Brake and Tire Wear Emissions from On-road Vehicles in MOVES2014

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 Introduction

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 are composed of different species and size than exhaust particulate matter.[1]

The literature review for the development of the brake and tire wear emission models was conducted in 2006 and 2007, the models were developed for MOVES2010, and this report was written in 2008. However this documentation was not revised until the peer review complete in 2014 and no revisions to the model were made. As of 2007, the references in this report were recent, yet there were likely a few publications on particulate matter from brake and tire wear which were not included in the original literature review. In the sections below we present the studies from the literature conducted at the time, as well as the models that were developed based on the best data presented in the papers cited. A more recent literature search and a potential model update will be conducted in the future.

2 Brakewear

2.1 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, when the brake pedal is pressed, force the shoes 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 each side of the rotor that clamp together when the brake pedal is pressed.[2]

The definition of wear versus airborne PM seems to have slightly different definitions in the literature. In this paper it is generally the mass of material lost, whether in the brake pads or the tires. A fraction of that wear is airborne PM. 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, their portion of wear particles that become airborne, and the size as well as composition of those particles. 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.

The overall size or mass of the brake pads also varies with vehicle type. Typically trucks use larger brakes than passenger vehicles because the mass of vehicle that requires slowing down or stopping 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, where more aggressive stop and go driving will naturally cause greater wear and emissions.

There are only 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 D. One of the earliest studies on brake wear emissions was done in 1983.[3] 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.[4] 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. These factors suggest the need for this update of the emission factors applicable to more modern vehicles.

Garg et al. (2000) 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).[5] 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)[6] looked at three more current (as of ~2003) classes of lining materials: low metallic, semi-metallic and non-asbestos organic (NAO) representing about 90% of automotive brakes at that time. Three kinds of tests were conducted: a dynamometer test, a wind tunnel test and a track test at the Ford Dearborn proving grounds. Three sets of brake conditions were used: (a) the first set of tests evaluated all three materials on a brake dynamometer under mild and aggressive driving conditions, the urban driving program (UDP) with a set of 24 stops and a -7.9 m/s^2 deceleration called the Auto Motor und Sport magazine (AMS) test; (b) a series of high speed 1.8 m/s^2 stops of a mid-size sedan with low metallic brakes were conducted in a wind tunnel; and c) measurements of the same vehicle on a test track where collected where decelerations were made from 60 mph at 0.15, 0.25 and 0.35 g-forces, the latter corresponding to the AMS test to compare to the brake dynamometer. The latter test included low metallic as well as NAO materials. The authors found that the mean particle size and the shape of the mass distribution are very similar for each of the three linings, however they found that the low metallic linings generate 2-3 times the number of wear particles compared to semi-metallic and NAO linings. They also found that wear (and portion of wear that is airborne PM emissions) increased non-linearly with higher levels of deceleration. Wear debris composition was found to have the most abundant elements consisting of Fe, Cu, Si, Ba, K and Ti, although the relative composition varied significantly by brake type. The authors further found that 50-70% of the total wear material was released in the form of airborne particles.

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 currently in use, 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 rates below, 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 their own includes all Light-duty vehicles, including trucks though the studies are not all equivalent in their definitions.

2.2 Developing Rates for MOVES

2.2.1 Emissions during braking

The MOVES2009 braking emission rate is 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

As discussed in Sanders et al. (2003), most brake pads (at the time of the publication of that paper) are either low-metallic, semi-metallic (full-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 2 front disc brakes, and 2 rear drum brakes
- 2/3 of braking power (and thus emissions) in front brakes (1/3 rear)[a]
- the fraction of total PM below 2.5um is ~ 10% (+/-5%)[b]
- 60% of brake wear is airborne PM (+/- 10%).

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. 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 AMS results are not presented in the Sanders paper, however, the authors provided the data for the purposes of this study.

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

[b] More will be discussed below.

Table 2-2 – UDP results[c]

Test	brake lining	PM_{10} emiss. filter	(mg/stop/brake) ELPI	
UDP				
	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/s²**
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 2-3 – Wind Tunnel results

Test	brake lining	PM_{10} emiss. filter*	(mg/stop/brake) ELPI	MOUDI
Tunnel				
	low metallic	44	45	40
deceleration=			**0.0018**	**in km/s²**
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**

[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 and 1/3 from the rear brakes.

