Brake and Tire Wear Emissions from Onroad Vehicles in MOVES3

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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1 List of Acronyms

AMS	Auto Motor Sports magazine
CMB	Chemical Mass Balance
CNG	Compressed Natural Gas
ELPI	Electrical Low Pressure Impactor
EPA	U.S. Environmental Protection Agency
ERG	Eastern Research Group
FTP	Federal Test Procedure
HD	Heavy-Duty
HHD	Heavy-Heavy-Duty
LD	Light-Duty
LDT	Light-Duty Trucks
LDV	Light-Duty Vehicle
LHD	Light-Heavy-Duty
MC	Motorcycle
MHD	Medium-Heavy-Duty
MOBILE	Original Highway Vehicle Emission Factor Model pre-2004
MOVES	Motor Vehicle Emission Simulator Model
NAO	non-asbestos organic
PART5	computer model (programmed in Fortran) for calculating PM_{10} and $PM_{2.5}$ emissions from vehicles
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
UDP	urban driving program

VMT	Vehicle Miles Traveled
VSP	vehicle specific power

2 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. Unlike $PM_{2.5}$ exhaust emissions, 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 located in AP-42.[3]

This report was 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 are essentially the same as in MOVES2014 versions. However, two general updates (among other MOVES3 onroad model changes) are 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 3.2.5.

2) MOVES3 now models “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 3.2.3.

3 Brake Wear

3.1 Literature Review

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 brakeliner 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. Disc brakes are sometimes used on rear wheels as well for higher performance (sportier) vehicles.

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. 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 C. 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 previous paragraphs 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 ($\leq 1.6\ m/s^2$) 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 3-1 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 3-1 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 their own includes all Light-duty vehicles, including trucks though the studies are not all equivalent in their definitions.

3.2 Developing Rates for MOVES

3.2.1 Emissions during Braking

The analysis for MOVES braking emission rates was based on the average of:

1. Composition of brake pad
2. Number (and type) of brakes
3. Front vs rear braking
4. Airborne fraction

and explicitly accounts for:

1. Particle mass size distribution ($PM_{2.5}$ vs PM_{10})
2. Braking intensity
3. Vehicle class: Light-Duty vs Heavy-Duty

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.

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).

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.

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.

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[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.

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 3-2 – 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**

Table 3-3 – Wind Tunnel results

Test	brake lining	PM$_{10}$ emiss.	(mg/stop/brake)	
Tunnel		filter	ELPI	MOUDI
	low metallic	44	45	40
deceleration=			**0.0018**	**in km/s^2**
Initial Velocity V(0) =			0.0267	in km/s
avg. brake time in sec =V(0)/dec			14.8	secs
avg. emissions in mg/stop =			129.0	mg/stop
emision rate for the wind tunnel test=			**31.4**	**g/hr**

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[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 PM10 were determined by multiplying the total PM reported in Table 5 of the paper with the PM10 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 PM10 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 3-4 – 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	in km/s^2
Initial Velocity V(0) =	0.0278	in km/s
avg. brake time in sec =V(0)/dec	3.5	secs
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 3-5 – 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	in km/s^2
Initial Velocity V(0) =	0.0139	in km/s
avg. brake time in sec =V(0)/dec	4.7	secs
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 shown in the following **Figure 3-1**. 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.

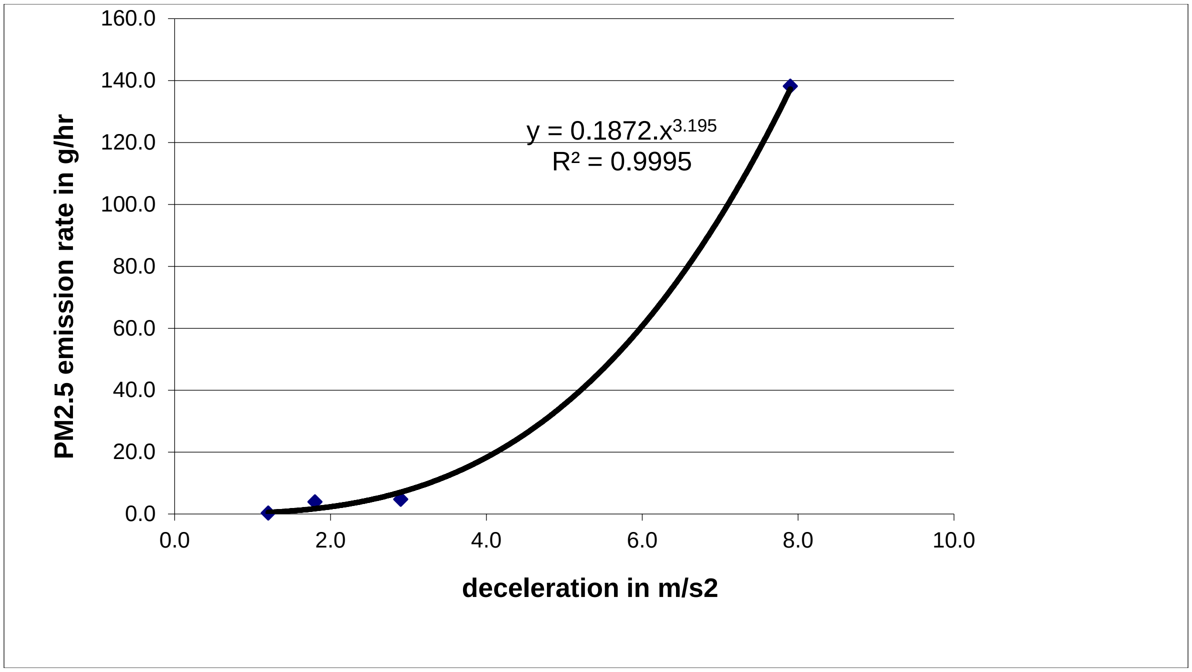

Figure 3-1- Brake wear $PM_{2.5}$ emission rates in units of grams per hour for light duty vehicles as a function of deceleration rate based on Sanders et al. (2003) and Garg et al. (2000)

3.2.2 Braking Activity

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, but classifies driving into operating modes that are quite different than the deceleration levels used in brake wear testing. There are four 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.
3. Assign an appropriate amount of this braking to each of the MOVES operating modes.
4. Modify these assignments for other types of vehicles.

Each of these steps is detailed below.

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 “coasting” bins by first determining the coast down curve, then combining that with the activity fraction as seen in the real-world driving surveys.

