{2.5}$ emission to mass relationship alongside the NAO and LM pad regressions. For reference, the pre-2011 brake wear rates for light-duty cars (source type 21) and light-duty trucks (source types 31, and 32) are plotted against their source type masses from the MOVES sourceUseTypePhysics table. Given the pre-2011 assumption that there was an equal mix of brake pad materials between low-metallic semi-metallic, and NAO pads, the older rates agree very well with these more recent testing results.

Table 2-10 lists the inputs used to generate the lines plotted in Figure 2-8, as well as the equivalent values for EV brake wear rates based on the results of the Tesla.

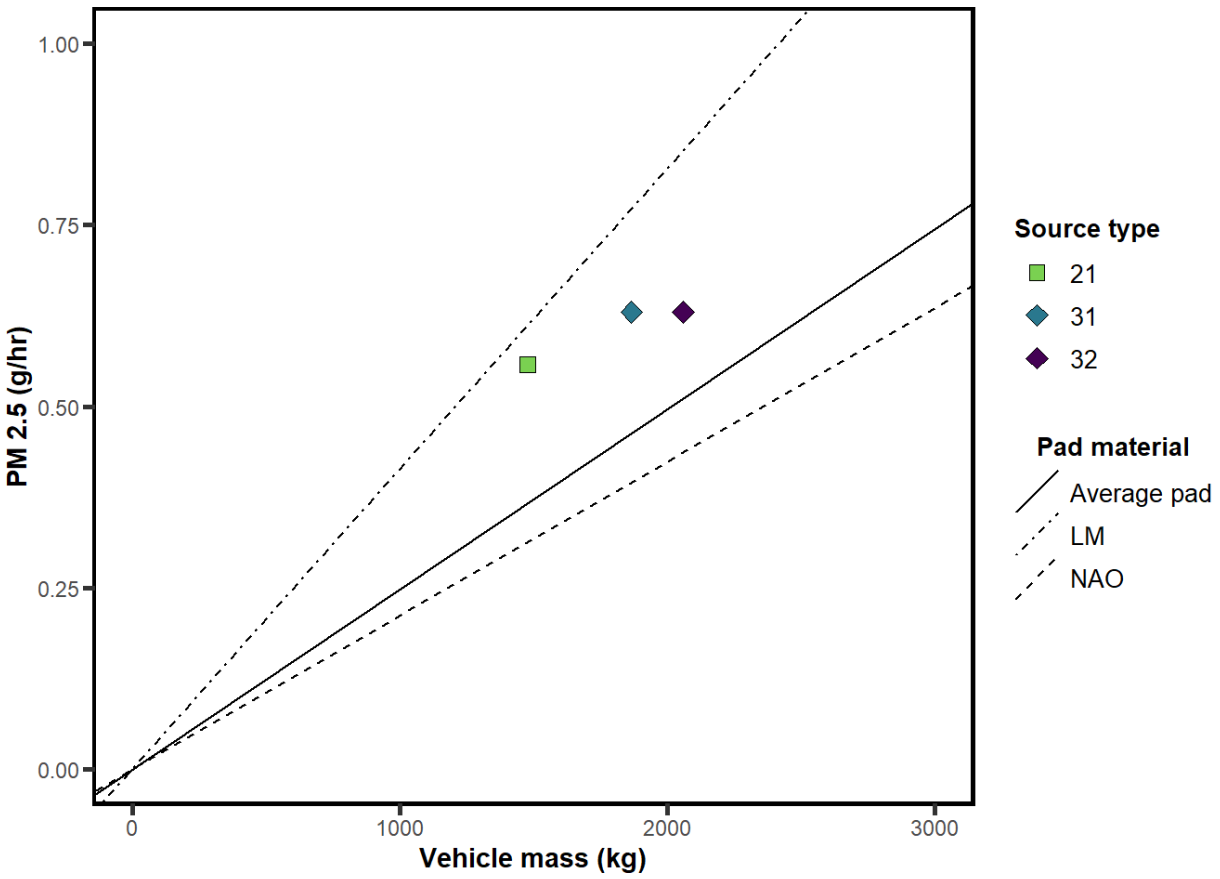


Figure 2-8 Airborne $PM_{2.5}$ g/h regressions for MY 2011 and later plotted against pre-2011 MOVES brake wear rates for source types 21, 31, and 32

Table 2-10 Airborne emission rate regression slopes by pad material and vehicle engine type corrected for airborne fraction

Engine Type	PM Size	NAO Fraction	LM Fraction	NAO Slope (g/hr kg)	LM Slope (g/hr kg)	Average Slope (g/hr kg)
ICE	$PM_{2.5}$	0.82	0.18	1.74×10^{-4}	3.78×10^{-5}	2.48×10^{-4}
ICE	PM_{10}	0.82	0.18	4.20×10^{-4}	9.12×10^{-5}	6.47×10^{-4}
EV	$PM_{2.5}$	1.00	0.00	5.96×10^{-5}	NA	5.96×10^{-5}
EV	PM_{10}	1.00	0.00	8.50×10^{-5}	NA	8.50×10^{-5}

2.2.2.5 *Vehicle Masses by MOVES Fuel Type*

With a relationship that defines an estimated emission rate based on a vehicle's weight, the final step to developing MOVES base rates is to identify the appropriate vehicle masses to use for the rate calculation. MOVES uses the source mass field from the sourceUseTypePhysics table to calculate VSP and operating modes. However, this mass is not split out by fuel type. This is a specific concern in the case of brake wear from electric vehicles because they tend to be heavier than their conventional ICE counterparts.

Therefore, instead of relying on the source mass in MOVES sourceUseTypePhysics table, we consulted the 2021 EPA Automotive Trends Report, to assess the state of light-duty vehicle masses.[22] Figure 2-9 shows trends in vehicle mass for model years 2011-2021 by fuel type. The fuel types reported by the trends report are grouped to match the MOVES fuel types as follows: gasoline, hybrid, and PHEV vehicles are assigned to the MOVES gasoline fuel type (fuel type 1); diesel is assigned to the MOVES diesel fuel type (fuel type 2), and electric and fuel cell vehicles are assigned to the MOVES electricity fuel type (fuel type 9). We assume that vehicles that use E85 (fuel type 5) weigh the same as regular gasoline vehicles.

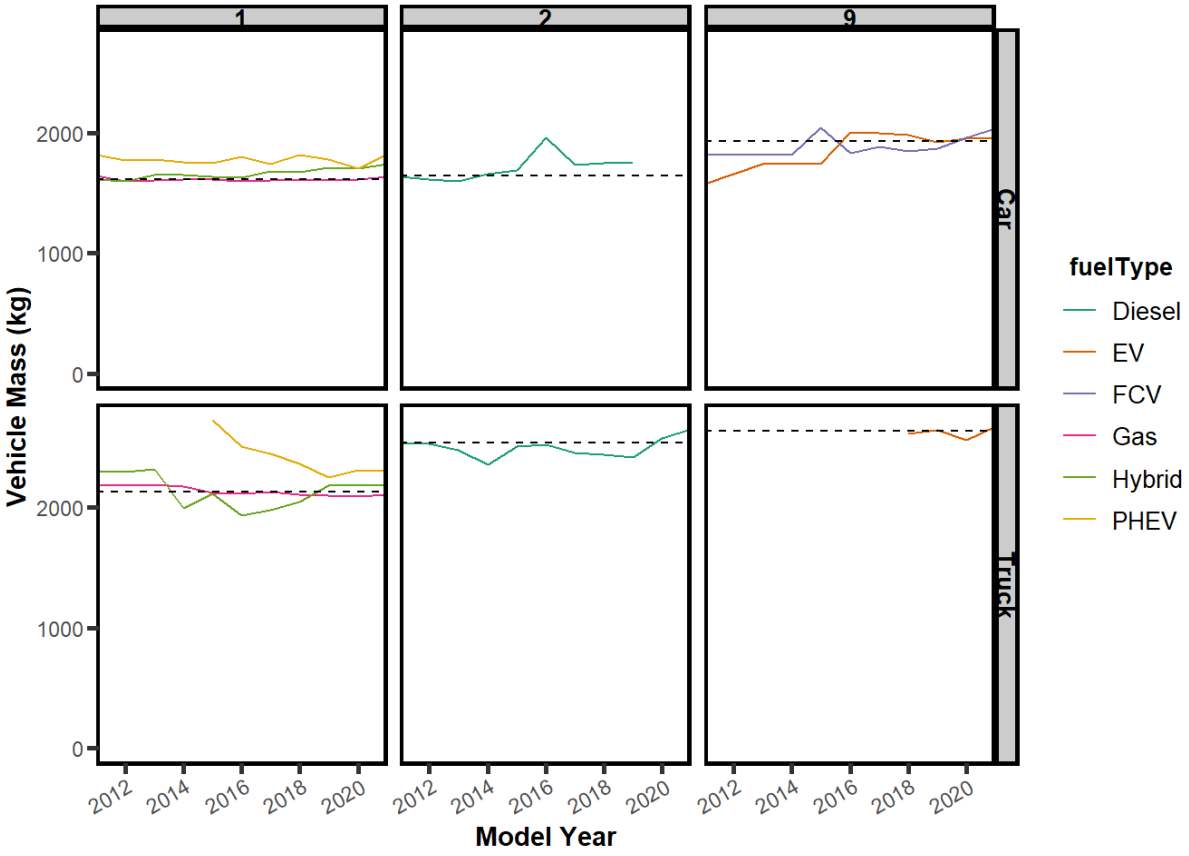


Figure 2-9 Average vehicle mass vs. model year by fuel type ID and regulatory class. The columns are grouped by MOVES fuel type, and the rows are MOVES regulatory classes. The dashed lines show averaged values for 2011-2021.

It is worth noting that not only do EVs have a larger vehicle mass than gasoline vehicles, but that diesel light-duty trucks also tend to be heavier than their gasoline counterparts.[e] Table 2-11 shows the average vehicle weight values by fuel type and regulatory class.

Table 2-11 Production-weighted average vehicle weight by MOVES regulatory class and fuel type for model years 2011-2021

Regulatory class	regClassID	fuelTypeID	Vehicle Weight (kg)
Car	20	1, 5	1,615
Car	20	2	1,645
Car	20	9	1,930
Truck	30	1, 5	2,132
Truck	30	2	2,538
Truck	30	9	2,634

Combining the vehicle masses from Table 2-11 with the PM vehicle mass relationship summarized in Table 2-10 (which accounts for regenerative braking for electric vehicles) yields a final set of brake wear PM base emission rates for MOVES. Figure 2-10 shows the $PM_{2.5}$ rates by model year with separate rates by fuel type after model year 2011. The final set of 2011 and later $PM_{2.5}$ rates are summarized in Table 2-12 along with the accompanying PM_{10} emission ratios derived at the end of Section 2.2.2.4.

[e] The difference likely suggests that the larger light-duty trucks are more frequently equipped with diesel engines, rather than that diesel trucks are heavier than their gasoline counterparts of similar size.

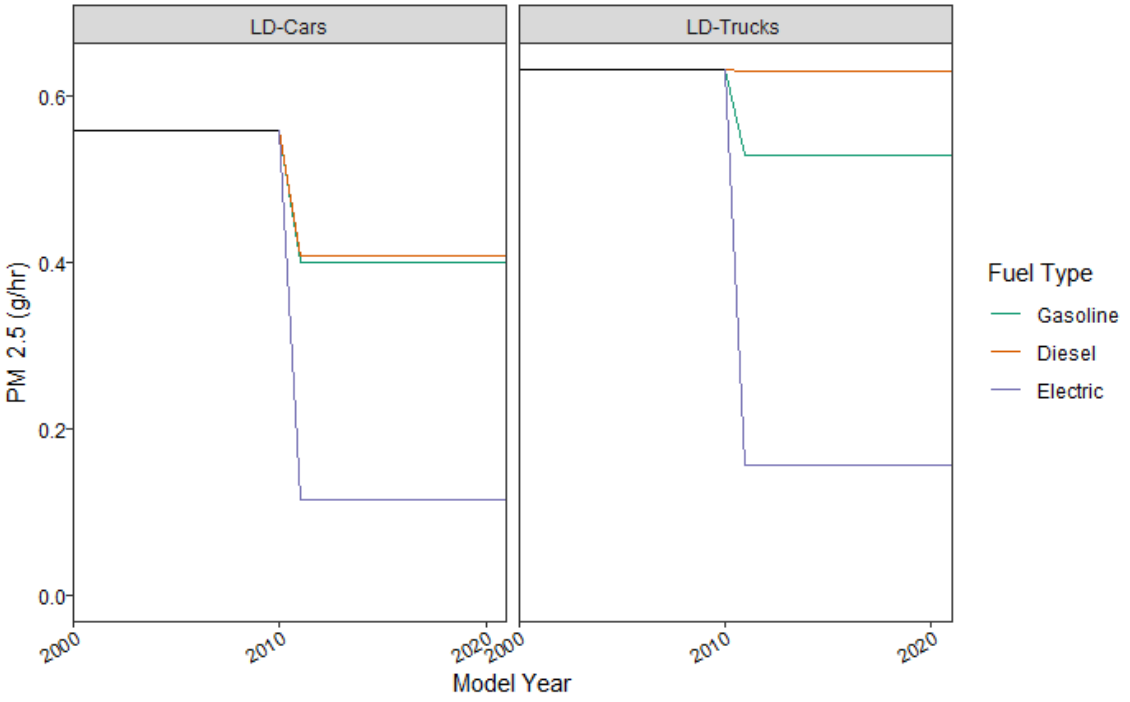


Figure 2-10 MOVES light-duty $PM_{2.5}$ base rates by model year and fuel type

Table 2-12 MOVES light-duty $PM_{2.5}$ base rates, and PM_{10} emission ratio by regulatory class and fuel type for MY 2011 and later

Regulatory Class	RegClassID	FuelTypeID	$PM_{2.5}$ Rate (g/h)	PM_{10} Emission Ratio
Car	20	1, 5	0.400	2.61
Car	20	2	0.408	2.61
Car	20	9	0.115	1.42
Truck	30	1, 5	0.529	2.61
Truck	30	2	0.629	2.61
Truck	30	9	0.157	1.42

2.2.3 Emission Rates for Heavy-Duty Vehicles for Model Years Prior to 2011

As noted in the Introduction, the pre-2011 brake wear emission factors in MOVES are unchanged from MOVES2014. There is very little literature on direct heavy-duty brake emissions measurements. To decelerate, heavy-duty vehicles employ technologies such as disc and drum as well as other braking

methods including downshifting and engine (or "jake") braking. In order to estimate brake wear emission factors for pre-2011 heavy-duty vehicles an engineering analysis was combined with results from a top-down study performed by Mahmoud Abu-Allaban et al. (2003).[23] The authors collected particulate matter on filters near roadways and apportioned them to sources utilizing Chemical Mass Balance (CMB) receptor modeling along with Scanning Electron Microscopy. The study was performed at roadside locations in Reno, Nevada, and Durham, North Carolina, where intensive mass and chemical measurements were taken. The authors of the paper attempted to collect and differentiate between PM measurements from tailpipe, tire wear, road dust, and brake wear from light- and heavy-duty vehicle types. Compared to the other papers described in the previous section (on light-duty braking) that include heavy-duty rates, the Abu-Allaban paper was one of the most recent studies of its kind available at the time of this analysis. The results are consistent with the heavy-duty rates measured from Luhana et al. (2004) as well as Westurland (2001), but it was the only paper to measure $PM_{2.5}$. The paper's light-duty rates are also aligned with the rates determined above.