Table 2-4 – AMS 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. break 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**

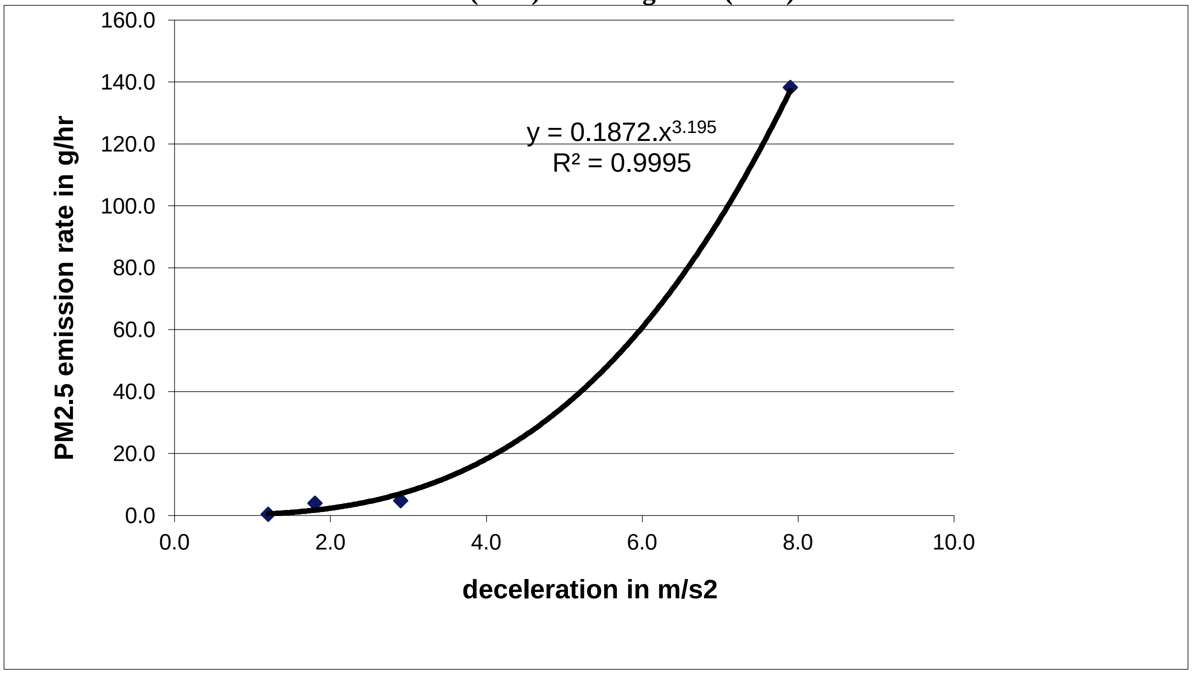
Table 2-5 – Garg et al. (2000) results

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. break 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 a power function to determine the emission rate at different deceleration levels shown in the following figure. The AMS test, at higher decelerations, clearly has a significant influence on results of the curve fit. Additional high speed tests 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)



2.2.2 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. However, for MOVES, we also need to determine the frequency of different levels of braking. The MOVES vehicle specific power (VSP) bins are relatively coarse for braking.[e,7] There is a large braking bin (operating mode 0) that contains a large fraction of driving activity, however there are also a number of "coasting" bins that also contain braking events in each speed category (Table 2-6). Each of these deceleration 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 frequencies, and including decelerations that do not include braking.

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

Table 2-6. VSP Operating Mode Bins by VSP and speed. Operating mode 0 and 1 (not listed) are braking and idle respectively