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 activity below coastdown is braking and all activity above the curve is low throttle deceleration. Figure 3-2 shows coastdown curves for cars of a variety of weights (and coastdown coefficients). The dotted curve is a typical coast down 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.

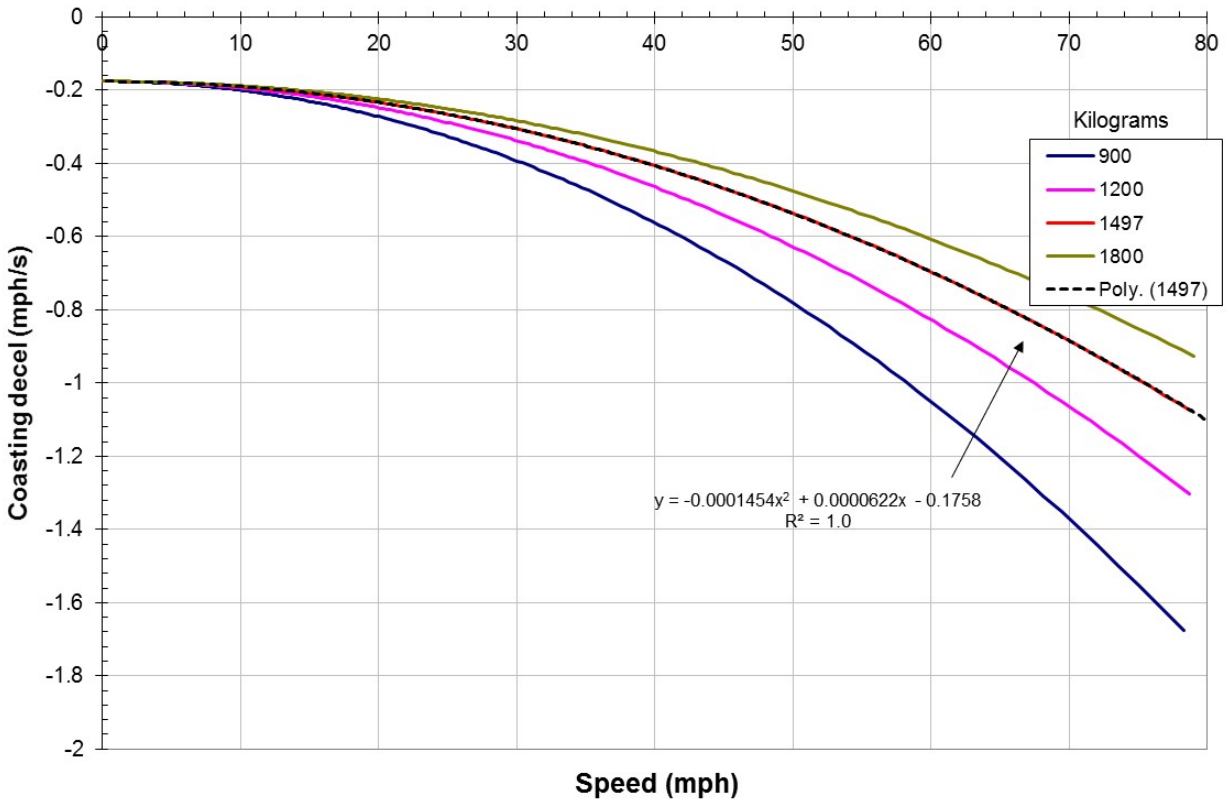

Figure 3-2- Modeled Coastdown curves using the PERE model for a variety of light-duty vehicles masses

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 on conventional as well as 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 with both instrumented vehicles as well as chase car data.[13,14,15] The deceleration data was analyzed for both of these studies.

Table 3-6 shows the distribution of braking activity across deceleration levels from both the Kansas City and Los Angeles studies. As expected, the vast majority of braking occurs during mild decelerations rather than full (high deceleration) stops.

Table 3-6 – 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 3-1** 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.

Third, as mentioned earlier, MOVES models the full range of driving conditions, and thus, we needed to establish the amount of braking in the MOVES operating modes.

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). This parameter represents the tractive power exerted by a vehicle to move itself and its cargo or passengers[11]. It is estimated in terms of a vehicle's speed and mass. The MOVES operating modes for light-duty running exhaust and brake wear emissions are listed in Table 3-7. Similar operationg modes are available for heavy-duty. More information on these operating modes is available in the MOVES3 light duty and heavy duty exhaust emission reports.[16,5]

Table 3-7 – MOVES Operating Mode Bins by VSP and speed

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

The MOVES vehicle specific power (VSP) bins are relatively coarse for braking.[e] There is a large “braking” bin (operating mode 0) where all of the activity is assumed to be braking. The “idle” bin covers speeds from -1 to 1 mph, and includes some braking in the transition

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[e] While this document does not provide a detailed discussion of vehicle specific power, the light duty emission rate report[16] have an extensive discussion

(deceleration) from non-zero speed to zero speed. In addition, however, there are also a number of “coasting” bins (operating modes 11, 21, 33) that also contain braking events in each speed category. Each of these operating modes include some braking as well as cruise and coasting operation (where the throttle is closed or nearly closed, but the brakes are not applied). Therefore, the emission rate assigned to these bins need to contain the appropriate average rates including the mix of driving and deceleration, and including decelerations that do not include braking. Bins 12 and 22 also contain a very small amount of braking, which are ignored – i.e, the rates in these bins are set to zero.

To estimate the amount of braking activity in modes 1, 11, 21, 33, the brake emission rates in those bins were multiplied by the amount of braking activity in each bin.[f] These braking fractions were derived by combining the amount of average activity from Kansas City and LA above and the coast down curves from PERE discussed earlier. The resulting fractions in operating mode 11, 21 and 31 for light-duty vehicles are shown in Table 3-8. Additional information about braking at idle is in Section 3.2.3.

Fourth, the braking fractions in other deceleration operating modes were also calculated using the PERE and Kansas City and LA driving cycles for other vehicle regulatory classes using the vehicle weights and road load coefficients as shown in Table 3-8 below. The vehicle weights and road load coefficients used for these vehicle classes have subsequently been updated in MOVES2014 and MOVES3. However, as shown in Table 3-8, the braking fractions are fairly consistent across different regulatory classes, and we have not updated this analysis for MOVES3. Motorcycle fractions and Urban Bus fractions were not estimated this way. Motorcycles use the braking fractions from light-duty vehicles (LDV), and Urban Buses use the same braking fractions as HHD vehicles.