In the Abu-Allaban study, $PM_{2.5}$ brake wear emission rates for heavy duty vehicles ranged from 0 to 15 mg/km (0 to 24 mg/mi). For our analysis we have assumed the emission rate was the midpoint of the range of emission factors, or 12 mg/mi. For the purposes of populating MOVES rates, we do not employ the measured emission rate directly due to the extreme uncertainty and variability of measurement and locations selected. Rather, we rely on the paper's comparison of light-duty to heavy-duty emission factors. The emission rates for the exit ramps in Table 5 of the paper, are reproduced below. Only the exit lanes were included of the many roads where measurements were collected. The remainder of the roads are represented by the average and the (min to max) range reported in the table. Because Abu-Allaban et al. did not report HHD brake wear at all sites, we also computed the average brake wear just for the sites with both HD and LD measurements.

Table 2-13 Brake Wear Emission Rates reproduced from Abu-Allaban et al. (2003)

Location	Vehicle Type	PM_{10} (mg/km)	$PM_{2.5}$ (mg/km)
J. Motley Exit	Heavy-Duty	610 ± 170	0 ± 0
	Light-Duty	79 ± 23	0 ± 0
Moana Lane Exit	Heavy-Duty	120 ± 33	0 ± 0
	Light-Duty	10 ± 3	0 ± 0
Average over all roads	Heavy-Duty	124 ± 71	2 ± 2
	Light-Duty	12 ± 8	1 ± 0
Average over all matching sites	Heavy-Duty	124±71	2 ± 2
	Light-Duty	15.50	0.67
Range (min to max) of measurements on all roads	Heavy-Duty	0 to 610	0 to 15
	Light-Duty	0 to 80	0 to 5

Due to the difficulty of differentiating a small brake emissions signal from the much larger signal coming from tailpipe, tire wear and road dust combined, there is much uncertainty in these measurements – yet another reason why adjusted laboratory measurements were favored above. Clearly $PM_{2.5}$ was difficult to measure from most sites. Interestingly, the exit lane heavy-duty measurements were highest for PM_{10}, however (rather inexplicably), the other road types had higher emissions than for $PM_{2.5}$. For these reasons, we rely more on averages to determine our ratio of heavy-duty to light-duty brake emission factors. From sites with both HD and LD measurements, we determined that the average ratios of HD to LD brake emissions are 8 and 3 for PM_{10} and $PM_{2.5}$ respectively.[f]

[f] Though it is not shown in the table here, according to Abu-Allaban, based on the highest sampling sites (maximum measurements from the table), the ratio of HD to LD brake emissions is 41 and 16 for PM_{10} and $PM_{2.5}$ respectively.

Table 2-14 Ratio of Heavy-Duty to Light-Duty PM from the literature.

Study	$PM_{2.5}$	PM_{10}
Luhana et al. (2004)		7.7
Abu-Allaban et al. (2003)	3	8.0
Westurland (2001)		6.0
Rauterburg-Wulff (1999)		24.5
Carbotech (1999)		0.7

For the purposes of MOVES, a simple model requiring a single ratio of HD to LD brake emissions and another ratio of PM_{10} to $PM_{2.5}$ brake emissions is attractive – particularly since the data to populate the model is sparse. Also the broad range of uncertainties in the literature can support such simplification. Based on the range in the table, above, the value of the HD to LD ratio chosen for development of MOVES emission rates is 7.5, close to the ratio as measured by Abu-Allaban et al. (2003), and consistent with the range of studies. While this HD to LD ratio was derived for PM_{10}, we apply it for $PM_{2.5}$. Equation 2-1 is used to calculate the $PM_{2.5}$ brake emission rate for the deceleration/braking mode (OpModeID 0) from the LDV emission rate.

$$HHD\ Emission\ rate\ \left(\frac{g}{hr}\right) = 7.5\ \times LDV\ Emission\ rate\ (\frac{g}{hr}) \qquad \text{Equation 2-1}$$

The resulting HHD emission rates for opMode 0 are shown in Table 2-15.

The estimated emission factors for all other regulatory classes were derived by linearly interpolating the rates between the light-duty vehicle (LDV) and heavy heavy-duty (HHD) vehicle classes by their respective weights as shown in the figure below (or extrapolating as in the case of motorcycles). This is based on a rather simple engineering (and unproven in this study) hypothesis that the relative brake emissions are proportional to the weight of the vehicle classes relative to (and bounded by) light and heavy-duty vehicles. The hypothesis is based on the assumption that relative mass of the vehicles is proportional to the relative energy required to stop the vehicles.

Since brake wear emission rates in MOVES are defined by regulatory class, we first estimated the vehicle weight for each regulatory class. We estimated the actual vehicle weight, including payload for heavy-duty trucks, not the gross vehicle weight rating (GVWR) which is used to define the regulatory class. The estimated vehicle weight was derived from the source mass value stored in the MOVES2014

sourceUseTypePhysics table by source type.[g] The average vehicle weight of each regulatory class was determined by VMT-weighting the contribution of each source type to each regulatory class. The resulting estimated vehicle weights from MOVES2014 are shown in Table 2-15.

Table 2-15 Vehicle Weights and $PM_{2.5}$ Brake Wear Emission Rates by Regulatory Class for opModeID 0 (Deceleration/Braking Mode)

Regulatory Class	regClassID	MOVES2014-estimated vehicle weight (lbs)	$PM_{2.5}$ Emission Rates (g/hr)
MC	10	628	0.355
LDV	20	3,260	0.558
LDT	30	4,197	0.631
LHD2b3	41	4,303	0.639
LHD45	42	18,849	1.76
MHD	46	28,527	2.51
HHD	47	50,285	4.19
Urban Bus	48	36,500	3.12
Gliders	49	50,285	4.19

Figure 2-11 and Table 2-15 shows the linear interpolation between the light-duty and heavy heavy-duty brake wear emission rates by the MOVES2014-estimated regulatory class weight.

[g] In MOVES3 and later, the heavy-duty vehicle weight is defined by both source use type and regulatory class[24]

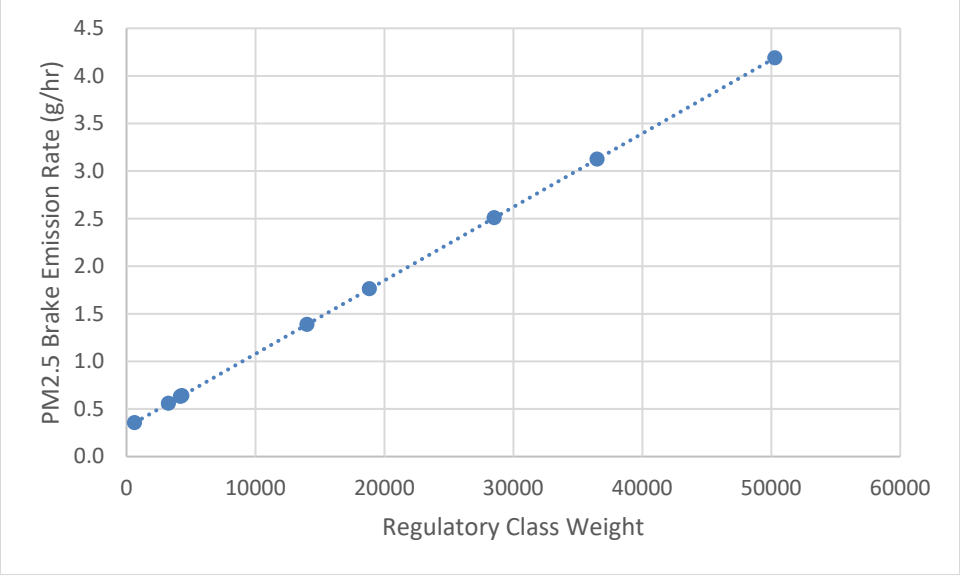


Figure 2-11 Interpolated Brake Wear $PM_{2.5}$ Emission Rates by MOVES2014-estimated Regulatory Class Weight. Passenger Cars and Combination Heavy duty Trucks define the slope.

In MOVES3, the vehicle weights for heavy-duty vehicles were updated with more current data sources. Additionally, the heavy-duty vehicle weights in MOVES vary according to regulatory class and source type as documented in the Population and Activity Report.[24] For MHD, HHD, and Urban Bus, the weights are generally within 10% of the weights used to derive the brake emission rates. For LHD2b3 and LHD45, the differences in weights are more significant. The average LHD2b3 weights for light-trucks and single-unit trucks in MOVES3 and later versions are estimated to be between 7,500 lbs to 7,879 lbs, compared to 4,303 lbs in MOVES2014b. The average LHD45 weight for single-unit trucks in MOVES3 and later versions is 12,716 lbs compared to 18,849 in MOVES2014b. One reason for the difference in weights for LHD2b3 is because MOVES2014b modeled Class 2b and 3 trucks in two regulatory classes (LHD <= 10k and LHD <=14K) and MOVES now models all Class 2b and 3 trucks in one regulatory class (LHD2b3). We applied the brake and tire emission rates from the MOVES2014b LHD <= 10k regulatory class to represent the emission rates of the LHD2b3 regulatory class in MOVES. This weight discrepancy is no longer relevant for the MY 2011 and later trucks (see Section 2.2.4) but suggests MOVES may be underestimating brake wear from 2010 and earlier LHD2b3 trucks and overestimating brake wear from 2010 and earlier LHD45 trucks.

In addition to the updated rates for LHD2b3, we added the glider regulatory class in MOVES3. In MOVES, gliders are defined as heavy heavy-duty (HHD) trucks with an old powertrain combined with a new chassis and cab assembly, as such they have the same vehicle weight and brake emissions as HHD vehicles.

2.2.4 Emission Rates for Heavy-Duty Vehicles for Model Years 2011 and Later

In MOVES5, the emission rates for heavy-duty vehicles were updated using the data from a heavy-duty brake test program conducted by CARB and Caltrans[17]. The testing was performed using a LINK heavy-duty brake dynamometer for various configurations to consider the impacts of different vehicle categories and other parameters such as axle types, brake types, vehicle loading conditions and vocational cycles. The raw test data was further analyzed and processed to develop full vehicle level MOVES emission rates using the process described below.

2.2.4.1 Individual Wheel Test Configurations

The heavy-duty dynamometer test bench in the CARB/Caltrans test program was largely the same as the one used for the light-duty testing as described in Section 2.2.2.2. For the heavy-duty testing, two Teflon filters were used to measure $PM_{2.5}$ and PM_{10}.

A set of individual wheel tests were performed for various configurations as summarized in Table 2-16 for the heavy-duty vehicle categories considered. As part of the HD test program, some tests were done with original friction material and then repeated with aftermarket fraction material. No statistically meaningful emission differences were observed since the material formulation do not vary significantly between original and aftermarket.[h] For MOVES modeling, we used the emission test data with original friction material.

[h] According to the HD testing report, the majority of commercial vehicle brake components in the U.S. are supplied by only a few companies, who provide both original and aftermarket parts.