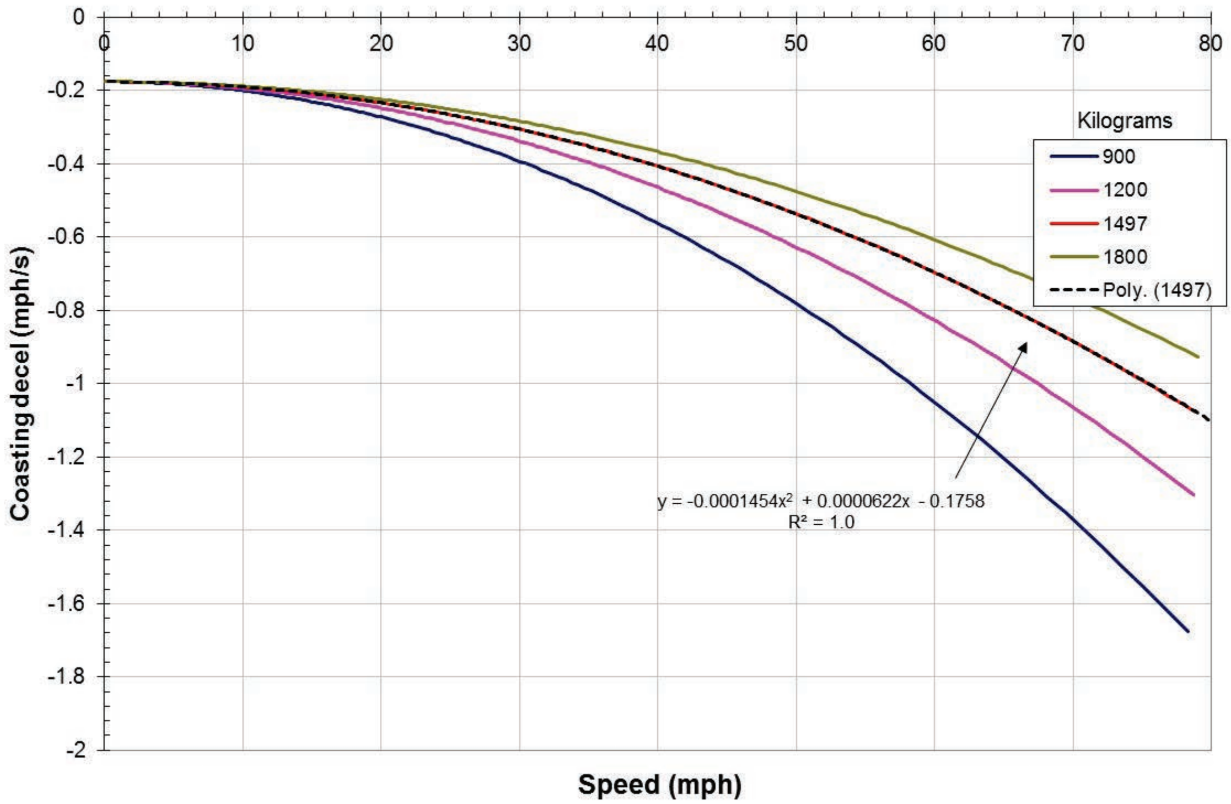
<table>
<tr><th rowspan="2">VSP Class (kW/tonne)</th><th colspan="3">Speed Class (MPH)</th></tr>
<tr><th>1-25</th><th>25-50</th><th>50+</th></tr>
<tr><td>30+</td><td rowspan="7">16</td><td>30</td><td>40</td></tr>
<tr><td>27-30</td><td rowspan="2">29</td><td rowspan="2">39</td></tr>
<tr><td>24-27</td></tr>
<tr><td>21-24</td><td rowspan="2">28</td><td rowspan="2">38</td></tr>
<tr><td>18-21</td></tr>
<tr><td>15-18</td><td rowspan="2">27</td><td rowspan="2">37</td></tr>
<tr><td>12-15</td></tr>
<tr><td>9-12</td><td>15</td><td>25</td><td rowspan="2">35</td></tr>
<tr><td>6-9</td><td>14</td><td>24</td></tr>
<tr><td>3-6</td><td>13</td><td>23</td><td rowspan="3">33</td></tr>
<tr><td>0-3</td><td>12</td><td>22</td></tr>
<tr><td><0</td><td>11</td><td>21</td></tr>
</table>

Operating mode where braking is assumed

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 real-world driving surveys.

The coastdown curves were generated using the Physical Emission Rate Estimator (PERE).[8] This was done by using the coastdown equations from PERE, 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 2-2 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 is the typical mass of a light duty vehicle. The average weight for passenger cars used in MOVES is 1,497 kg.

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



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.[9] 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[10,11,12]. The deceleration data was analyzed for both of these studies.