Table 3-8 – Vehicle Weights and Road Load Coefficients By Regulatory Class used to Calculate Braking Fraction by Operating Mode Class

	Light-duty Vehicles (LDV)	Light-duty Trucks (LDT)	LHD2b3	LHD45	MHD	HHD
weight (lbs)	3,300	3,968	12,350	20,576	29,800	50,001
mass (kg)	1,497	1,800	5,602	9,333	13,517	22,680
Cr0 (rolling resistance)	0.008	0.008	0.008	0.008	0.01	0.01
Cd (drag coeff)	0.32	0.36	0.37	0.44	0.44	0.44
A (frontal area m^2)	2.25	2.5	2.75	6.7	6.7	8.64
OpModeID	Braking Fraction					
0	1	1	1	1	1	1
1	0.0437	0.0437	0.0316	0.0316	0.0316	0.016
11	0.978	0.978	0.913	0.906	0.91	1
21	0.641	0.661	0.743	0.685	0.725	0.641
33	0.115	0.122	0.126	0.116	0.121	0.068

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[f] For example, the brake wear $PM_{2.5}$ emission rate in VSP bin 11 for light-duty vehicles is 0.557 * 0.978 = 0.546 g/hr

3.2.3 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, MOVES does not estimate brake emissions, because the vehicle is completely stopped during this non-drive-cycle idle time.

In project-mode, MOVES assigns all operation with speed=0 to operating mode 501 (brake wear; stopped), and 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 (as shown in Appendix B). In county-scale and national-scale, opMode 1 is used for estimating brake wear emissions for all speeds < 1 including 0. The difference in project-mode from county-scale was made so that when project-level users define links with actual speed=0, no brake wear emission rates are estimated. At county-scale, we use opMode 1 at speed=0, because a percentage of stopped time was accounted for in the derivation of the opMode1 brake wear emission rates from the driving cycles as discussed above. In project-mode, MOVES users have the option to input their own operating mode distributions, including using operating mode 501 (brake wear; stopped) and operating mode 1 (idle).

3.2.4 $PM_{10}/PM_{2.5}$ 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. 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), report 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. 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), report 72 percent of PM_{10} is $PM_{2.5}$, which is disputed by Sanders et al. (2003). The current study 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 3-1, which is dominated by the more recent data from Sanders et al. (2003).

The emission rates in g/hr $PM_{2.5}$ by operating mode and regulatory class are included in Appendix B. The rates are calculated per the methodology described above and is independent of model year and environmental conditions. The average $PM_{2.5}$ and PM_{10} brake wear emission rates for passenger cars and trucks (from a national-scale run inventory for calendar year 2017 using MOVES3) are displayed in Table 3-9. MOVES brake wear emission rates by source type will vary according to the inputs of average speed, and VMT by road type, which impacts the distribution of operating modes within each source type in MOVES.

Table 3-9 Average $PM_{2.5}$ and PM_{10} brake wear emission rates (mg/mile) for passenger cars and trucks from a national-scale run inventory for calendar year 2017 using MOVES3

	$PM_{2.5}$	PM_{10}
Passenger Cars (21)	2.77	22.17
Passenger Trucks (31)	2.88	23.08

The average passenger car MOVES PM_{10} brake wear emission rates of 22.17 mg/mi (output from the model) is compared to the previous studies (in the literature) in Table 3-1. Carbotech (1999), Sanders et al. (2003), Garg et al. (2000), are all laboratory measurements and have significantly smaller 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 measurement or tunnel measurements. These studies generally have higher emissions than laboratory measurements. The MOVES rates are also considerably larger 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.

3.2.5 Heavy-Duty and Other Vehicle Types

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. A scientific study comparing the emissions and relative activity of each of these methods of braking is beyond the scope of this report. In order to estimate brake wear emission factors for heavy-duty vehicles an engineering analysis was combined with results from a top-down study performed by Mahmoud Abu-Allaban et al. (2003).[17] 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, road dust, and brake 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 performed at the time of the writing of this paper. The results are consistent with the heavy-duty rates measured from Luhana et al. (2004) as well as Westurland (2001), but it is the only paper to measure $PM_{2.5}$. The paper’s light-duty rates are also aligned with the rates determined above.

In this 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 this 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.

Table 3-10 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
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 these measurements, we can determine that the average ratio of HD to LD brake emissions is 10 and 2 for PM_{10} and $PM_{2.5}$ respectively.[g] On average, based on Table 3-10, the ratio is 7.6 for PM_{10}. The following table compares the ratio for the remaining studies for comparison.

Table 3-11- 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	7.6
Westurland (2001)		6.0
Rauterburg-Wulff (1999)		24.5
Carbotech (1999)		0.7

For the purposes of MOVES, a simpler 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 ratio chosen for development of MOVES emission rates is 7.5, very close to the ratio as measured by Abu-Alaban et al. (2003), and consistent with the range of studies. Equation 3-1 is used to calculate

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[g] Though it is not shown in the table here, according to Abu-Alaban, 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.

the brake emission rate for the deceleration/braking mode (OpModeID 0) from the LDV emission rate.

$$HHD\ Emission\,rate\ \left(\frac{g}{hr}\right) = 7.5\ \times LDV\ Emission\,rate\ (\frac{g}{hr}) \qquad \text{Equation 3-1}$$

As stated in the Introduction, the brake emission factors for MOVES3 are unchanged from MOVES2014. 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. The resulting HHD emission rates for opMode0 is shown in Table 3-12.

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 defined the regulatory class vehicles. The estimated vehicle weight is derived from the source mass value stored in the MOVES2014 sourceUseTypePhysics table by source type.[h] 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 3-12.

Table 3-12 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 3-3 and Table 3-12 shows the linear interpolation between the light-duty and heavy heavy-duty brake wear emission rates by the MOVES2014-estimated regulatory class weight.