Table 2-16 Individual wheel test configurations in CARB/Caltrans HD test program

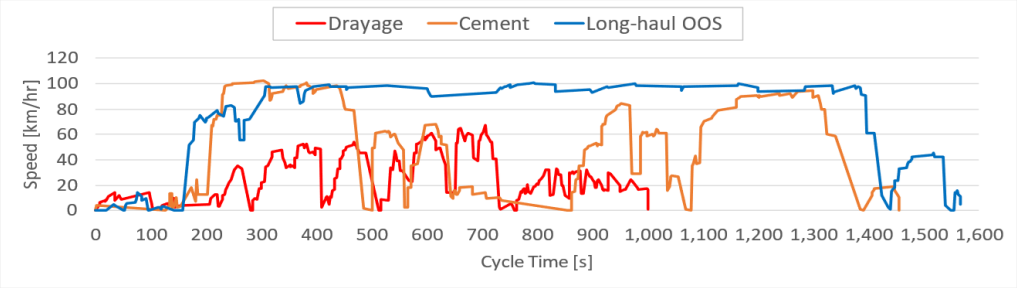
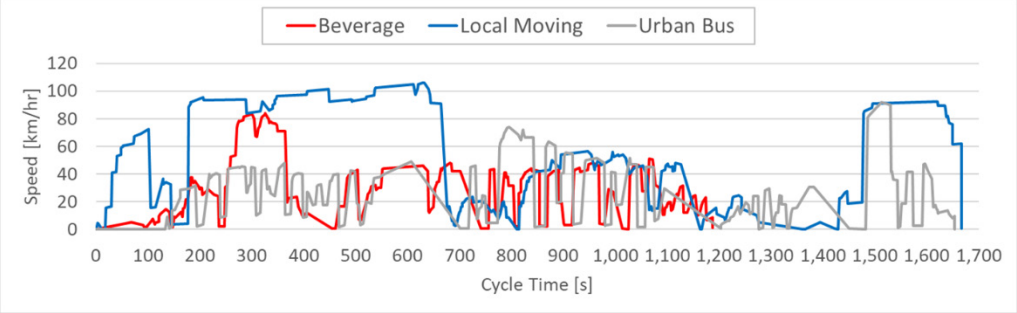
Vehicle Category	Axle Type	Brake Type	Vehicle Weight (lbs)	Vocational Cycle
Heavy-heavy duty (Class 8)	• Steer[i] • Drive • Trailer[j]	• Drum • Air disc	• Loaded: 81,011 • Unloaded: 28,759	• Drayage (Northern California) • Cement • Long-haul out-of-state (OOS)
Medium-heavy duty (Delivery truck)	• Steer • Drive	• Hydraulic disc	• 27,785	• Beverage • Local moving
Urban bus	• Steer • Drive	• Air disc	• 36,299	• Urban bus
Refuse	• Steer • Drive	• Air disc	• 44,701	• Refuse

In Table 2-17, the speed traces of selected vocational cycles are shown for comparison.

[i] Loaded condition tested only.

[j] Drum brake type tested only.

Table 2-17 Vocational cycle speed traces

Vehicle Category	Vocational cycle speed traces
Heavy-heavy duty (Class8)	
Medium-heavy duty (Delivery truck) & Urban Bus	

Each individual wheel test provided filtered $PM_{2.5}$ and PM_{10} gravimetric mass measurement data, cycle distance, braking event history and other information. In MOVES, emission rates are expressed in the unit of "grams per hour" by regulatory class. For brake wear base rates, the $PM_{2.5}$ "filter mass" (reported from the testing) is divided by the "total cumulative cycle braking time" to estimate $PM_{2.5}$ base rate for each test configuration.

2.2.4.2 Full Vehicle Rate Development Process

To develop full vehicle level emission rates starting from the individual wheel test data, additional processing steps are necessary to apply fleet-average weighting factors for each vehicle category that include:

- the number of wheels per axle
- the mix of loaded and unloaded operation (for HHD only)
- the mix of drum and disc brake types (for HHD only)
- the mix of vocational cycles (for HHD and MHD)

We used the estimates in Table 2-18 from the CARB/Caltrans HD brake wear test report where the CA-Vehicle Inventory and Use Survey (VIUS) database was used to estimate the wheels per axle and load/unloaded weighting. The drum/disc type weighting was based on a market survey; vocational cycle weighting was estimated using EMFAC speed distribution data.

Table 2-18 Estimates of the number of wheels per axle and fleet-average weighting factors

Test vehicle category	Individual wheel test configurations	Wheels per axle	Vehicle load weighting	Brake type weighting	Vocational cycle weighting
Heavy-heavy duty (Class 8)	• Drum/Steer • Drum/Drive • Drum/Trailer • Disc/Steer • Disc/Drive	• Steer axle: 2 • Drive axle: 4 • Trailer: 4.16	• Loaded: 73% • Unloaded: 27%	• Drum: 85% • Disc: 15%	• Drayage: 18% • Cement: 24% • Long-haul OOS: 58%
Medium-heavy duty (Delivery truck)	• Hydraulic disc/Steer • Hydraulic disc/Drive	• Steer axle: 2 • Drive axle: 2.21	N/A	N/A	• Beverage: 27% • Local moving: 73%
Urban bus	• Air disc/ Steer • Air disc/ Drive	• Steer axle: 2 • Drive axle: 2	N/A	N/A	N/A

2.2.4.3 MOVES Heavy-Duty Brake Wear Base Rates

The full vehicle emission rates by test vehicle category are transformed into MOVES emission rates by regulatory class. Table 2-19 shows the mapping between test vehicle categories and MOVES regulatory classes.

Table 2-19 Mapping between test vehicle categories and MOVES regulatory classes

MOVES regulatory class (regClassID)	Classification	Test data source for mapping
HHD (47), Gliders (49)	Class 8 trucks (GVWR>33,000 lbs)	Heavy-heavy duty (Class 8) test data
MHD (46)	Class 6 & 7 trucks (19,500<GVWR<=33,000 lbs)	Medium-heavy duty (Delivery truck) test data
Urban Bus (48)	See CFR Sec 8.091_2	Urban bus test data

The CARB/Caltrans HD brake test program did not include the LHD2b3 (41) and LHD45 (42) regulatory class vehicles. To fill the data gaps, we developed the MOVES rates for those regulatory classes by adjusting the diesel light-duty truck rate shown in Table 2-12 by the class average weights in Table 2-20 for LHD2b3 and LHD45, respectively.

For MOVES, the emission rates were adjusted based on the weight ratios between the test vehicle weights (listed inTable 2-16) and the corresponding MOVES regulatory class average weights (Table 2-20).

Table 2-20 MOVES class average weights by regulatory class

MOVES HD regulatory class (regClassID)	Class average weights (Tons)	Class average weights (lbs)
LHD2b3 (41)	3.456	7,619
LHD45 (42)	5.870	12,942
MHD (46)	13.374	29,484
HHD (47)	24.032	52,982
Urban Bus (48)	15.603	34,398
Gliders (49)	24.664	54,374

MOVES5 has the added capability to model electric vehicles (EVs) as part of heavy-vehicle fleet population[25] and it is desirable to consider the effect of regenerative braking on brake wear emissions. The CARB/Caltrans HD brake test program, however, did not consider any heavy-duty electric vehicles and there is little data available in the literature. As an approximation, we used the ratio of the light-duty ICE vehicle rate vs. the EV (based on Tesla) rate in Table 2-10 to calculate the HD EV rates for each regulatory class by scaling down the HD ICE $PM_{2.5}$ emission rates proportionally. This approach assumes implicitly that the electric heavy-duty fleet has the same vehicle characteristics (weight, wheel configuration, number of axles, etc.) as its non-EV counterpart. This approach differs from the approach for light-duty because we lacked data on the weight of HD EVs and assume that heavy-duty truck weights depend less on powertrain weight and more on payload and GVWR.

The updated $PM_{2.5}$ base rates for MY2011+ heavy-duty vehicles are summarized in Table 2-21. The ICE rates are used for gasoline, diesel and CNG-powered vehicles.

Table 2-21 Updated $PM_{2.5}$ base rates for MY2011+ heavy-duty vehicles

MOVES HD regulatory class (regClassID)	$PM_{2.5}$ base rates [g/h] for ICE vehicles	$PM_{2.5}$ base rates [g/h] for electric vehicles
LHD2b3 (41)	0.86	0.21
LHD45 (42)	1.46	0.35
MHD (46)	3.60	0.87
HHD (47)	16.69	4.01
Urban Bus (48)	1.71	0.41
Gliders (49)	16.69	N/A

2.2.5 Braking Activity

In MOVES, braking activity is modelled as a portion of running activity. For light-duty running emissions, the operating modes are defined in terms of vehicle-specific power (VSP)[k]. This parameter represents the tractive power exerted by a vehicle to move itself and its cargo or passengers. The VSP equation used in MOVES is given as:

$$VSP = \frac{Av + Bv^2 + Cv^3 + mv\big(a + gsin(\theta)\big)}{m}$$

Where *v* is the vehicle's speed, *a* is the vehicle's acceleration *m* is the vehicle's mass, and ϑ is the road grade. The coefficients A, B, and C are known as the road load coefficients and represent rolling resistance, rotational resistance, and aerodynamic drag of the vehicle respectively. When VSP equals 0 it indicates that the vehicle does not not need to apply any power to achieve its current speed and acelleration. When VSP is positive, it means that power is required to achieve the speed and acelleration. Finally, when VSP is negative, it means that the vehicle needs to provide braking power to achieve the associated speed and acceleration.

The MOVES operating modes for running exhaust and brake wear emissions are listed in Table 2-22. More information on these operating modes is available in the MOVES light-duty and heavy-duty exhaust emission reports.[26,5] The MOVES vehicle specific power (VSP) bins are coarsely defined for braking.[l] There is a large "braking" bin (operating mode 0) where deceleration is large or sustained. The "idle" bin covers speeds from -1 to 1 mph and includes some braking in the transition (deceleration) from non-zero speed to zero speed. In addition, there are three "coasting" bins (operating modes 11, 21, 33) where VSP can be less than zero and, as such, also contain braking events. Therefore, the emission rates assigned to

k For heavy-duty vehicles, the MOVES operating modes are the same, but use Scaled Tractive Power (STP) instead of VSP.

these bins need to contain the appropriate average rates including the mix of driving and deceleration, including decelerations that do not include braking. When deceleration is between -1 mph/s and -2 mph/s, the operating mode is assigned by the duration of the deceleration. If the vehicle has been decelerating for the two consecutive seconds prior to the current second, it is assigned to be operating Mode 0. Otherwise, it is assigned to one of the "coasting" bins.

Table 2-22 – MOVES Operating Mode Bins by VSP and speed

Operating Mode	Operating Mode Description	Vehicle-Specific Power (VSP, kW/Mg)	Vehicle Speed (v,mi/hr)	Vehicle Acceleration including grade (a_t, mph/sec)
0	Deceleration/Braking			$a_t + g \cdot \sin(\theta_t) \leq -2.0$ OR [$a_t + g \cdot \sin(\vartheta_t) < -1.0$ AND $a_{t-1} + g \cdot \sin(\vartheta_{t-1}) < -1.0$ AND $a_{t-2} + g \cdot \sin(\theta_{t-2}) < -1.0$)
1	Idle		$-1.0 \leq v < 1.0$	
11	Coast	VSP < 0	$1 \leq v < 25$	
12	Cruise/Acceleration	$0 \leq$ VSP < 3	$1 \leq v < 25$	
13	Cruise/Acceleration	$3 \leq$ VSP < 6	$1 \leq v < 25$	
14	Cruise/Acceleration	$6 \leq$ VSP < 9	$1 \leq v < 25$	
15	Cruise/Acceleration	$9 \leq$ VSP < 12	$1 \leq v < 25$	
16	Cruise/Acceleration	$12 \leq$ VSP	$1 \leq v < 25$	
21	Coast	VSP < 0	$25 \leq v < 50$	
22	Cruise/Acceleration	$0 \leq$ VSP < 3	$25 \leq v < 50$	
23	Cruise/Acceleration	$3 \leq$ VSP < 6	$25 \leq v < 50$	
24	Cruise/Acceleration	$6 \leq$ VSP < 9	$25 \leq v < 50$	
25	Cruise/Acceleration	$9 \leq$ VSP < 12	$25 \leq v < 50$	
27	Cruise/Acceleration	$12 \leq$ VSP < 18	$25 \leq v < 50$	
28	Cruise/Acceleration	$18 \leq$ VSP < 24	$25 \leq v < 50$	
29	Cruise/Acceleration	$24 \leq$ VSP < 30	$25 \leq v < 50$	
30	Cruise/Acceleration	$30 \leq$ VSP	$25 \leq v < 50$	
33	Cruise/Acceleration	$VSP_t < 6$	$50 \leq v$	
35	Cruise/Acceleration	$6 \leq$ VSP < 12	$50 \leq v$	
37	Cruise/Acceleration	$12 \leq$ VSP <18	$50 \leq v$	
38	Cruise/Acceleration	$18 \leq$ VSP < 24	$50 \leq v$	
39	Cruise/Acceleration	$24 \leq$ VSP < 30	$50 \leq v$	
40	Cruise/Acceleration	$30 \leq$ VSP	$50 \leq v$	

To estimate the amount of braking activity in modes 1, 11, 21, and 33, the brake emission rates in those bins were multiplied by the proportion of activity with VSP < 0 in each bin. These braking fractions were derived separately for light and heavy-duty vehicles and applied for all model years.

2.2.5.1 Braking Fractions for Light-Duty Vehicles

To estimate the amount of time light duty vehicles spend braking in each of the braking-associated opModes, we analyzed drive traces from the 2010-2012 California Household Travel Survey.[27] The dataset contains data for 2,910 light-duty vehicles which were split into groups of passenger cars (regClass 20), and passenger trucks (regClass 30) for analysis. The dataset contained 1.875×10^5 hours, and 9.049×10^4 hours of second-by-second driving activity, for cars and trucks, respectively. The drive traces were processed to calculate VSP and MOVES opMode for each second of driving activity. The dataset did not include the road load coefficients for the vehicles, so the MOVES defaults were used to represent each regulatory class. Braking time was assigned to all time intervals where VSP was less than zero. Figure 2-12 and Table 2-23 show the results of the drive cycle analysis.