Table 2-7 shows the distribution of braking activity across deceleration levels from both of these studies. As expected, the vast majority of braking occurs during mild decelerations rather than full (high decel) stops. More information about the PERE coastdown calculation process is described in Appendix A.

Table 2-7 – Activity 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%

2.2.3 Emission Rate for Light Duty vehicles

The emission rate curve from Figure 2-1 was combined with the average activity in Table 2-7 discussed above (using a sum of the product) to calculate MOVES rates for light duty vehicles. This gives an average $PM_{2.5}$ braking emission rate of 0.557 g/hr.

However, as mentioned earlier, MOVES has brake emissions in not only VSP op-mode bin 0 (defined as the braking bin), but also in modes 1,11,21,33. Idle (zero speed, op-mode bin 0) braking occurs in the transition (deceleration) from non-zero speed to zero speed which is a small amount of activity in this bin. 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. The brake emission rate in the other bins were reduced 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 results are shown in Table 2-8 below.

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

Table 2-8 – Vehicle Specification (top) and Fraction of Activity in VSP bin that is braking (last 5 rows) for a variety of vehicle types (motorcycle and bus activity fractions were copied from Light-duty and heavy-duty trucks respectively).

	Mid-size car (LDV)	SUV (LDT)	LHDT (<=14k)	LHDT (>14k)	MHDT	HHDT
wgt (kg)	1497	1800	5602	9333	13517	22680
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
vsp bin						
0	1	1	1	1	1	1
1	0.0437	0.0437	0.0316	0.0316	0.0316	0.016
11	0.975	0.975	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

2.2.4 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% of PM_{10} is $PM_{2.5}$, which is consistent with Sanders. Garg et al. (2000), report 72% 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 2-1, which is dominated by the more recent data from Sanders et al. (2003).

The emission rates in g/hr $PM_{2.5}$ and PM_{10} 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 three urban county inventories, using MOVES2014 are displayed in Table 2-9. 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 2-9 Average PM2.5 and PM10 brake wear emission rates (mg/mile) for passenger cars and trucks from 3 urban county inventories using MOVES2014

	$PM_{2.5}$	PM_{10}
Passenger Cars (21)	3.7	29.8
Passenger Trucks (31)	6.2	49.8

The average passenger car MOVES PM_{10} emission rates of 29.8 mg/mi (output from the model) 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 smaller reported emission rates than the present study. 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 largely generated from Sanders et al. (2003), are also considerably larger than the publication cites. This is largely due to the fact that 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 to the milder deceleration emission rates to give higher rates comparable now 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.

2.2.5 Brake Wear Emissions for Heavy-Duty Vehicles 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).[13] 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 is 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 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 from this study 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. On table 5 of the paper, the emission rates for the exit ramps 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 2-10 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 heavy-duty measurements were highest on the exit lanes for PM_{10}, however (rather inexplicably), the other road types had higher emissions than the exit lanes 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 2-10, the ratio is 7.6 for PM10. The following table compares the ratio for the remaining studies for comparison.

Table 2-11- Ratio of Heavy-Duty to Light-Duty PM from the literature.

Study	**$PM_{2.5}$**	**PM10**
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 is 7.5, very close to the ratio as measured by Abu-Alaban et al. (2003), and consistent with the range of studies.

[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 estimated emission factors for all other categories of vehicles (between light and heavy-duty) were derived by linearly interpolating the rates between light-duty and combination heavy-duty vehicle classes by their respective weights as shown in the figure below. This is based on a rather simple engineering (and unproven in this study) hypothesis that the relative brake emissions is 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. Figure 2-3 below shows the relative mass of light- and heavy-duty vehicles. The corresponding emission rates are in Table 2-12.

Figure 2-3 – Interpolated Brake $PM_{2.5}$ Emission Rates by Regulatory Class Weight. Passenger Cars and Combination Heavy duty Trucks Define the Slope.