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[h] In MOVES3, the heavy-duty vehicle weight is defined by both source use type and regulatory class[18]

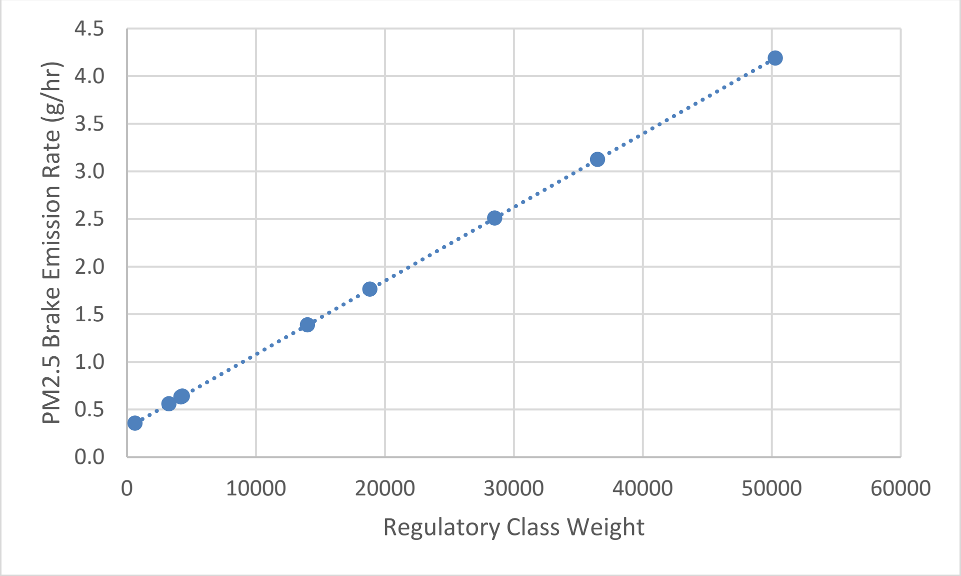

Figure 3-3 Interpolated Brake Wear PM$_{2.5}$ Emission Rates by MOVES2014-estimated Regulatory Class Weight. Passenger Cars and Combination Heavy duty Trucks define the slope.

In MOVES3, the vehicle weights for heavy-duty vehicles were updated with more current data sources. Additionally, the heavy-duty vehicle weights in MOVES3 now vary according to regulatory class and source type as documented in the Population and Activity Report.[18] For MHD, HHD, and Urban Bus the updated 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 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 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 MOVES3 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 MOVES3.

Rather than updating the MOVES3 brake wear emission rates to be consistent with the updated vehicle weights, we have decided to wait to update the MOVES brake wear emission rates with a more comprehensive update, including using brake wear measurements from more recent studies.

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.

Table 3-13 contains average brake wear $PM_{2.5}$ emission rates from a national-scale MOVES3 run for calendar year 2017[i] using default activity input, for each source type. Brake emission rates by source type will vary for local users according to inputs such as road type distribution and speed distribution that impact the operating mode distribution of vehicle operation.

Table 3-13 Average $PM_{2.5}$ and PM_{10} brake wear PM emission rates for the MOVES source types from a national-scale run inventory for calendar year 2017 using MOVES3

SourceTypeID	Source Type	$PM_{2.5}$		PM_{10}	
		mg/veh-mile	mg/veh-km	mg/veh-mile	mg/veh-km
11	Motorcycle	1.58	0.98	12.61	7.83
21	Passenger Car	2.77	1.72	22.17	13.78
31	Passenger Truck	2.88	1.79	23.08	14.34
32	Light Commercial Truck	3.08	1.91	24.64	15.31
41	Intercity Bus	15.50	9.63	123.98	77.04
42	Transit Bus	9.45	5.87	75.62	46.99
43	School Bus	9.94	6.18	79.55	49.43
51	Refuse Truck	13.35	8.29	106.77	66.34
52	Single Unit Short-haul Truck	8.24	5.12	65.89	40.94
53	Single Unit Long-haul Truck	6.88	4.28	55.04	34.20
54	Motor Home	10.66	6.62	85.26	52.98
61	Combination Short-haul Truck	9.52	5.91	76.13	47.30
62	Combination Long-haul Truck	7.96	4.94	63.64	39.55

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[i] Calendar year 2017 run was shown as an example. The rates for other calendar years tested (2006 and 2035) show little differences.

4 Tire Wear

4.1 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.[19]

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.[20]

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 increases 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.[21] 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.[22] 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.[23] Table 4-1 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.[24]

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.[25] 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.[26] Rauterberg-Wulff (1999) determined particle emission factors for tire wear using modeling in combination with measurements conducted in the Berlin-Tegel tunnel.[27]

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 4-1 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.[28]

Table 4-1 - 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)[29]	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[30]	Calculated rate based on literature	200
Warner et al. (2002)[31]	Average tire wear for a vehicle	97
Kolioussis and Pouftis (2000)[32]	Average estimated tire wear	40
EMPA (2000)[33]	Light duty vehicle tire wear rate	53
	Heavy duty vehicle tire wear rate	798
SENCO (Sustainable Environment Consultants Ltd.) (1999)[34]	Light duty vehicle tire wear rate	53
	Wear rate for trucks	1403
Legret and Pagotto (1999a)	Estimated rate for light duty vehicles	68
	Estimated rate for heavy vehicles (>3.5t)	136
Baumann (1997)[35]	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)[36]	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)[37]	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)[38]	Estimated tire wear rate	64
Sakai,H (1995)	Measured tire wear rate	184
Baekken (1993)[39]	Estimated tire wear rate	200
CARB (1993)	Passenger car tire wear rate	120
Muschack (1990)	Estimated tire wear rate	120
Schuring and Clark (1988)[40]	Estimated tire wear rate	240-360
Pierce,R.N. (1984)	Estimated tire wear rate	120
Malmqvist (1983)[41]	Estimated tire wear rate	120
Gottle (1979)[42]	Estimated tire wear rate	120
Cadle et al. (1978)[43]	Measured tire wear rate	4
Dannis (1974)[44]		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.

4.2 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.[28] 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[j]) 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 4-2 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.

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

Table 4-2: 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

4.3 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 4-3.

Table 4-3: 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 4-1**.

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).