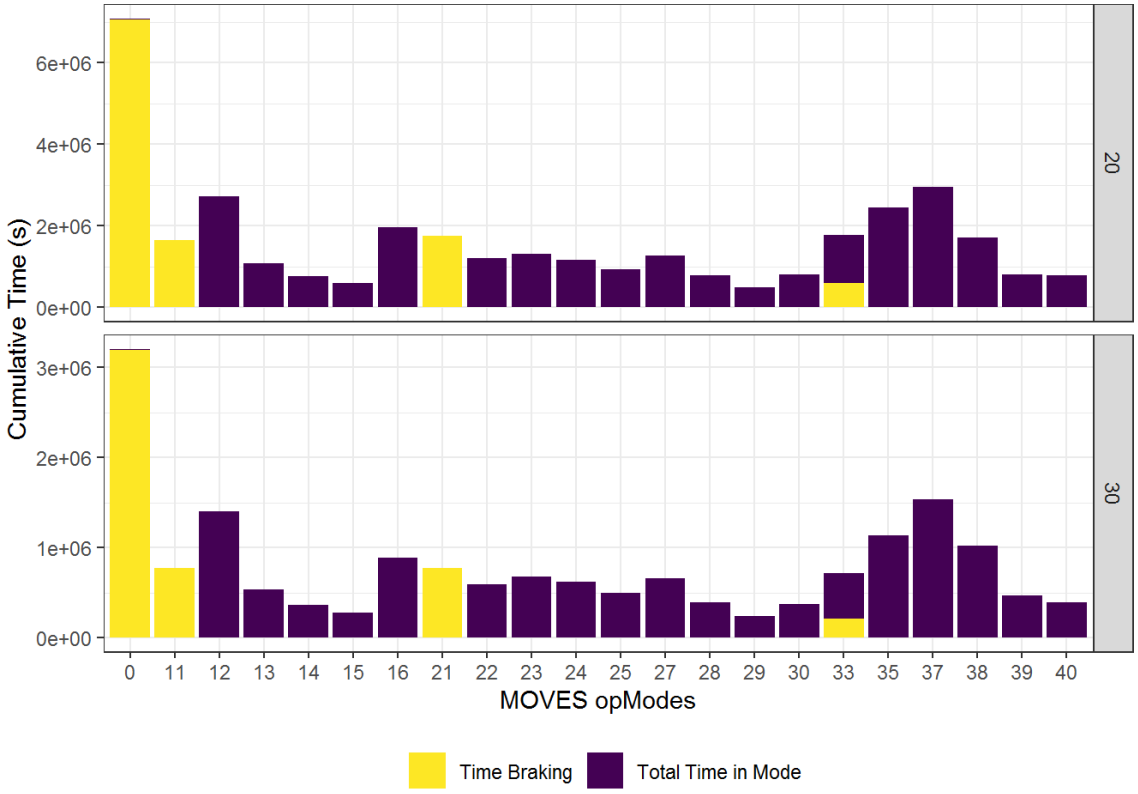


Figure 2-12 MOVES opMode distributions with associated braking activity. Note: idle activity (which has negligible braking) was omitted for scale purposes

Table 2-23 Braking fractions by MOVES opMode and regClass

opMode	regClass 20	regClass 30
0 (braking)	0.9979621	0.9948194
1 (idle)	0.0000018	0.0000014
11 (coasting/decel)	1.0	1.0
21 (coasting/decel)	1.0	1.0
33 (coasting/decel)	0.3320758	0.2908599

As the figure and table show, opModes 11 and 21 are entirely made up of braking activity. This makes intuitive sense because, by definition, these operating modes only contain activity with negative VSP. OpMode 33 was shown to be roughly a third braking activity for both cars and trucks. Interestingly, the braking opMode (opMode 0) contained a very small but quantifiable amount of non-braking deceleration. Likewise, the idle opMode (opMode 1) only contained a tiny fraction of braking activity. Figure 2-13 helps to interpret these results. It depicts a mapping of the light-duty car opModes onto a speed and acceleration space. The line separating opModes 11 and 12, and opModes 21 and 22 represents the line of VSP = 0 and is continued as a dotted line through opMode 33. The lighter grey hatched rectangle overlapping op modes 11, 21, and 33 is the low-deceleration (e.g., acceleration between -1.0 and -2.0 mph/sec) portion of opMode 0 that is defined based on the number of seconds spent decelerating. At high driving speeds, this low deceleration braking space crosses into the area of positive VSP values, which accounts for the small fraction of non-braking activity observed in the braking opMode.

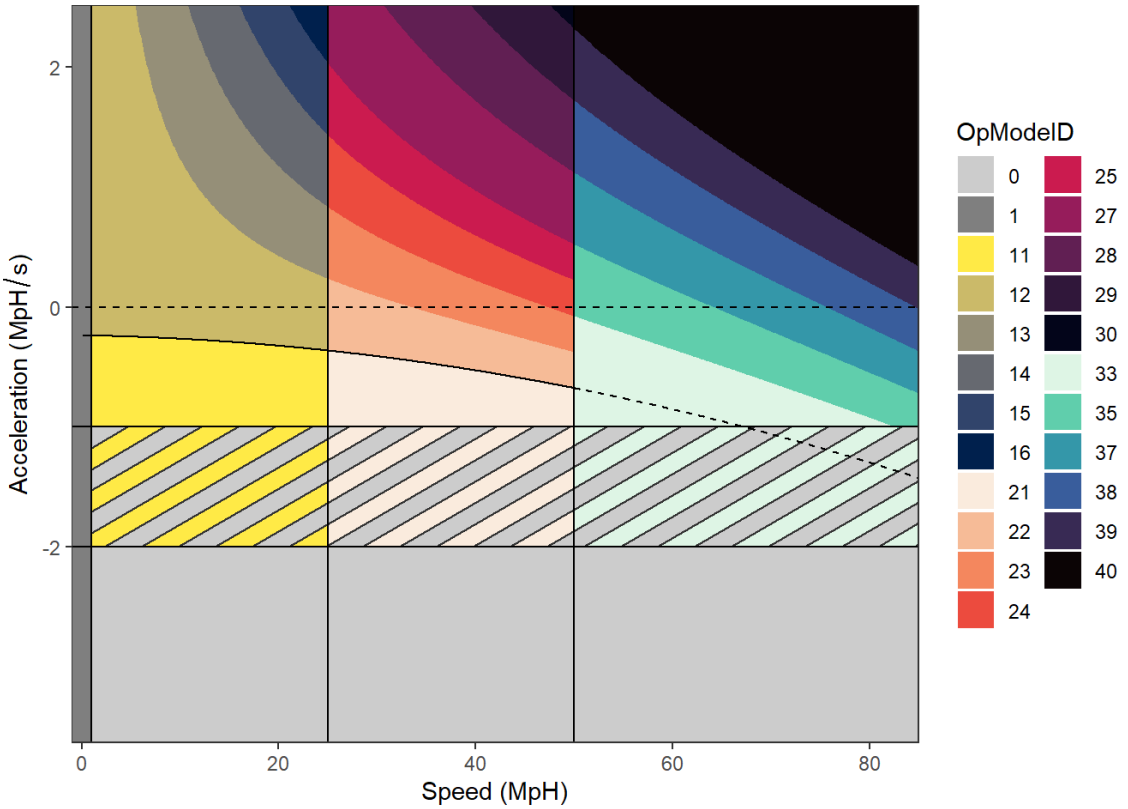


Figure 2-13 MOVES opModes mapped in speed and acceleration space

2.2.5.2 Braking Fractions for Heavy-Duty Vehicles

To estimate the amount of time heavy-duty vehicles spend braking in each of the braking associated opModes, we analyzed the drive traces from the Heavy-Duty Diesel In-Use Testing (HDIUT) data for MY2010+ vehicles. This HDIUT dataset was extensively used in MOVES to develop exhaust emission rates. Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES5[28] provides detailed descriptions of the HDIUT program and the methodology to calculate MOVES opMode distributions for heavy-duty vehicles.

As explained in that report, the HDIUT data includes second-by-second information about engine speed, torque, axle power, vehicle speed, and acceleration, from which we calculated scaled tractive power (STP) and MOVES opMode. For braking faction estimates, we count time intervals with STP < 0 (while excluding a subset of those records where either the vehicle speed is 0 or the acceleration is greater than 0) as “braking time” in each of the braking associated opModes.

The braking factions based on the HDIUT[m] data are summarized in Table 2-24 and applied to all model years[n].

Table 2-24 Braking factions by MOVES opMode and regClass for heavy-duty vehicles

	LHD2b3(=LDT)	LHD45	MHD	HHD	Urban Bus
OpModeID	Braking Fraction				
0 (braking)	0.994819	0.87996	0.877744	0.786902	0.97811
1 (idle)	1.44E-06	0.001594	0.016118	0.004802	0.003346
11 (coasting/decel)	1	0.652373	0.710629	0.70482	0.679883
21 (coasting/decel)	1	0.743501	0.874805	0.797833	0.690515
33 (coasting/decel)	0.29086	0.312656	0.262391	0.274519	0.179825

2.2.5.3 Braking Activity in Idle Mode

As discussed above, the braking fraction for idling is estimated from the braking that occurs during the idle mode within a driving cycle. MOVES uses driving cycles to estimate the operating mode distribution from on-network driving, including the fraction of idling that occurs on-network. For off-network idling such as during passenger pick-up and drop-off, MOVES does not estimate brake emissions, because the vehicle is completely stopped during this non-drive-cycle idle time.

At County Scale and Default Scale, opMode 1 is used for estimating brake wear emissions for all speeds less than 1 including zero because a percentage of stopped time was accounted for in the derivation of the opMode 1 brake wear emission rates from the driving cycles as discussed above. However, when estimating brake wear at Project Scale, MOVES assigns all operation with speed equal to zero to operating mode 501 (brake wear; stopped), and with speeds between 0 and 1 mph as operating mode 1 (idle). Operating mode 501 produces zero brake wear emissions, while operating mode 1 produces brake wear emissions. This approach allows Project Scale modelers to define links with sustained idling and no brake wear. At Project Scale, MOVES users also have the option to input their own operating mode distributions, including using operating mode 501 (brake wear; stopped) and operating mode 1 (idle).

[m] Since HDIUT program doesn't include LHD2b3, we set the LHD2b3 braking fraction equal to the LDT values in Table 2-23.

[n] The heavy-duty braking fractions in pre-MOVES5 versions were estimated based on light-duty vehicle activity data.

2.3 $PM_{10}/PM_{2.5}$ Brake Wear Ratio

MOVES stores $PM_{2.5}$ brake wear emission rates by operating mode bin, then estimates PM_{10} emission rates by applying a $PM_{10}/PM_{2.5}$ ratio.

For model years 2010 and earlier, the $PM_{10}/PM_{2.5}$ ratio is based on the assumptions that the mass fraction of particles below PM_{10} is 0.8, and the mass fraction of particles below $PM_{2.5}$ is 0.1. More specifically, Sanders et al. (2003) reports PM "fractions and cutoffs of 0.8 at 10 µm, 0.6 at 7 µm, 0.35 at 4.7 µm, 0.02 at 1.1 µm, and <0.01 at 0.43 µm for the UDP stops typical of urban driving". These assumptions result in a $PM_{10}/PM_{2.5}$ ratio of 8. This ratio is used for all source types and model years prior to 2011. Where no $PM_{2.5}$ values were reported, we calculated $PM_{2.5}$ from PM_{10} emission rates using this fraction. This estimate widely varies in the literature. Abu-Allaban et al. (2003) reports that only 5-17 percent of PM_{10} is $PM_{2.5}$, which is consistent with Sanders. Garg et al. (2000) reports 72 percent of PM_{10} is $PM_{2.5}$, which is disputed by Sanders et al. (2003). Our calculation does use the $PM_{2.5}$ measurement reported by Garg et al. (2000), however, in reality, this single value has little impact on the curve fit in Figure 2-1, which is dominated by the more recent data from Sanders et al. (2003).

For model years 2011 and later, the PM_{10} ratio for light-duty vehicles is taken as the ratio of the average slopes for PM_{10} and $PM_{2.5}$ rates in Table 2-10. We get a PM_{10} to $PM_{2.5}$ ratio of 2.61 for light-duty ICE vehicles, and 1.42 for light-duty EVs. For MY 2011 and later, we set the ratio to 2.857 for all MY2011+ heavy-duty vehicles. This estimate is based on the ratio of the aggregated $PM_{2.5}$ and PM_{10} emission rates across the heavy-duty vehicle categories in the CARB/Caltrans HD brake test program.[17]

2.4 Summary of MOVES Brake Wear Rates

Figure 2-14 through Figure 2-20 below summarize the MOVES brake wear emission rates across model years for light and heavy-duty vehicles. The gram-per-mile rates in the figures are averaged at the national scale and are calculated using the vehicle populations modeled by MOVES. Some changes in rates, especially for heavy-duty vehicles, reflect changes in source type populations and operating mode distributions rather than base rates. For example, the increase in HHD gasoline brake wear from MY 2010 to MY 2011 reflects a change in underlying rates while the changes before MY 2010 and after MY 2011 reflect changes in the relative population of the HD source types within the HHD regulatory class.

Finally, the figures below present brake wear emission rates for $PM_{2.5}$. These trends do not necessarily apply to PM_{10} because the calculation of brake wear PM_{10} rates depends on the ratios in the PM10EmissionRatio table.