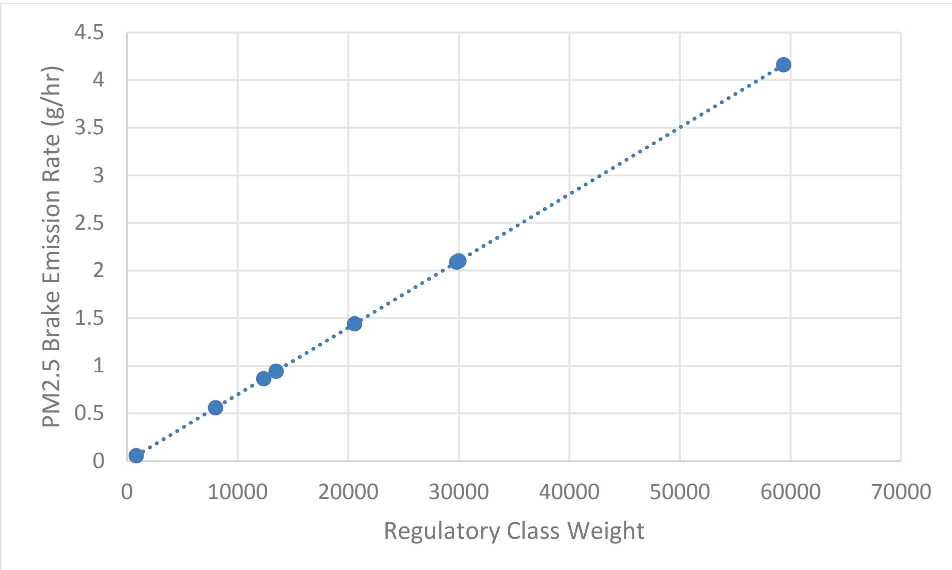


Table 2-12contains average brakewear PM emission rates from three MOVES runs for urban counties using MOVES2014, for each source types. As mentioned earlier, average emission rates by source type will vary for local users according to inputs that impact the operating mode distribution of vehicle operation

Table 2-12. Scaling Emission Rates to their vehicle class. regclass id is the MOVES identifier for regulatory class.

	regclasswt in lbs.	regclassid	g/hr
MC	830	10	0.056
LDGV	8000	20	0.56
LDT	13,474	30	0.94
HD<=14k	12,358	41	0.87
HD>14k	20,575	42	1.4
MHDD	29,808	46	2.1
HHDD	59,369	47	4.2
Urban Bus	30,000	48	2.1

Table 2-13 Average PM2.5 and PM10 brake wear PM emission rates (mg/veh-mile) for the MOVES regulatory classes from three urban county inventories using MOVES2014

sourceTypeID	Source Type	$PM_{2.5}$	PM_{10}
11	Motorcycle	0.3	2.6
21	Passenger Car	3.7	29.8
31	Passenger Truck	6.2	49.8
32	Light Commercial Truck	6.2	49.8
41	Intercity Bus	23.3	186.4
42	Transit Bus	12.6	100.9
43	School Bus	13.2	105.3
51	Refuse Truck	25.6	204.4
52	Single Unit Short-haul Truck	13.6	109.2
53	Single Unit Long-haul Truck	16.6	132.4
54	Motor Home	11.5	92.2
61	Combination Short-haul Truck	24.3	194.0
62	Combination Long-haul Truck	26.6	213.0

3 Tirewear

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.[14]

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.[15]

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.[16] 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% of the tire tread volume that new tires had. Cenek et al. (1993) reported that 20% of New Zealand passenger tire sales were retreads and that retreads made up 75% of the tire tread in a sample of buses in the New Zealand fleet.[17] 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.[18] Table 3-1shows 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.[19]

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.[20] 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.[21] Rauterberg-Wulff (1999) determined particle emission factors for tire wear using modeling in combination with measurements conducted in the Berlin-Tegel tunnel.[22]

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 emission 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.[23]

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)[24]	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[25]	Calculated rate based on literature	200
Warner et al. (2002)[26]	Average tire wear for a vehicle	97
Kolioussis and Pouftis (2000)[27]	Average estimated tire wear	40
EMPA (2000)[28]	Light duty vehicle tire wear rate	53
	Heavy duty vehicle tire wear rate	798
SENCO (Sustainable Environment Consultants Ltd.) (1999)[29]	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)[30]	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)[31]	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)[32]	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)[33]	Estimated tire wear rate	64
Sakai,H (1995)	Measured tire wear rate	184
Baekken (1993)[34]	Estimated tire wear rate	200
CARB (1993)	Passenger car tire wear rate	120
Muschack (1990)	Estimated tire wear rate	120
Schuring and Clark (1988)[35]	Estimated tire wear rate	240-360
Pierce,R.N. (1984)	Estimated tire wear rate	120
Malmqvist (1983)[36]	Estimated tire wear rate	120
Gottle (1979)[37]	Estimated tire wear rate	120
Cadle et al. (1978)[38]	Measured tire wear rate	4
Dannis (1974)[39]		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 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.[40] 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[h]) 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 seems to lean towards 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.