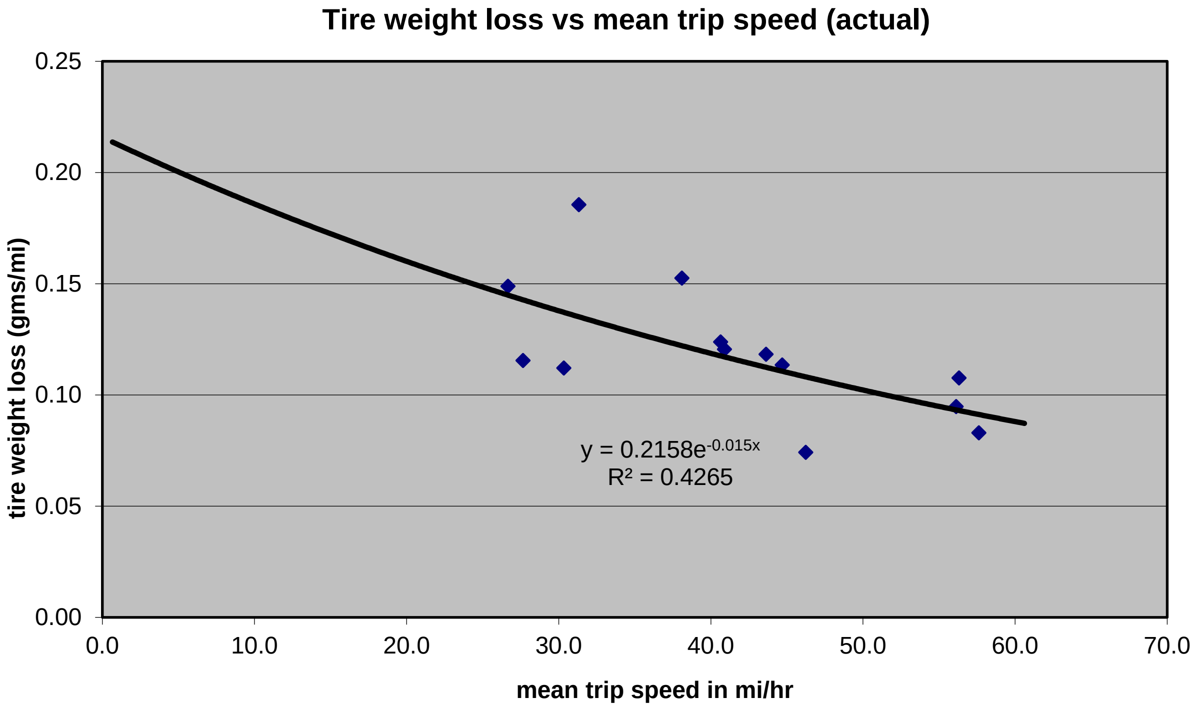

Figure 4-1 Relationship between light-duty tire weight loss (per vehicle) and mean trip speed

The shape of the curve in **Figure 4-1** 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 3-3 below.

Table 4-4 - 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

In the future, this analysis could be improved with data on tire wear from heavy-duty trucks.

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}.[29] 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 B. 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 4-5.

Table 4-5 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

4.3.1 $PM_{10}/PM_{2.5}$ 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)[k]. Grigoratos et al. (2018)[45] 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 4-5.

4.4 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

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[k] 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)[29].

distribution (using the opModeDistribution table)[l]. 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 B) used at all scales of analysis.

5 Ongoing and Future Work

As exhaust emissions decrease, brake and tire emissions are projected to contribute an increasingly larger share of particulate matter emissions from onroad vehicles. The brake and tire emission rates in MOVES3 have had only minor revisions since the original brake and tire analysis was conducted for MOVES2009. While this report notes some minor updates to the tire and brake wear calculations since then, many inconsistencies remain. MOVES2014 and MOVES3 included changes to vehicle specifications described in this report. For example, the default assumptions regarding axle count (and thus number of wheels per vehicle), average weights, aerodynamics, and rolling resistance have changed for many regulatory classes. The most significant of these implications may be impact of updated vehicle weights on brake wear rates.

The MOVES3 emission rates have not been updated to account for more recent studies that capture improved methods in estimating brake and tire emissions, or that incorporate updated brake and tire materials and technologies. This analysis looked at front wheel drive brakes, primarily from vehicles equipped with disc brakes in the front and drum brakes in the rear (the most common light duty configuration at the time of the literature review). Current light-duty vehicles are now typically equipped with four disc brakes and hybrid and electric vehicles sold today use electric regenerative braking. Vehicles with four disc brakes should presumably have higher emissions, while hybrids and electric vehicles should have lower brake emissions. As stated in the report, the heavy-duty brake emission data are limited. Moreover, the incident rate of other forms of decelerating a truck such as downshifting and engine (or jake) braking are also not considered in this study due to a lack of data.

For tire emissions, it was beyond the scope of this study to quantify the differences in emissions (per tire) between light duty and various heavy duty tires. It was also beyond the scope of this study to look at how trends in rolling resistance improvement may increase or decrease tire wear emissions.

As mentioned in the Introduction, MOVES does not conduct speciation of tire and brake PM emissions. Some of the references employed did include some of speciated measurements, however brake material has been known to evolve over time. The current speciation profiles used for the national emissions inventory and emissions platform for air quality modeling is based on a study conducted in 2001 with a limited number of samples.[46] Updating the speciation profiles using modern brake configurations and materials is recommended for work.

The EPA has conducted more recent literature review of brake and tire emissions rates.[47] In general, the brake and tire emission rates from MOVES fall within the wide range of the literature values. The EPA and CARB have recently cooperated on a research program to measure brake emissions from modern light-duty vehicles.[48] We anticipate using this and other research programs to update the brake emissions in a future update to MOVES.

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.

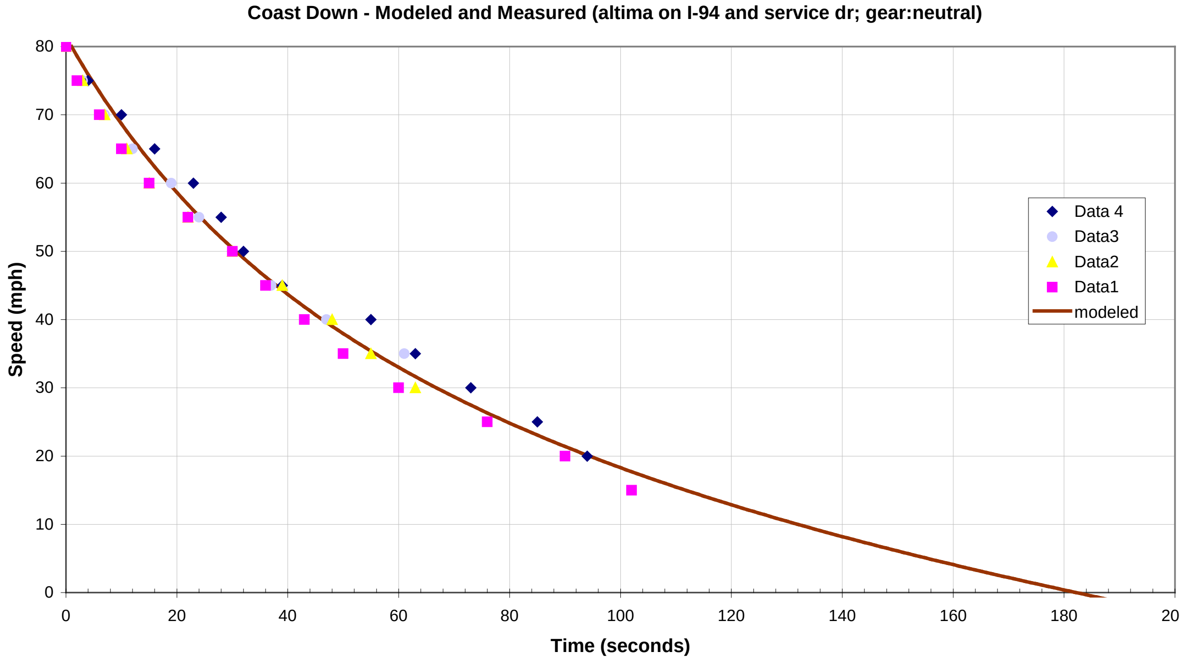

Figure A-1 Coast Down- Modeled and Measured (Altima on I-94 and Service Drive; Gear: neutral)

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.