Overall, these figures are intended to provide a summary of the MOVES brake wear rates that result from the base rates developed in Sections 2.2.1 through 2.2.4 and the braking activity described in Section 2.2.5. For the purpose of comparison, these figures are presented in the same format as the analogous figures presented in the MOVES reports for exhaust emissions from light and heavy-duty vehicles.[26 28]

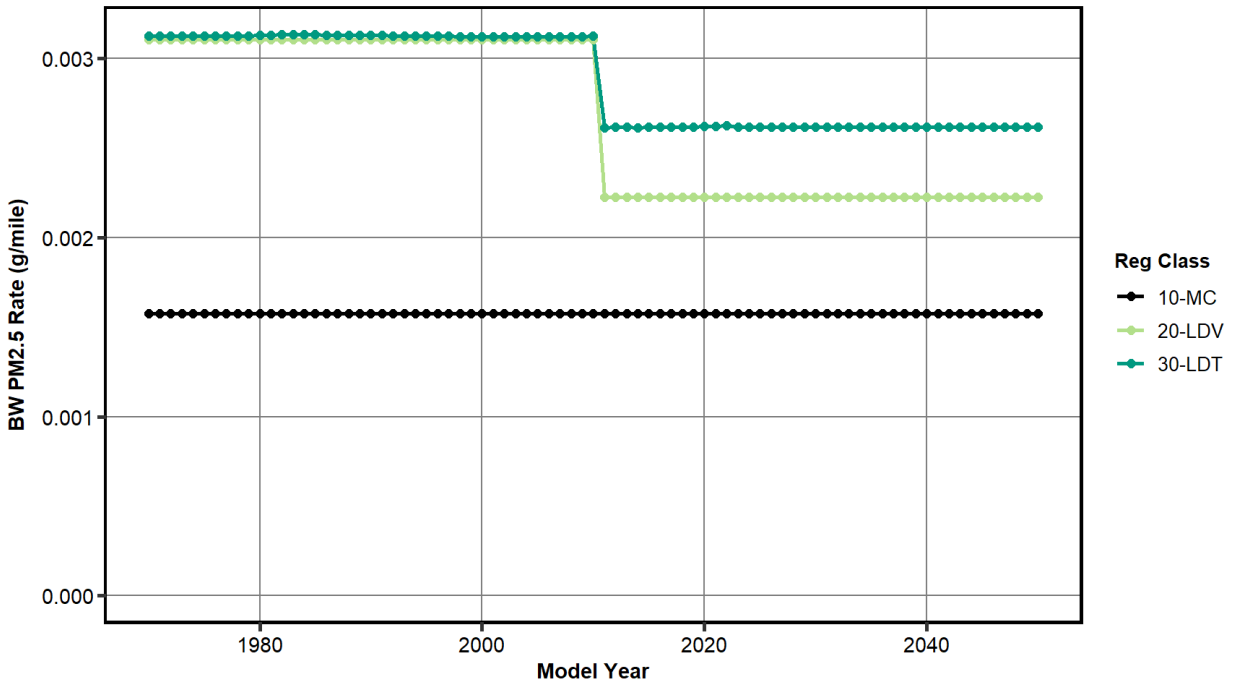


Figure 2-14 Brake wear $PM_{2.5}$ emission rates for light-duty gasoline vehicles averaged over a nationally representative operating mode distribution

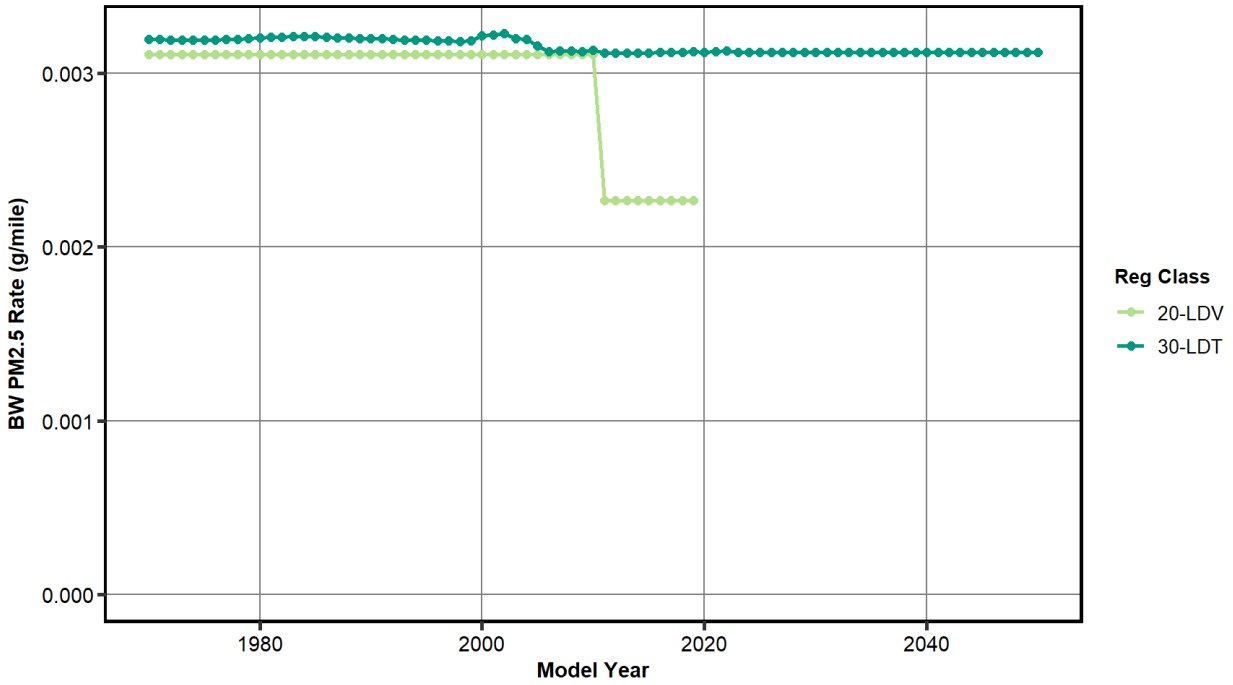


Figure 2-15 Brake wear $PM_{2.5}$ emission rates for light-duty diesel vehicles averaged over a nationally representative operating mode distribution[o]

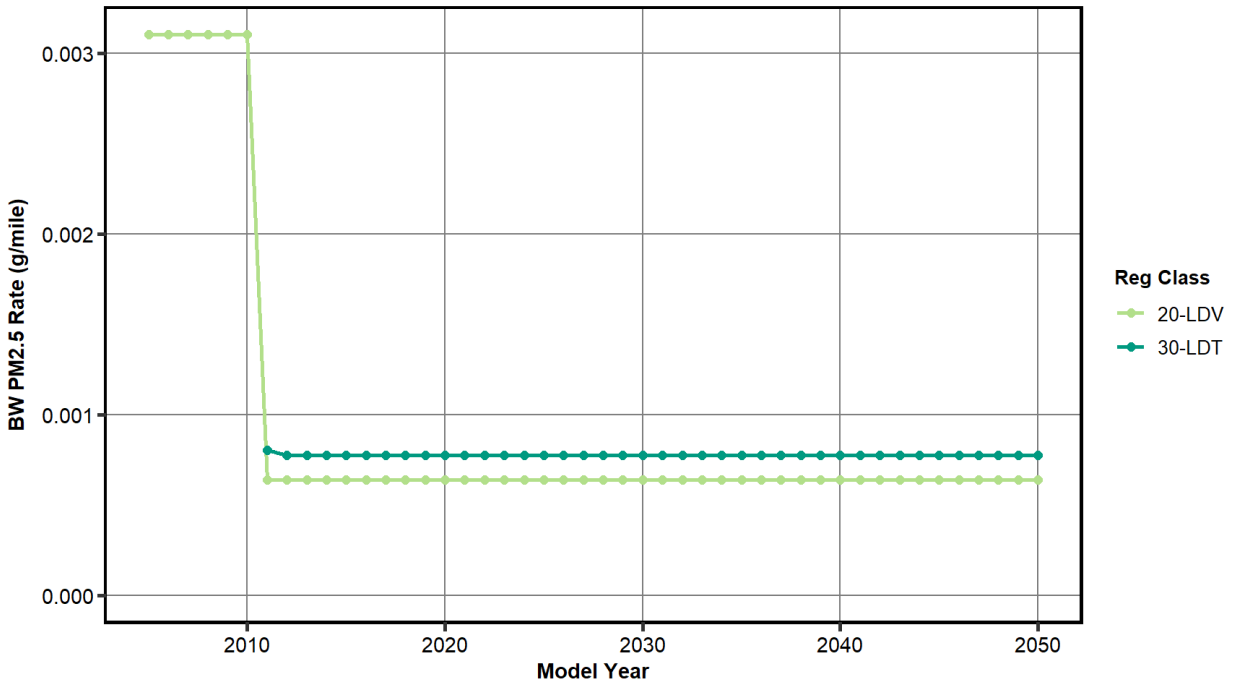


Figure 2-16 Brake wear $PM_{2.5}$ emission rates for light-duty electric vehicles averaged over a nationally representative operating mode distribution

[o] MOVES defaults have no light-duty diesel vehicles after model year 2019.

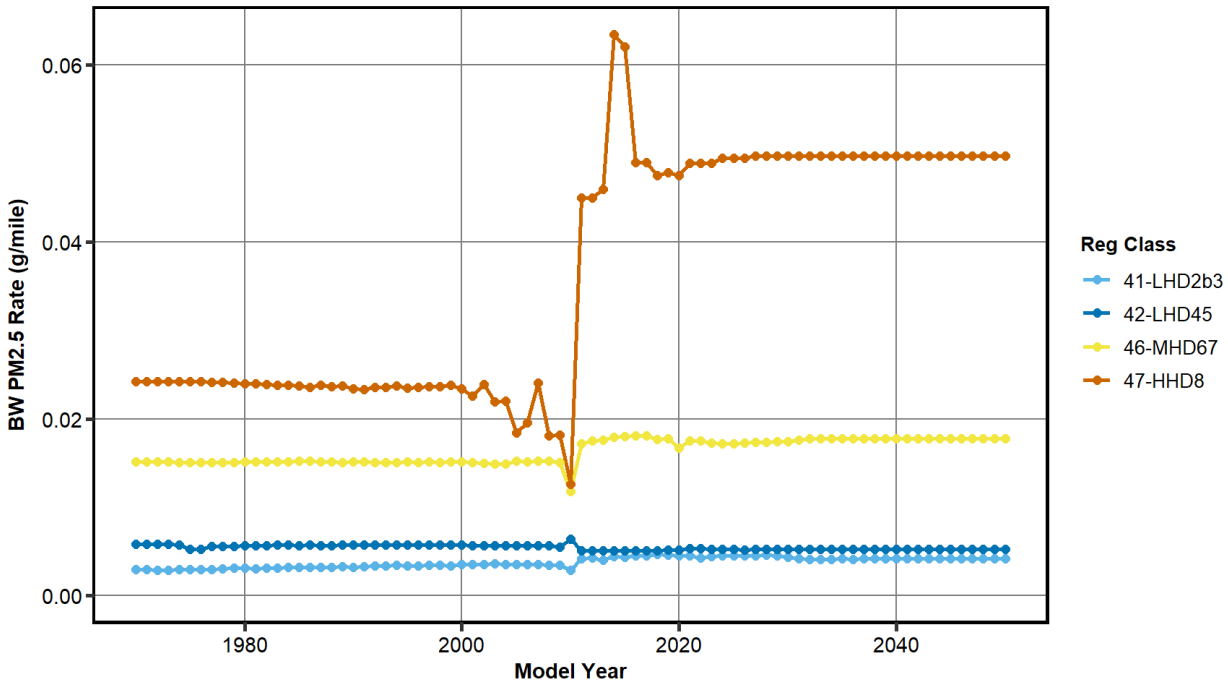


Figure 2-17 Brake wear $PM_{2.5}$ emission rates for heavy-duty gasoline vehicles averaged over a nationally representative operating mode distribution

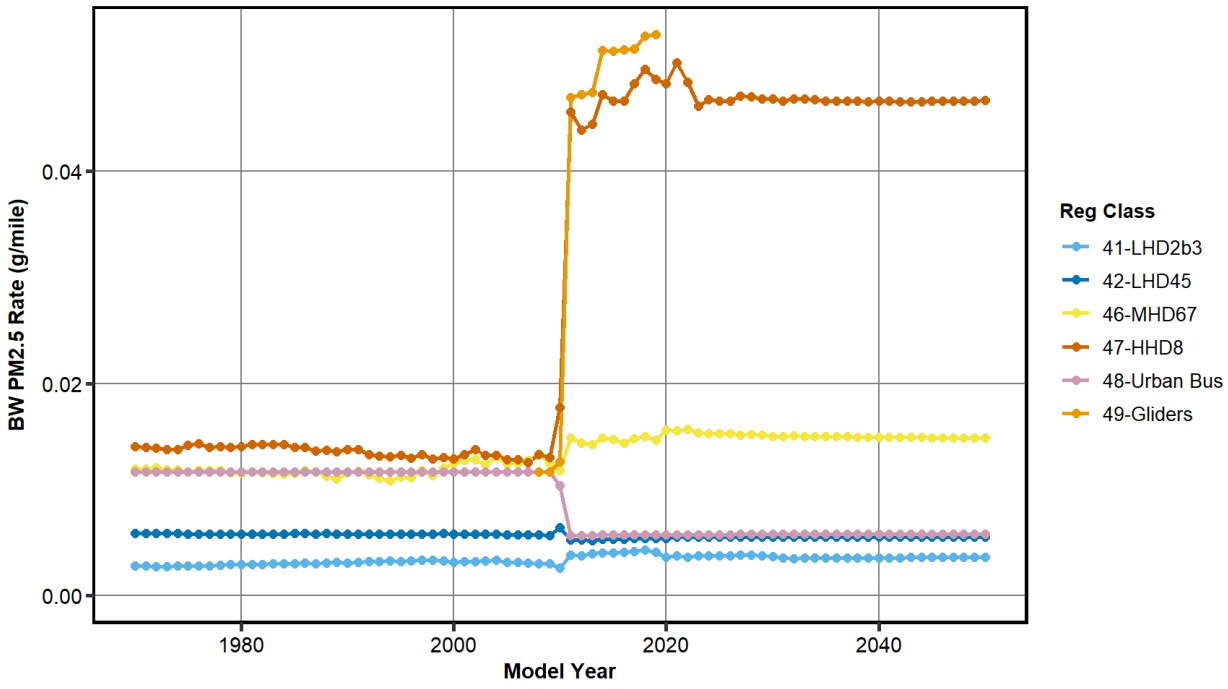
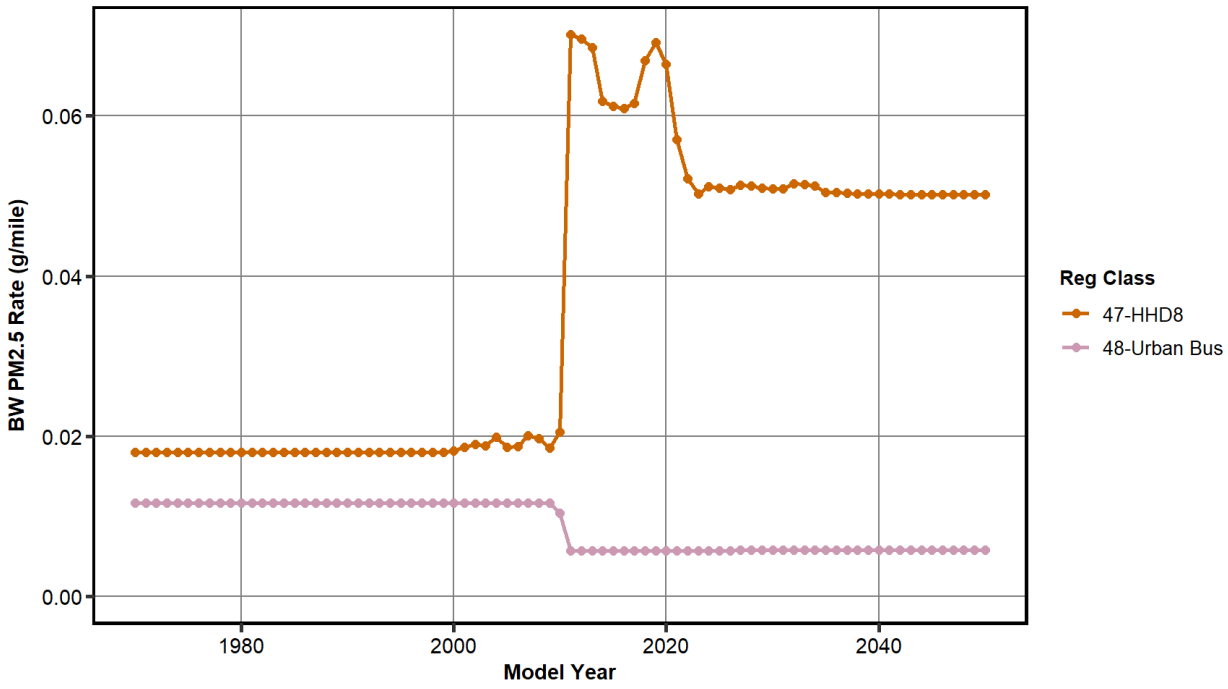


Figure 2-18 Brake wear PM2.5 emission rates for heavy-duty diesel vehicles averaged over a nationally representative operating mode distribution[p]



[p] MOVES defaults have no gliders after model year 2020.