[h] 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

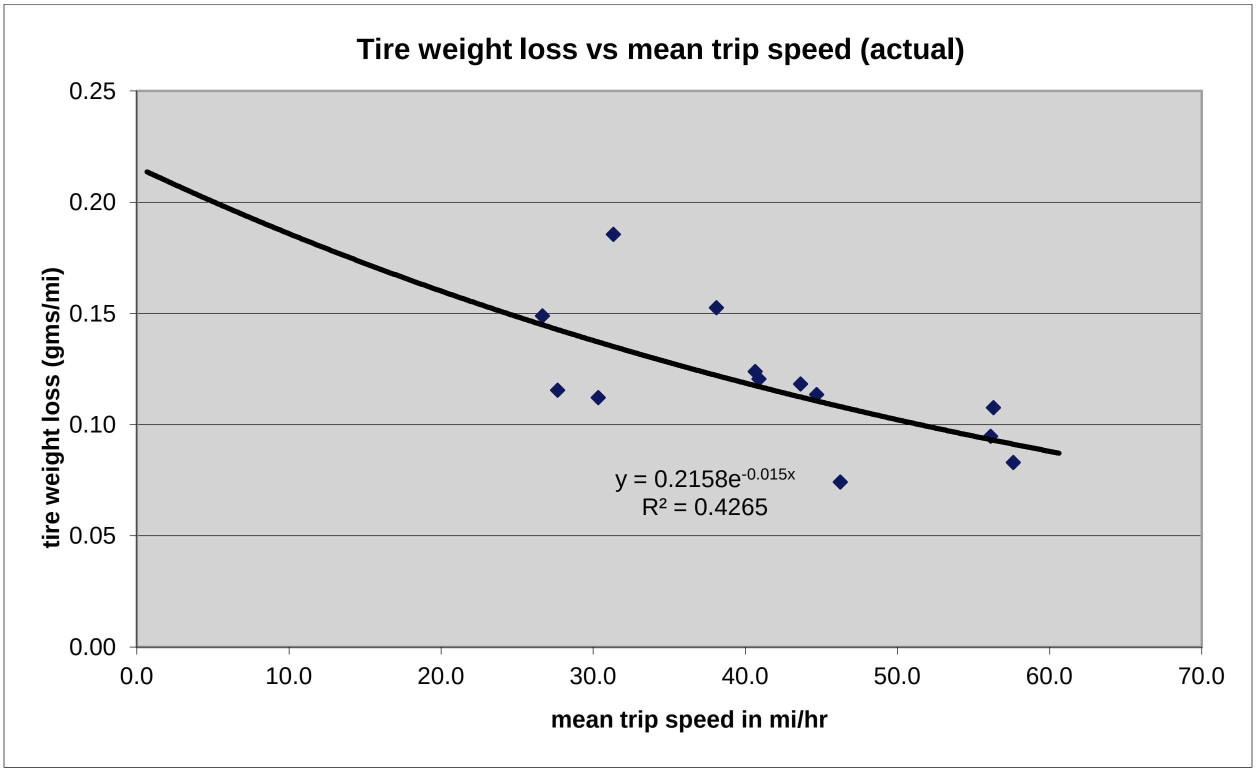
	Avg. trip speed	Tire Wt. Loss (per axle)		total wt. loss (per vehicle)	total wt. loss (per vehicle)	avg. speed
vehicle tests	km/hr	Front mean (g/km)	Rear Mean (g/km)	g/km	g/mi	mi/hr
test1-A	90.3	0.0202	0.0092	0.0589	0.0947	56.1
test2-A	90.6	0.0209	0.0126	0.0669	0.1076	56.3
test3-A	93.9	-	0.0069	-	-	58.4
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

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% 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 between tests



The shape of the curve in Figure 3-1 deserves some discussion. It can be seen from the curve that the wear is 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 is highest when speed equals zero, however, it is important to note that the relationship does not take accelerations (and turning) into account. Much of the tirewear 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. A more improved relationship would be by VSP bin, however there is insufficient data to characterize tire wear on a second-by-second basis to enable binning by operating mode bins. The model has been simplified to be based on speed at this time. However, for MOVES, the emission rate at zero speed is set to zero to avoid anomalous results in project level analyses where increased idling would result in an over prediction of tire emissions.