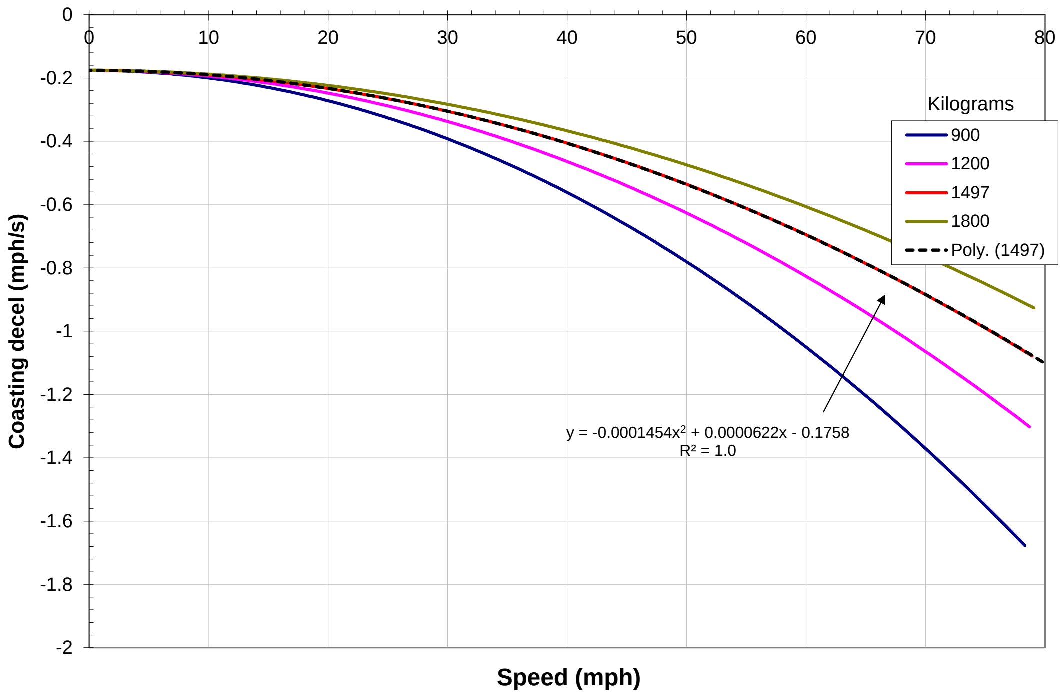

Figure A-2. Coast down Curves as a Function of Vehicle Mass

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

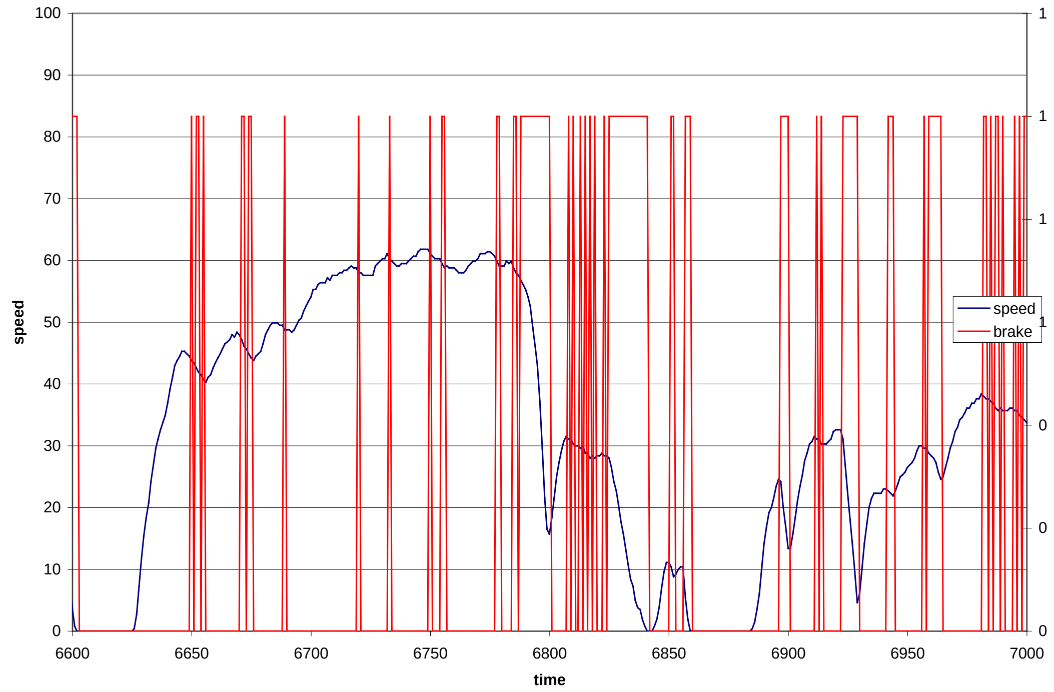

Figure A-3 Braking Episodes over the FTP cycle

Appendix B Brake and Tire Wear Emission Rates

This appendix includes the brake and tire emission rates as a function of regulatory class and operating mode which are stored in the MOVES3 emissionrate table.