Figure 2-19 Brake wear PM2.5 emission rates for heavy-duty compressed natural gas (CNG) vehicles averaged over a nationally representative operating mode distribution

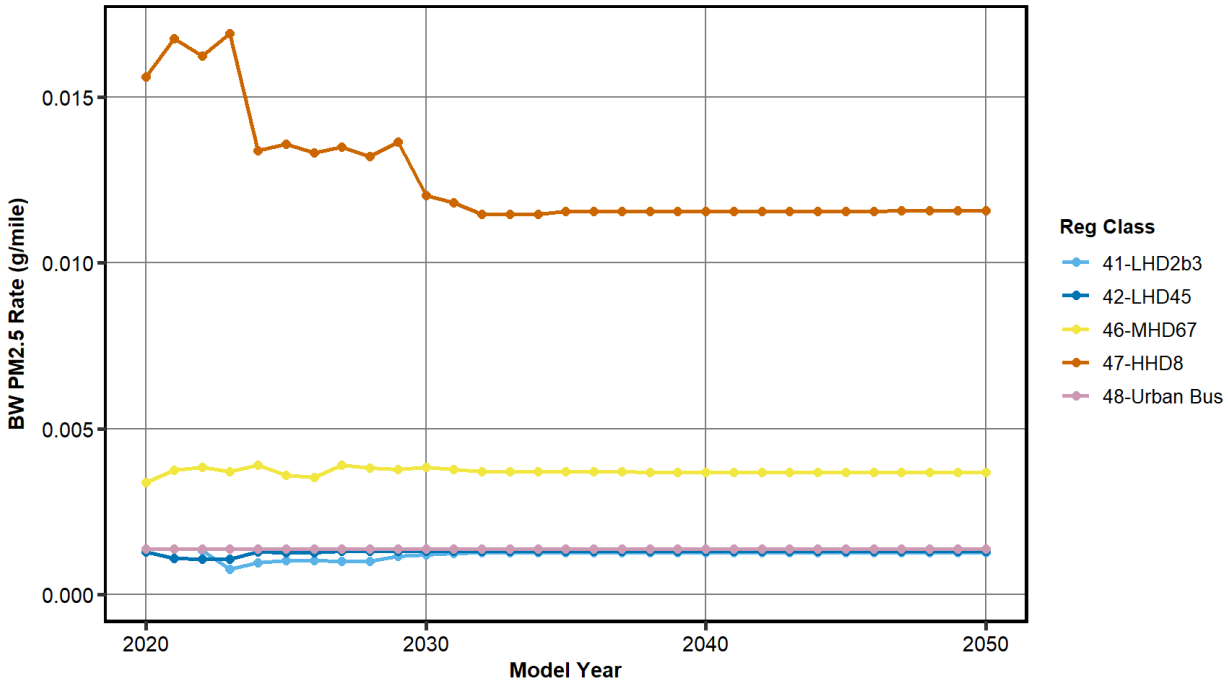


Figure 2-20 Brake wear $PM_{2.5}$ emission rates for heavy-duty electric vehicles averaged over a nationally representative operating mode distribution

3 Tire Wear

3.1 Introduction

Tires are an essential part of any vehicle, and the number and size of tires increase with the size of the vehicle. Contact between tires and the road surface causes the tires to wear, with the rate dependent on a variety of factors.

EPA's previous estimates of tire wear are contained in the PART5 model and are emission rates of 0.002 grams per mile per wheel. Two LDV studies from the 1970s are the basis for these emission rates. The PART5 emissions factors are based on tests of older bias-ply tires rather than more modern radial tire technologies. The National Resource Council report on the MOBILE model, suggested that the PART5 rates may be out of date.[29]

Tire wear occurs through frictional contact between the tire and the road surface. Friction causes small and larger particles to wear from tire, which are then either released as airborne particulates, deposited onto the road surface or retained in the wheel hub temporarily or permanently until washed off. The road surface causes friction and abrasion and therefore the roughness of the surface affects the wear rate by a factor of 2-3.[30]

In addition to road surface roughness, tires wear is dependent upon a combination of activity factors such as route and style of driving, and seasonal influences. Heavy braking and accelerating (including

turning and road grade) especially increase tire wear. The route and style of driving determine the amount of acceleration. Highway geometry is a key factor with rise and fall in roads also resulting in increased tread wear. The acceleration of the vehicle determines the forces applied to the tire and includes turning. Tire wear due to tire/road interface is determined by and is directly proportional to these forces.[31] The season results in temperature, humidity and water contact variations. Wear rates are lower in wet compared to dry conditions.

Finally, vehicle characteristics also influence tire wear. Key factors are the weight, suspension, steering geometry, and tire material and design. Axle geometry changes result in uneven wear across the tire width. The type of tire influences the wear significantly. In particular, the physical characteristics like the shape of the tire (determined by stiffness), the rubber volume (tread pattern), and the characteristic of the tire (rubber type etc.). As a consequence of different manufacturing specifications, different brands of tires wear at different rates. Retreads are also considered to wear more than new tires. Wear rate studies on tire fleets reported in Bennett & Greenwood (2001) also indicated that retreads had only about 75 percent of the tire tread volume that new tires had. Cenek et al. (1993) reported that 20 percent of New Zealand passenger tire sales were retreads and that retreads made up 75 percent of the tire tread in a sample of buses in the New Zealand fleet.[32] However, modeling emissions from retreads was deemed beyond the scope of the report.

According to the literature, the most straightforward method for determining tire wear is the periodic measurement of tread depth. However, variations in the extent of wear across the tire and irregularities in tire shape could lead to inaccurate measurements. Determining tire weight loss is a more sensitive approach than the measurement of tire depth, though care must be taken to avoid errors due to damage to tires as a result of their removal from the vehicle and hubs, and material embedded in the tire. To minimize damage to the tire, Lowne (1970) weighed both the wheel and tire simultaneously after the wheel was brushed and stones embedded in the tire were removed.[33] Table 3-1 shows a summary of the literature search conducted as of 2006 on the mass of tire wear.

Wear rates for tires have typically been calculated based on tire lifetime (in kilometers traveled), initial weight and tread surface depth. Tire wear occurs constantly for moving vehicles but may be significantly higher for cars which tend to brake suddenly or accelerate rapidly. Tire wear rates have been found to vary significantly between a wide range of studies.[34]

Speed variation is an important factor as well. Carpenter & Cenek (1999) have shown that the effect of speed variation is highest at low speeds as a result of inertial effects and effective mass.[35] They also examined lateral force effects on tires and assessed tire wear on routes of different amounts of horizontal curvature and found that there was little variation.

Tire abrasion is difficult to simulate in the laboratory, since the varied nature of the road and driving conditions influence wear rates in urban environments. Hildemann et al. (1991) determined the chemical composition of tire wear particles using a rolling resistance testing machine at a tire testing laboratory over a period of several days.[36] Rauterberg-Wulff (1999) determined particle emission factors for tire wear using modeling in combination with measurements conducted in the Berlin-Tegel tunnel.[37]

Tire wear rates have been measured and estimated for a range of vehicles from passenger cars to light and heavy-duty trucks with results reported either as emissions per tire or per vehicle. Most of the

studies report only wear, not airborne PM. The wear rates found in the literature are summarized in Table 3-1 below and are converted to a per vehicle rate (units are in per vehicle kilometer). A range of light-duty tire wear rates from 64-360 mg/vehicle/km has been reported in the literature. Much of the variability in these wear rates can probably be explained by the factors mentioned above. These studies made no distinction between front and rear tires, even though they can wear at different rates.[38]

Table 3-1 - Tire wear rates found in the literature. Rates are per vehicle. Estimated number of tires is described later.

Source	Remarks	rate in mg/vkm
Kupiainen,K.J. et al(2005)[39]	Measured tire wear rate	9 mg/km - PM_{10} 2 mg/km -$PM_{2.5}$
Luhana et al (2003)	Measured tire wear rate	74
Councell,T.B. et al (2004) U.S. Geological Survey[40]	Calculated rate based on literature	200
Warner et al. (2002)[41]	Average tire wear for a vehicle	97
Kolioussis and Pouftis (2000)[42]	Average estimated tire wear	40
EMPA (2000)[43]	Light duty vehicle tire wear rate	53
	Heavy duty vehicle tire wear rate	798
SENCO (Sustainable Environment Consultants Ltd.) (1999)[44]	Light duty vehicle tire wear rate Wear rate for trucks	53 1403
	Estimated rate for light duty vehicles	68
Legret and Pagotto (1999a)	Estimated rate for heavy vehicles (>3.5t)	136
Baumann (1997)[45]	Passenger car tire wear rate	80
	Heavy duty vehicle tire wear rate	189
	Articulated lorry tire wear rate	234
	Bus tire wear rate	192
Garben (1997)[46]	Passenger car tire wear rate	64
	Light duty vehicle tire wear rate	112
	Heavy duty vehicle tire wear rate	768
	Motorbike tire wear rate	32
Gebbe (1997)[47]	Passenger car tire wear rate	53
	Light duty vehicle tire wear rate	110
	Heavy duty vehicle tire wear rate	539
	Motorbike tire wear rate	26.4

Lee et al (1997)[48]	Estimated tire wear rate	64
Sakai,H (1995)	Measured tire wear rate	184
Baekken (1993)[49]	Estimated tire wear rate	200
CARB (1993)	Passenger car tire wear rate	120
Muschack (1990)	Estimated tire wear rate	120
Schuring and Clark (1988)[50]	Estimated tire wear rate	240-360
Pierce,R.N. (1984)	Estimated tire wear rate	120
Malmqvist (1983)[51]	Estimated tire wear rate	120
Gottle (1979)[52]	Estimated tire wear rate	120
Cadle et al. (1978)[53]	Measured tire wear rate	4
Dannis (1974)[54]		90

While there is significant literature on tear wear, there is relatively little published on airborne particulate matter from tires. In this report, a model for tire wear rates are first determined, and then a discussion of the modeling of airborne $PM_{2.5}$ and PM_{10} follows building off the wear model.

3.2 Data and Methodology

This report begins by estimating the tire wear from light-duty vehicles, then, based on the per tire wear, extrapolates to other vehicle types. Then the emission rates are derived from the wear rates.

The method primarily depends on the data from work published by Luhana et al. (2004) wherein wear loss rates for tires have been determined gravimetrically for in-service cars.[38] At the time of this analysis, this paper was both a recent and comprehensive study. The authors weighed car tires at two-month intervals, and asked drivers to note the details of each trip undertaken. Five test vehicles (labeled A-E) were selected for the tests. Of these vehicles A (1998 Audi A3), B (1994 Ford Mondeo), C (1990 Peugeot 205) and E (1992 Vauxhall Cavalier) were front-wheel drive vehicles (FWD). According to the driver surveys, the predominant road type used by vehicles A and B were motorways, for vehicle D (1990 Ford Sierra) it was rural roads and motorways; for vehicle C it was suburban roads, and for vehicle E, it was rural roads. Vehicle D was excluded from this study since it was a rear-wheel drive (RWD) vehicle. RWD vehicles are relatively uncommon amongst passenger vehicles in the United States, and the wear from this particular vehicle was more than double the other FWD vehicles. It is uncertain whether the discrepancy from this vehicle was because it was a rear-wheel drive or for some other reason. The selection of vehicles was based primarily on driving conditions, as defined by the main type of road used by the owner and annual distance driven.

Results from the Luhana et al. (2004) study indicated that the lowest tire wear rates (56 mg/vkm and 67 mg/vkm respectively[q]) were for vehicles A and B that were driven predominantly on motorways. Vehicles C and E had very similar wear rates (around 85 mg/vkm) although these vehicles tended to be driven on different roads. Based on the wear rates from the four front-wheel drive cars alone, the study concluded that the average wear rate is around 74 mg/vkm. This value is in the lower end of the range of wear rates reported in the literature.