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. The latter data were found to be available 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 3-3 - Average Number of Tires per Truck – 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	LHD<=14K	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 a future study, another literature search should be conducted to search for differences in (per tire) wear and emission rates from heavy-duty tires compared to those from the light-duty market. There is another assumption made for the sake of simplicity, which is to keep the emission rates of the tractive wheels identical to those of the wheels disconnected from the drivetrain axles. A more recent literature search may also help determine whether another approach is warranted.

Now that the average tire wear is quantified, it is critical to determine the fraction of that wear that becomes airborne PM. The literature indicates that probably less than 10% of car tire wear is emitted as PM_{10} under 'typical' driving conditions but the proportion could be as high as 30% (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% and 15% 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% of tire wear is emitted as PM_{10} (average of 1% and 16%. According to Kupiainen et al (2005), $PM_{2.5}$ fractions were on average 15% of PM_{10}.[24] Based on this study, it is assumed that 1.2% of the total tire wear is emitted as $PM_{2.5}$ to develop our brakeweare emission rate. The 1.2% is derived from assuming that 8% of tire wear to be emitted as PM_{10} and 15% of PM_{10} is $PM_{2.5}$.

We then convert the g/vehicle/mile brakewear emission rates to g/hr by multiplying by the average speed of each MOVES speed bin. The g/hour brakewear emission rate for all regulatory classes used in MOVES can be found in Appendix B. MOVES applies the same brake wear emission rate for all vehicle fuel types (gasoline, diesel, flex-fuel, and CNG) within a MOVES regulatory class. The average $PM_{2.5}$ tire wear emission rates in (mg/mile) for each regulatory class, from three urban county inventories in MOVES2014 is shown in Table 3-4.

Table 3-4 Average $PM_{2.5}$ and PM_{10} tire wear PM emission rates (mg/veh-mile) for the MOVES regulatory classes from three urban county inventories using MOVES2014

sourceTypeID	sourcetypename	$PM_{2.5}$	PM_{10}
11	Motorcycle	0.7	4.9
21	Passenger Car	1.5	9.8
31	Passenger Truck	1.5	10.0
32	Light Commercial Truck	1.5	10.2
41	Intercity Bus	4.4	29.3
42	Transit Bus	2.9	19.7
43	School Bus	2.7	17.8
51	Refuse Truck	5.1	34.3
52	Single Unit Short-haul Truck	2.7	17.7
53	Single Unit Long-haul Truck	3.1	20.6
54	Motor Home	2.4	15.8
61	Combination Short-haul Truck	4.7	31.6
62	Combination Long-haul Truck	5.2	34.9

3.2.1 $PM_{10}/PM_{2.5}$ 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)[i]. The average PM_{10} emission rates from three urban county inventories using MOVES2014 are displayed in Table 3-4.

4 Next Steps

As mentioned in the earlier section, this report underwent revisions since the previous version, but these changes were largely editorial in nature in response to the peer review. There were no changes made to the model or the rates since MOVES2010. There are a number of updates that can be made to both this report and the model.

As a number of years have passed, it is possible that there are more publications in the literature or airborne brake and tire emissions from mobile sources. These papers may shed light on emission rates, size distributions, activity or speciation of PM. There is especially little information in the literature on the latter. These newer papers can either be used to modify the model, or validate the current rates.

The MOVES model has undergone changes since MOVES2010b. MOVES2014 includes some changes to the vehicle specifications described in this report. For example, the default

[i] 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).

assumptions regarding axle count (and thus number of wheels per vehicle), average weights, aerodynamics, and rolling resistance, of certain regulatory classes have changed. The weights will have a more significant impact on the brake rates (in particular) than the latter coefficients.