Table B-1 $PM_{2.5}$ Brake Emission Rates by Regulatory Class and Operating Mode (g/hr)

regclassID	regClassName	opModeID	opModeName	MeanBaseRate (g/hr)
10	MC	0	Braking	0.355
10	MC	1	Idling	0.016
10	MC	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0.348
10	MC	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0.229
10	MC	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.036
20	LDV	0	Braking	0.558
20	LDV	1	Idling	0.024
20	LDV	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0.546
20	LDV	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0.359
20	LDV	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.064
30	LDT	0	Braking	0.631
30	LDT	1	Idling	0.028
30	LDT	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0.617
30	LDT	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0.418
30	LDT	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.077
41	LHD2b3	0	Braking	0.639
41	LHD2b3	1	Idling	0.020
41	LHD2b3	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0.583
41	LHD2b3	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0.475
41	LHD2b3	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.081
42	LHD45	0	Braking	1.762
42	LHD45	1	Idling	0.056
42	LHD45	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	1.609
42	LHD45	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	1.307
42	LHD45	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.227

46	MHD67	0	Braking	2.509
46	MHD67	1	Idling	0.079
46	MHD67	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	2.283
46	MHD67	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	1.819
46	MHD67	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.304
47	HHD8	0	Braking	4.188
47	HHD8	1	Idling	0.067
47	HHD8	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	4.188
47	HHD8	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	2.685
47	HHD8	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.285
48	Urban Bus	0	Braking	3.124
48	Urban Bus	1	Idling	0.050
48	Urban Bus	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	3.124
48	Urban Bus	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	2.003
48	Urban Bus	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.212
49	Gliders	0	Braking	4.188
49	Gliders	1	Idling	0.067
49	Gliders	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	4.188
49	Gliders	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	2.685
49	Gliders	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.285

Table B-2 $PM_{2.5}$ Tire Wear Emission Rates by Regulatory Class and Operating Mode (g/hr) in MOVES3.

regclassID	regClassName	opModeID	opModeName	MeanBaseRate (g/hr)
10	MC	400	idle	0.0000
10	MC	401	speed < 2.5mph	0.0032
10	MC	402	2.5mph <= speed < 7.5mph	0.0060
10	MC	403	7.5mph <= speed < 12.5mph	0.0112
10	MC	404	12.5mph <= speed < 17.5mph	0.0155
10	MC	405	17.5mph <= speed <22.5mph	0.0192
10	MC	406	22.5mph <= speed < 27.5mph	0.0223
10	MC	407	27.5mph <= speed < 32.5mph	0.0248
10	MC	408	32.5mph <= speed < 37.5mph	0.0269
10	MC	409	37.5mph <= speed < 42.5mph	0.0285
10	MC	410	42.5mph <= speed < 47.5mph	0.0298
10	MC	411	47.5mph <= speed < 52.5mph	0.0308
10	MC	412	52.5mph <= speed < 57.5mph	0.0314
10	MC	413	57.5mph <= speed < 62.5mph	0.0318
10	MC	414	62.5mph <= speed < 67.5mph	0.0320
10	MC	415	67.5mph <= speed < 72.5mph	0.0319
10	MC	416	72.5mph <= speed	0.0318
20	LDV	400	idle	0.0000
20	LDV	401	speed < 2.5mph	0.0064
20	LDV	402	2.5mph <= speed < 7.5mph	0.0120
20	LDV	403	7.5mph <= speed < 12.5mph	0.0223
20	LDV	404	12.5mph <= speed < 17.5mph	0.0311
20	LDV	405	17.5mph <= speed <22.5mph	0.0384
20	LDV	406	22.5mph <= speed < 27.5mph	0.0446
20	LDV	407	27.5mph <= speed < 32.5mph	0.0497
20	LDV	408	32.5mph <= speed < 37.5mph	0.0538
20	LDV	409	37.5mph <= speed < 42.5mph	0.0571
20	LDV	410	42.5mph <= speed < 47.5mph	0.0596
20	LDV	411	47.5mph <= speed < 52.5mph	0.0615
20	LDV	412	52.5mph <= speed < 57.5mph	0.0628
20	LDV	413	57.5mph <= speed < 62.5mph	0.0635
20	LDV	414	62.5mph <= speed < 67.5mph	0.0639
20	LDV	415	67.5mph <= speed < 72.5mph	0.0639
20	LDV	416	72.5mph <= speed	0.0635
30	LDT	400	idle	0.0000
30	LDT	401	speed < 2.5mph	0.0064
30	LDT	402	2.5mph <= speed < 7.5mph	0.0120
30	LDT	403	7.5mph <= speed < 12.5mph	0.0223
30	LDT	404	12.5mph <= speed < 17.5mph	0.0311

30	LDT	405	17.5mph <= speed <22.5mph	0.0384
30	LDT	406	22.5mph <= speed < 27.5mph	0.0446
30	LDT	407	27.5mph <= speed < 32.5mph	0.0497
30	LDT	408	32.5mph <= speed < 37.5mph	0.0538
30	LDT	409	37.5mph <= speed < 42.5mph	0.0571
30	LDT	410	42.5mph <= speed < 47.5mph	0.0596
30	LDT	411	47.5mph <= speed < 52.5mph	0.0615
30	LDT	412	52.5mph <= speed < 57.5mph	0.0628
30	LDT	413	57.5mph <= speed < 62.5mph	0.0635
30	LDT	414	62.5mph <= speed < 67.5mph	0.0639
30	LDT	415	67.5mph <= speed < 72.5mph	0.0639
30	LDT	416	72.5mph <= speed	0.0635
41	LHD2b3	400	idle	0.0000
41	LHD2b3	401	speed < 2.5mph	0.0088
41	LHD2b3	402	2.5mph <= speed < 7.5mph	0.0166
41	LHD2b3	403	7.5mph <= speed < 12.5mph	0.0308
41	LHD2b3	404	12.5mph <= speed < 17.5mph	0.0429
41	LHD2b3	405	17.5mph <= speed <22.5mph	0.0531
41	LHD2b3	406	22.5mph <= speed < 27.5mph	0.0616
41	LHD2b3	407	27.5mph <= speed < 32.5mph	0.0686
41	LHD2b3	408	32.5mph <= speed < 37.5mph	0.0743
41	LHD2b3	409	37.5mph <= speed < 42.5mph	0.0788
41	LHD2b3	410	42.5mph <= speed < 47.5mph	0.0823
41	LHD2b3	411	47.5mph <= speed < 52.5mph	0.0849
41	LHD2b3	412	52.5mph <= speed < 57.5mph	0.0866
41	LHD2b3	413	57.5mph <= speed < 62.5mph	0.0877
41	LHD2b3	414	62.5mph <= speed < 67.5mph	0.0882
41	LHD2b3	415	67.5mph <= speed < 72.5mph	0.0882
41	LHD2b3	416	72.5mph <= speed	0.0877
42	LHD45	400	idle	0.0000
42	LHD45	401	speed < 2.5mph	0.0095
42	LHD45	402	2.5mph <= speed < 7.5mph	0.0180
42	LHD45	403	7.5mph <= speed < 12.5mph	0.0334
42	LHD45	404	12.5mph <= speed < 17.5mph	0.0464
42	LHD45	405	17.5mph <= speed <22.5mph	0.0575
42	LHD45	406	22.5mph <= speed < 27.5mph	0.0667
42	LHD45	407	27.5mph <= speed < 32.5mph	0.0743
42	LHD45	408	32.5mph <= speed < 37.5mph	0.0804
42	LHD45	409	37.5mph <= speed < 42.5mph	0.0853
42	LHD45	410	42.5mph <= speed < 47.5mph	0.0891
42	LHD45	411	47.5mph <= speed < 52.5mph	0.0919