The data presented in Table 3-2 includes calculations for the distances completed by each vehicle between successive tests, the estimated average trip speeds and predominant road types for the equivalent periods. It was assumed that the weight of the wheels remained constant during the tests, and any weight loss was due solely to the loss of tire rubber during driving.

[q] vkm is “vehicle kilometer” and assumes four times a per tire rate for light-duty vehicles.

Table 3-2: Data from Luhana et al. (2004) with measurements of tire wear for a variety of trips

	Avg. trip speed	Tire Wt. Loss (per axle)		total wt. loss (per vehicle)	total wt. loss (per vehicle)	avg. speed
vehicle tests	km/hr	Front mean (g/km)	Rear Mean (g/km)	g/km	g/mi	mi/hr
test1-A	90.3	0.0202	0.0092	0.0589	0.0947	56.1
test2-A	90.6	0.0209	0.0126	0.0669	0.1076	56.3
test3-A	93.9	-	0.0069	-	-	58.4
test4-A	92.7	0.0172	0.0086	0.0516	0.083	57.6
test1-B	65.4	0.0298	0.0087	0.077	0.1239	40.6
test2-B	71.9	0.0262	0.0091	0.0705	0.1135	44.7
test3-B	74.4	0.019	0.004	0.0461	0.0742	46.2
test4-B	70.2	0.0297	0.007	0.0735	0.1183	43.6
test1-C	44.5	0.0312	0.0047	0.0718	0.1155	27.7
test2-C	42.9	0.0331	0.0132	0.0925	0.1489	26.7
test3-C	48.8	0.0284	0.0064	0.0697	0.1121	30.3
test4-C	50.4	0.0532	0.0045	0.1153	0.1855	31.3
test3-E	61.3	0.037	0.0104	0.0948	0.1525	38.1
test4-E	65.8	0.0265	0.0109	0.0749	0.1205	40.9

Note: Vehicles A and B were driven mainly on motorways (freeways)
Vehicle C was driven on Suburban Roads and
Vehicle E was driven mostly on Rural roads

3.3 Analysis

Tire wear clearly varies with acceleration as well as speed, and we would like to model it by VSP bin as we model brake wear. However, there is insufficient data to characterize tire wear on a second-by-second basis to enable binning by operating mode bins. Thus, MOVES currently models tire wear based on average speed as shown in Table 3-3.

Table 3-3: MOVES tire wear operating mode bins based on average speed

opModeID	opModeName	speed lower in mph	speed upper in mph
400	tirewear;idle		
401	tirewear;speed < 2.5mph	0	2.5
402	tirewear;2.5mph <= speed < 7.5mph	2.5	7.5
403	tirewear;7.5mph <= speed < 12.5mph	7.5	12.5
404	tirewear;12.5mph <= speed < 17.5mph	12.5	17.5
405	tirewear;17.5mph <= speed <22.5mph	17.5	22.5
406	tirewear;22.5mph <= speed < 27.5mph	22.5	27.5
407	tirewear;27.5mph <= speed < 32.5mph	27.5	32.5
408	tirewear;32.5mph <= speed < 37.5mph	32.5	37.5
409	tirewear;37.5mph <= speed < 42.5mph	37.5	42.5
410	tirewear;42.5mph <= speed < 47.5mph	42.5	47.5
411	tirewear;47.5mph <= speed < 52.5mph	47.5	52.5
412	tirewear;52.5mph <= speed < 57.5mph	52.5	57.5
413	tirewear;57.5mph <= speed < 62.5mph	57.5	62.5
414	tirewear;62.5mph <= speed < 67.5mph	62.5	67.5
415	tirewear;67.5mph <= speed < 72.5mph	67.5	72.5
416	tirewear;72.5mph <= speed	72.5	

Using the above data on average speed and total weight loss, an exponential regression curve was fitted which was characterized by an R^2 value of 0.43. The actual and predicted values are presented in Figure 3-1.

A weak negative correlation is shown between tire wear and average trip speed, with wear being around 50 percent higher at an average speed of 40 km/h (dominated by urban driving) than at an average speed of 90 km/h (dominated by motorway driving).

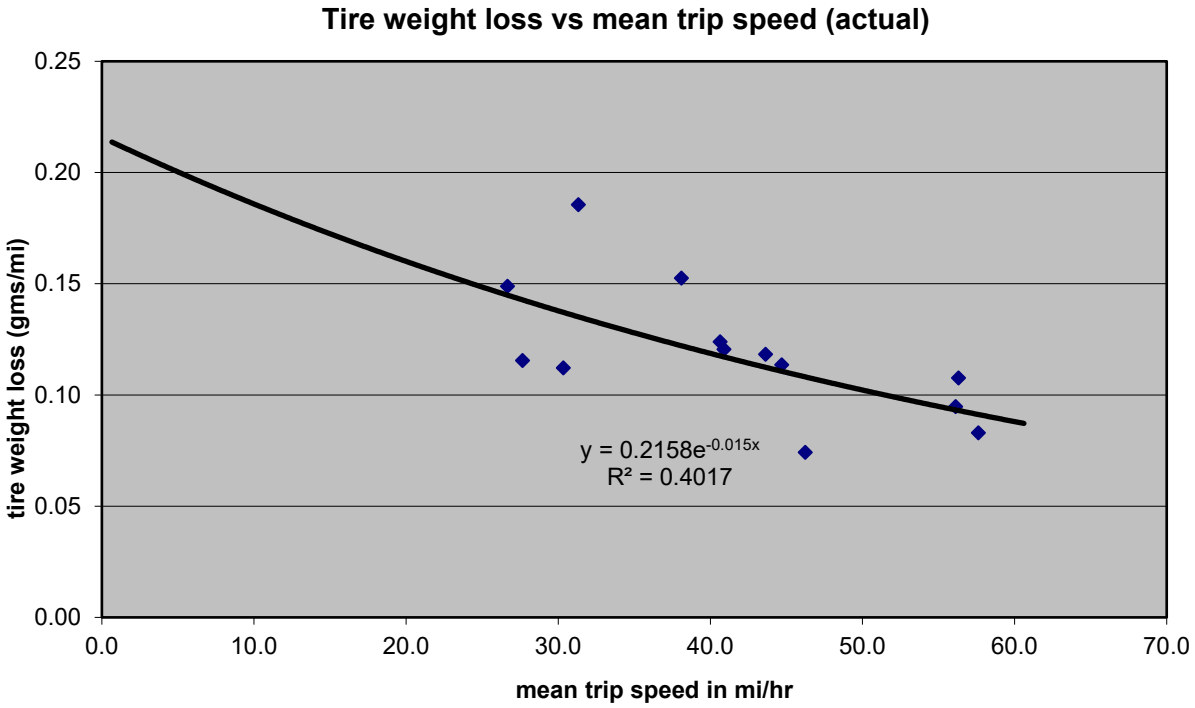


Figure 3-1 Relationship between light-duty tire weight loss (per vehicle) and mean trip speed

The shape of the curve in Figure 3-1 deserves some discussion. It can be seen from the curve that the wear approaches a maximum at zero speed and goes down as the speed goes up. This is based on the extrapolation of the fitted curve. It may seem counter-intuitive that emissions are highest when speed nears zero, however, it is important to note that we do not otherwise account for acceleration and turning. Much of the tire wear occurs when the magnitude of a vehicle's acceleration/deceleration is at its greatest, e.g. at low speeds when the vehicle is accelerating from rest, or when the vehicle is braking hard to stop.

However, for MOVES, the emission rate for average speeds less than 2.5 mph is set to zero at all scales to avoid anomalous results in project level analyses where increased idling would result in an over prediction of tire emissions. In addition, MOVES does not model off-network idle or extended idle emissions for tire wear because the vehicle is completely stopped during this non-drive-cycle idle time.

The predicted values as determined above are for passenger cars (LDVs). To determine tire wear loss rates for other regulatory classes it was assumed that total tire wear per vehicle is dependent upon the number of tires on the vehicle which, in turn, is a function of the number of axles per vehicle by vehicle

class. We did not distinguish between drive axles and other axles. Axle counts were found in the Vehicle Inventory and Use Survey (VIUS 2002) data base. This data enabled the calculation of tires per vehicle for each of the six truck classes and thereby tire-wear losses for the different truck categories (regulatory classes) were determined. The average number of tires per truck is given in Table 3-4 below.

Table 3-4 Average Number of Tires per Vehicle – Calculated from 2002 VIUS Survey of axle count.

RegClassID	RegClass name	Average Tires Per Vehicle
10	MC	2.0
20	LDV	4.0
30	LDT	4.0
41	LHD2b3	5.5
42	LHD45	6.0
46	MHDD	7.0
47	HHDD	14.9
48	Urban Bus	8.0

* Note: Tires per vehicle for LDT is the same as that for LDV

Once the average tire wear was quantified, it was necessary to determine the fraction of that wear that becomes airborne PM. The literature indicates that probably less than 10 percent of car tire wear is emitted as PM_{10} under 'typical' driving conditions but the proportion could be as high as 30 percent (Boulter2005a). According to Luhana et al. (2004), PM_{10} appears to be released from (all 4) tires at a rate of between 4 and 6 mg/vkm for passenger cars. This suggests that generally between around 1 percent and 15 percent by mass of passenger car tire wear material is emitted as PM_{10} (though much higher proportions have been reported in some studies). For this study, it is assumed that 8 percent of tire wear is emitted as PM_{10} (average of 1 percent and 16 percent. According to Kupiainen et al (2005), $PM_{2.5}$ fractions were on average 15 percent of PM_{10}.[39] Based on this study, it is assumed that 1.2 percent of the total tire wear is emitted as $PM_{2.5}$ to develop our tire wear emission rate. The 1.2 percent is derived from assuming that 8 percent of tire wear to be emitted as PM_{10} and 15 percent of PM_{10} is $PM_{2.5}$.

We then convert the g/vehicle/mile tire wear emission rates to g/hr by multiplying by the average speed of each MOVES speed bin. The g/hour tire wear emission rate by speed bin for all regulatory classes used in MOVES can be found in Appendix A. MOVES applies the same tire wear emission rate for all vehicle fuel types (gasoline, diesel, flex-fuel, CNG or electric) within a MOVES regulatory class. The average $PM_{2.5}$ tire wear emission rates in (mg/mile) for each regulatory class, across road types and speed bins, from a national-scale run for calendar year 2017 using MOVES3 is shown in Table 3-5.

Table 3-5 Average $PM_{2.5}$ and PM_{10} tire wear PM emission rates for the MOVES regulatory classes from a national-scale run inventory for calendar year 2017 using MOVES3

sourceTypeID	sourcetypename	$PM_{2.5}$		PM_{10}	
		mg/veh-mile	mg/veh-km	mg/veh-mile	mg/veh-km
11	Motorcycle	0.64	0.40	4.29	2.66
21	Passenger Car	1.28	0.80	8.55	5.32
31	Passenger Truck	1.28	0.80	8.57	5.32
32	Light Commercial Truck	1.37	0.85	9.16	5.69
41	Intercity Bus	3.87	2.40	25.77	16.01
42	Transit Bus	2.35	1.46	15.68	9.74
43	School Bus	2.30	1.43	15.31	9.51
51	Refuse Truck	3.93	2.44	26.19	16.27
52	Single Unit Short-haul Truck	2.25	1.40	15.03	9.34
53	Single Unit Long-haul Truck	2.17	1.35	14.48	9.00
54	Motor Home	2.21	1.37	14.75	9.16
61	Combination Short-haul Truck	3.81	2.37	25.39	15.78
62	Combination Long-haul Truck	4.13	2.56	27.51	17.10

3.3.1 $PM_{10}/PM_{2.5}$ Tire Wear Ratio

MOVES stores $PM_{2.5}$ tire wear emission rates by operating mode bin (in this case, speed bins), then estimates PM_{10} emission rates by applying a $PM_{10}/PM_{2.5}$ ratio. Thus, MOVES applies a $PM_{10}/PM_{2.5}$ ratio of 6.667, which is based on the particle size distribution of tire wear measured by Kupianen et al. (2005)[r]. Grigoratos et al. (2018)[55] reported $PM_{10}/PM_{2.5}$ ratios between 2 and 2.5 (rather than 6.67). These values will be considered in future tire wear updates in MOVES. The average PM_{10} emission rates from the national-scale run inventories using MOVES3 are displayed in Table 3-5.

[r] The $PM_{10}/PM_{2.5}$ ratio is derived from dividing the PM_{10} fraction of total PM, by the $PM_{2.5}$ fraction of total PM: .08/.012 = 6.667 from values reported by Kupianen et al. (2005)[39].

3.4 Tire Wear Emissions in Project-Scale

In project scale, tire-wear emissions are estimated using the link average speed, with one exception. If the user provides a link-level driving cycle (using the MOVES driveScheduleSecondLink input table), then MOVES will calculate the average speed from the input driving schedule, rather than the average speed associated in the link table). As opposed to brake wear emissions, MOVES users do not have the option to input their own operating mode distribution (using the opModeDistribution table)[5]. Because the tire wear emission rates are based on average speed over a roadway link, MOVES only uses the most appropriate average speed over the link.

As stated earlier, the tire wear emission rate at idle is set to zero in the default emission rate table (Appendix A) used at all scales of analysis.

Appendix A Deceleration from PERE

This appendix briefly describes some of analytical methods used to determine the deceleration point at which coasting becomes braking. A full description of the PERE model is provided in a separate EPA report as cited earlier. This section provides additional information beyond what can be found in the PERE documentation.

The basis for the tractive load equations in the PERE model are found in the A, B, C coastdown coefficients described in the report. The author of this report conducted coastdown testing on a ~2001 Nissan Altima on relatively "flat" roads in Southeast Michigan. The A, B, C coefficients for this vehicle can be found in the EPA database. The A, B, C tractive load equations in PERE were converted to a coastdown curve and plotted compared to the data below. The area above the curve is throttle and the area below the curve is braking. The curve itself is "coasting" on neutral gear.