42	LHD45	412	52.5mph <= speed < 57.5mph	0.0938
42	LHD45	413	57.5mph <= speed < 62.5mph	0.0950
42	LHD45	414	62.5mph <= speed < 67.5mph	0.0956
42	LHD45	415	67.5mph <= speed < 72.5mph	0.0955
42	LHD45	416	72.5mph <= speed	0.0950
46	MHD67	400	idle	0.0000
46	MHD67	401	speed < 2.5mph	0.0110
46	MHD67	402	2.5mph <= speed < 7.5mph	0.0209
46	MHD67	403	7.5mph <= speed < 12.5mph	0.0388
46	MHD67	404	12.5mph <= speed < 17.5mph	0.0540
46	MHD67	405	17.5mph <= speed <22.5mph	0.0668
46	MHD67	406	22.5mph <= speed < 27.5mph	0.0775
46	MHD67	407	27.5mph <= speed < 32.5mph	0.0864
46	MHD67	408	32.5mph <= speed < 37.5mph	0.0935
46	MHD67	409	37.5mph <= speed < 42.5mph	0.0992
46	MHD67	410	42.5mph <= speed < 47.5mph	0.1036
46	MHD67	411	47.5mph <= speed < 52.5mph	0.1069
46	MHD67	412	52.5mph <= speed < 57.5mph	0.1091
46	MHD67	413	57.5mph <= speed < 62.5mph	0.1105
46	MHD67	414	62.5mph <= speed < 67.5mph	0.1111
46	MHD67	415	67.5mph <= speed < 72.5mph	0.1110
46	MHD67	416	72.5mph <= speed	0.1104
47	HHD8	400	idle	0.0000
47	HHD8	401	speed < 2.5mph	0.0237
47	HHD8	402	2.5mph <= speed < 7.5mph	0.0447
47	HHD8	403	7.5mph <= speed < 12.5mph	0.0831
47	HHD8	404	12.5mph <= speed < 17.5mph	0.1156
47	HHD8	405	17.5mph <= speed <22.5mph	0.1431
47	HHD8	406	22.5mph <= speed < 27.5mph	0.1661
47	HHD8	407	27.5mph <= speed < 32.5mph	0.1850
47	HHD8	408	32.5mph <= speed < 37.5mph	0.2003
47	HHD8	409	37.5mph <= speed < 42.5mph	0.2125
47	HHD8	410	42.5mph <= speed < 47.5mph	0.2219
47	HHD8	411	47.5mph <= speed < 52.5mph	0.2288
47	HHD8	412	52.5mph <= speed < 57.5mph	0.2336
47	HHD8	413	57.5mph <= speed < 62.5mph	0.2366
47	HHD8	414	62.5mph <= speed < 67.5mph	0.2379
47	HHD8	415	67.5mph <= speed < 72.5mph	0.2378
47	HHD8	416	72.5mph <= speed	0.2365
48	Urban Bus	400	idle	0.0000
48	Urban Bus	401	speed < 2.5mph	0.0127

48	Urban Bus	402	2.5mph <= speed < 7.5mph	0.0240
48	Urban Bus	403	7.5mph <= speed < 12.5mph	0.0446
48	Urban Bus	404	12.5mph <= speed < 17.5mph	0.0621
48	Urban Bus	405	17.5mph <= speed <22.5mph	0.0769
48	Urban Bus	406	22.5mph <= speed < 27.5mph	0.0892
48	Urban Bus	407	27.5mph <= speed < 32.5mph	0.0994
48	Urban Bus	408	32.5mph <= speed < 37.5mph	0.1076
48	Urban Bus	409	37.5mph <= speed < 42.5mph	0.1142
48	Urban Bus	410	42.5mph <= speed < 47.5mph	0.1192
48	Urban Bus	411	47.5mph <= speed < 52.5mph	0.1230
48	Urban Bus	412	52.5mph <= speed < 57.5mph	0.1255
48	Urban Bus	413	57.5mph <= speed < 62.5mph	0.1271
48	Urban Bus	414	62.5mph <= speed < 67.5mph	0.1278
48	Urban Bus	415	67.5mph <= speed < 72.5mph	0.1278
48	Urban Bus	416	72.5mph <= speed	0.1271
49	Gliders	400	idle	0.0000
49	Gliders	401	speed < 2.5mph	0.0237
49	Gliders	402	2.5mph <= speed < 7.5mph	0.0447
49	Gliders	403	7.5mph <= speed < 12.5mph	0.0831
49	Gliders	404	12.5mph <= speed < 17.5mph	0.1156
49	Gliders	405	17.5mph <= speed <22.5mph	0.1431
49	Gliders	406	22.5mph <= speed < 27.5mph	0.1661
49	Gliders	407	27.5mph <= speed < 32.5mph	0.1850
49	Gliders	408	32.5mph <= speed < 37.5mph	0.2003
49	Gliders	409	37.5mph <= speed < 42.5mph	0.2125
49	Gliders	410	42.5mph <= speed < 47.5mph	0.2219
49	Gliders	411	47.5mph <= speed < 52.5mph	0.2288
49	Gliders	412	52.5mph <= speed < 57.5mph	0.2336
49	Gliders	413	57.5mph <= speed < 62.5mph	0.2366
49	Gliders	414	62.5mph <= speed < 67.5mph	0.2379
49	Gliders	415	67.5mph <= speed < 72.5mph	0.2378
49	Gliders	416	72.5mph <= speed	0.2365

Appendix C Literature Review conducted for MOVES2009

Table C-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 Emisions 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*	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

Environment and Health Protection Administration, 100,64,Stockholm,Sweden,2001.		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 8th International Symposium on Transport and Air Pollution*, Graz, 1999.	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 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.

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