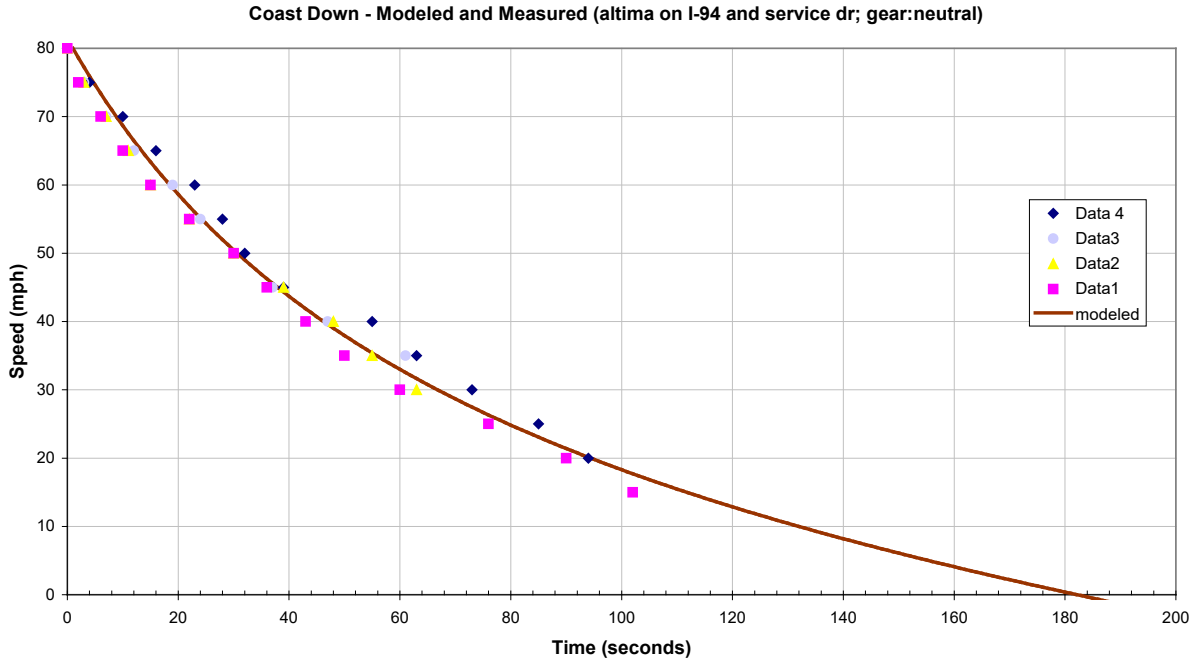


Figure A-1 Coastdown- Modeled and Measured (Altima on I-94 and Service Drive; Gear: neutral)

Based on these coastdown equations, a series of coastdown curves are generated as a function of vehicle mass. As in the previous plot, the area under the curve is braking and the area above the curve is throttling.

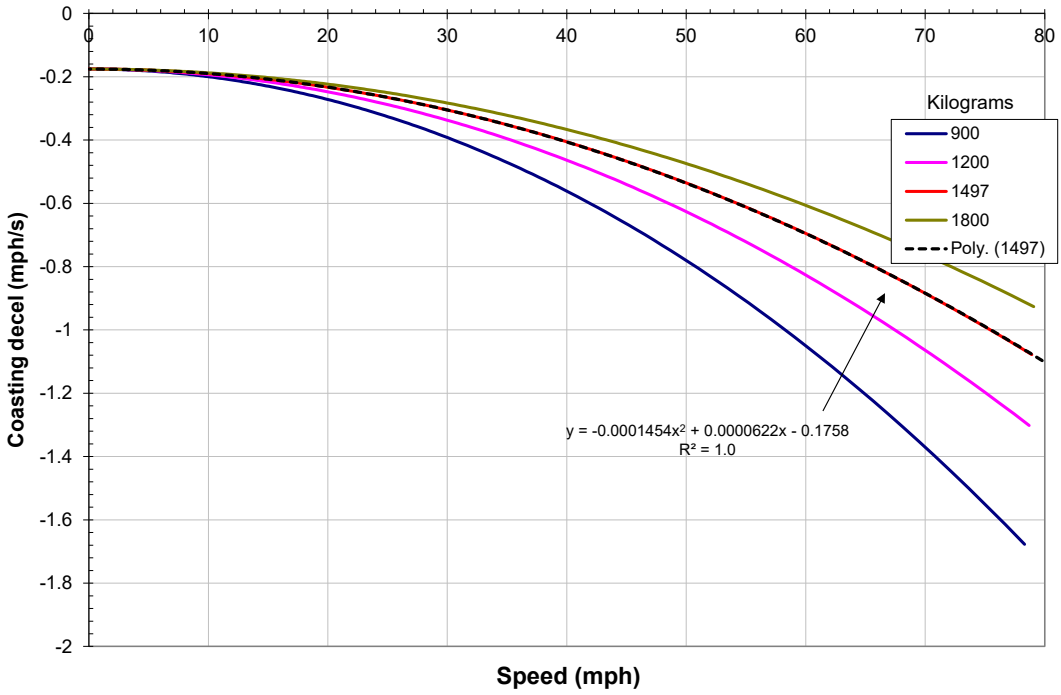


Figure A-2. Coastdown Curves as a Function of Vehicle Mass

A PERE simulation is run on the FTP cycle and the braking episodes are flagged in the figure below (for a typical 1497kg LDV).

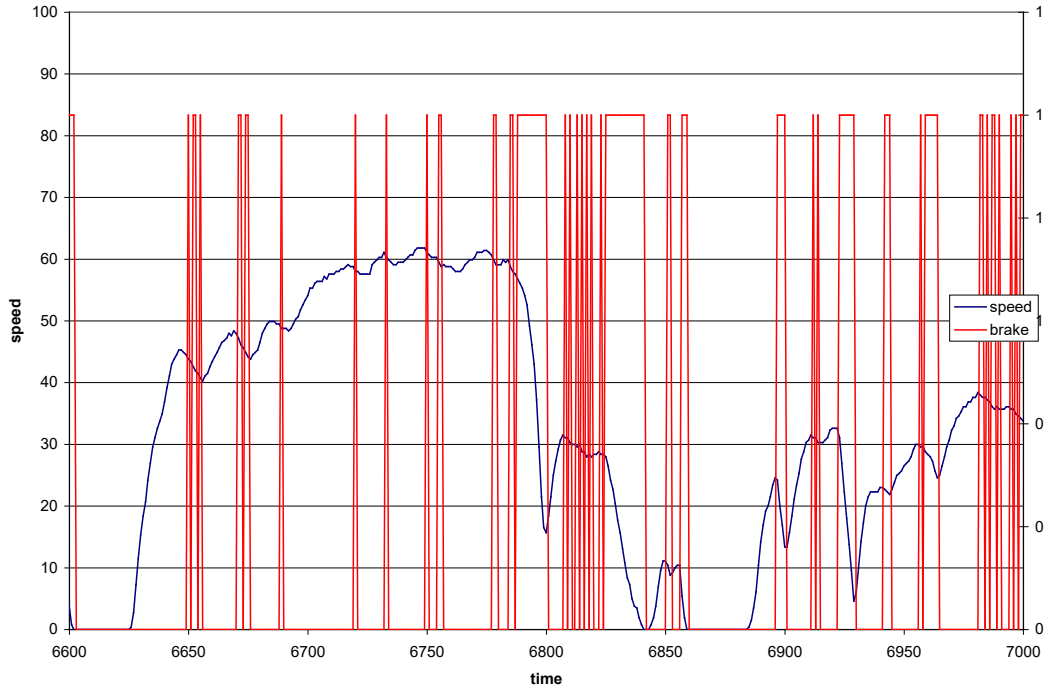


Figure A-3 Braking Episodes over the FTP cycle

Appendix B Literature Review conducted for MOVES2009

Table B-1 Brief review of literature on brake and tire wear

Luhana, L.;Sokhi,R.;Warner,L.;Mao,H; Boulter,P;McCrae,I.S.;Wright,J and Osborn,D,"Non-exhaust particulate measurements:results," *Deliverable 8 of the European Commission DG TrEn, 5th Framework PARTICULATES project , Contract No.* 2000 - RD.11091, Version 2.0 , October 2004.	2004	Non-exhaust particle research was conducted in the Hatfield road tunnel. Combined tire and brake wear emissions for PM_{10} from LDVs and HDVs in the tunnel were found to be 6.9mg/vkm and 49.7mg/vkm respectively. These emission factors from the Hatfield Tunnel Study appears to be at the lower end of the range of values reported elsewhere. The report also includes a literature review which examines the state of the art in the field. Tire wear and brake wear rates are listed below.
Sanders, Paul G.; Xu, Ning ; Dalka, Tom M.; and Maricq, M. Matti, "Airborne Brake Wear Debris: Size Distributions, Composition, and a Comparison of Dynamometer and Vehicle Tests", *Environ. Sci. Technol.,* 37,4060-4069,2003	2003	A brake wear study was performed using seven brake pad formulations that were in high volume use in 1998. Included were low-metallic, semi-metallic and non-asbestos organic (NAO) brakes. The quantity of airborne PM generated by automotive disk brakes was measured on a brake dynamometer that simulated: urban driving (low velocity, low g) and the Auto Motor und Sport (AMS, high velocity, high g). Airborne fractions from the low-metallic and semi-metallic linings were 5 and 1.5 times higher than the NAO lining.
L.R.Warner; R.S. Sokhi; L.Luhana; P.G. Boulter; and I. McCrae, "Non-exhaust particle Emissions from Road Transport", *Proceedings of the 11th International Symposium on Transport and Air Pollution,* Graz, 2002.	2002	The paper presents preliminary results of gravimetric determination of tire and brake wear for cars, and chemical analysis of ambient particle samples for source identification using Inductively Coupled Plasma (ICP) spectrometry. Results suggest that the average loss rates of tire and brake material are 97 and 9 mg/vkm respectively. The ICP analysis shows a high relative abundance of Ba, Sb, Zr and Sr for brake and Zn for tire material. The chemical analysis also suggests that for tire wear it is much

		more difficult to use metal concentrations as tracers.
Abu-Allaban, M.;Gillies, J.A.; Gertler, A.W.; Clayton ,R.; and Proffitt, D., "Tailpipe, re-suspended road dust, and brake wear emission factors from on-road vehicles," *Atmospheric Environment,* 37(1),5283-5293,2002.	2002	Intensive mass and chemical measurements were performed at roadside locations to derive brake-wear emission factors from in-use vehicles. PM_{10} emission rates for LDSI vehicles ranged from 0 to 80 mg/vkm and for HDVs from 0 to 610 mg/vkm. The $PM_{2.5}$ emissions ranged from 0 to 5mg/vkm for LDSI vehicles and from 0 to 15mg/vkm for HDVs. Emissions from brake wear were highest near motorway exits.
Lukewille,A.; Bertok,I.; Amann, M., Cofala,J.; Gyarfas,F.; Heyes,C.; Karvosenoja,N.; Klimont Z.; and Schopp, W., " A framework to estimate the potential and costs for the control of fine particulate emissions in Europe", *IIASA Interim Report IR-01-023,* Laxenburg, Austria,2001.		
Westerlund,K.G.," Metal emissions from Stockholm traffic – wear of brake linings ",*The Stockholm Environment and Health Protection Administration*, 100,64,Stockholm,Sweden,2001.	2001	Westerlund estimated the amount of material lost due to brake wear from passenger cars and heavy goods vehicles. The PM_{10} emission factors were determined to be 6.9 and 41.2mg/vkm for LDVs and HDVs respectively.
Garg, B.D.; Cadle, S.H.; Mulawa, P.A.; Groblicki, P.J.; Laroo, C.; and Parr, G.A., "Brake wear particulate matter emissions", *Environmental Science & Technology,* 34(21),4463,2000b.	2000	A brake wear study was performed using seven brake pad formulations (non-asbestos) that were in high volume use in 1998. Brakes were tested on a brake dynamometer under four wear conditions. The brake application was designed to simulate real world events by braking from 50km/h to 0km/h at a deceleration of 2.94 m/s^2. The estimated range of PM emission rates for small vehicles to large pickup trucks are 2.9 -7.5 mg/vkm and 2.1 – 5.5 mg/vkm for PM_{10} and $PM_{2.5}$ respectively.
Annette Rauterberg-Wulff, "Determination of emission factors for tire wear particles up to 10um by tunnel measurements", *Proceedings of*	1999	PM_{10} emission factors were determined for tire and brake wear using receptor modeling in combination with measurements conducted in the Berlin-Tegel tunnel. Tire

8th International Symposium on Transport and Air Pollution, Graz, 1999.		wear emission factors for LDVs and HGVs in the tunnel was calculated to be 6.1 mg/vkm and 31 mg/vkm. For brake wear it was 1.0 and 24.5 mg/vkm respectively.
Carbotech, "PM_{10} Emissionsfaktoren:Mechanischer …….",*Arbeitsunterlage,* ,17,1999	1999	Cited in Lukewille et al. (2001). The PM_{10} brake wear emission factor for LDVs was determined to be 1.8 mg/km and for HDVs it was 3.5 mg/vkm.
Cha,S.; Carter,P.; and Bradow, R.L., "Simulation of automobile brake wear dynamics and estimation of emissions,"*SAE Transactions Paper,*831036, Society of Automotive Engineers, Warrendale, Pennsylvania,1983	1983	Particulate emissions from asbestos-based brakes from automobiles were measured under conditions simulating downtown city driving. The report presents a systematic approach to simulating brake applications and defining particulate emissions. Based on the 1.6:1.1 wear ratio between disc and drum brakes, the estimated airborne particulate (PM_{10}) emission rate was estimated to be 12.8mg/vmi or 7.9 mg/vkm.

4 References

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[5] USEPA (2020). *Exhaust Emission Rates of Heavy-Duty Onroad Vehicles in MOVES3*. EPA-420-R-20-018. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports.

[6] Edmunds.com, http://www.edmunds.com/car-technology/brakes-drum-vs-disc.html.

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