For brakes, the analysis from this study also only looked at front wheel drive brakes and primarily from vehicles equipped with disc brakes in the front and drum brakes in the rear (the most common light duty configuration). It was beyond the scope of this study to modify the rates the fraction of vehicles with four disc brakes, or to update the speciation profile for brake emissions, or to capture more advanced technology vehicles with electric regenerative braking. Vehicles with four disc brakes should presumably have higher, while hybrids and electric vehicles should have lower brake emissions. 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.

Since the writing of this report, the only change that was made to the brake wear model in MOVES2014 was that for project level analysis, the emission rates in the idle bin was set to zero. This was done to avoid results where users may get increasing brake emissions in particular cases where idle rates are high. As mentioned above, the idle operating mode bin does contain a small amount of deceleration when a vehicle transitions from motion to non-motion (stop). However, if a user is increasing idle rates based on local knowledge compared to the MOVES default, it is logical to assume that they should not get higher brake emissions. Therefore, for inventory mode, the emission rates were maintained as described above in the idle bin and the change was made only to project level analysis.

The idling tire wear emission rate is set to zero in the default emission rate table (Appendix B). Thus, for idling tire wear emission rate is zero for both project level and inventory mode.

For tire emissions, it was beyond the scope of this study to quantify the differences in emissions (per tire) between light duty and heavy duty tires (and everything in between). 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. Finally a more complete model including speciation of tire and break PM, was beyond the scope of this study. Some of the references employed did include some of these measurements, however brake material has been known to evolve over time. These are all subjects for future study.

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 there 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.

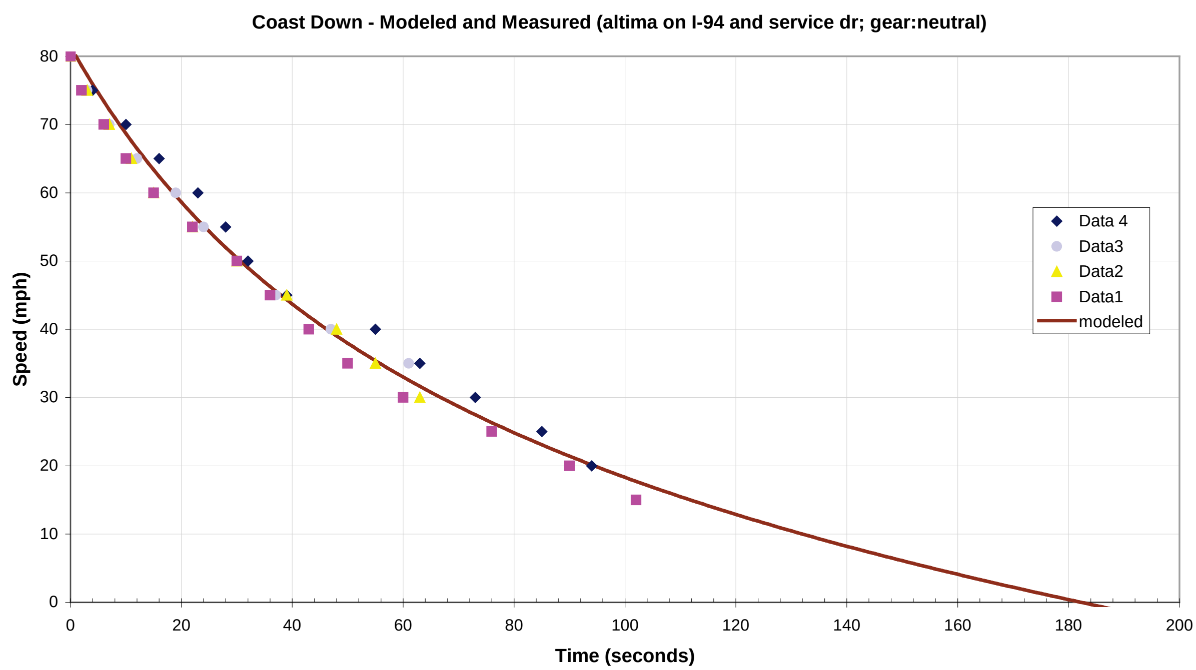


Figure A-1 Coast Down- Modeled and Measured (Altima on I-94 and Service Drive; Gear: neutral)

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.

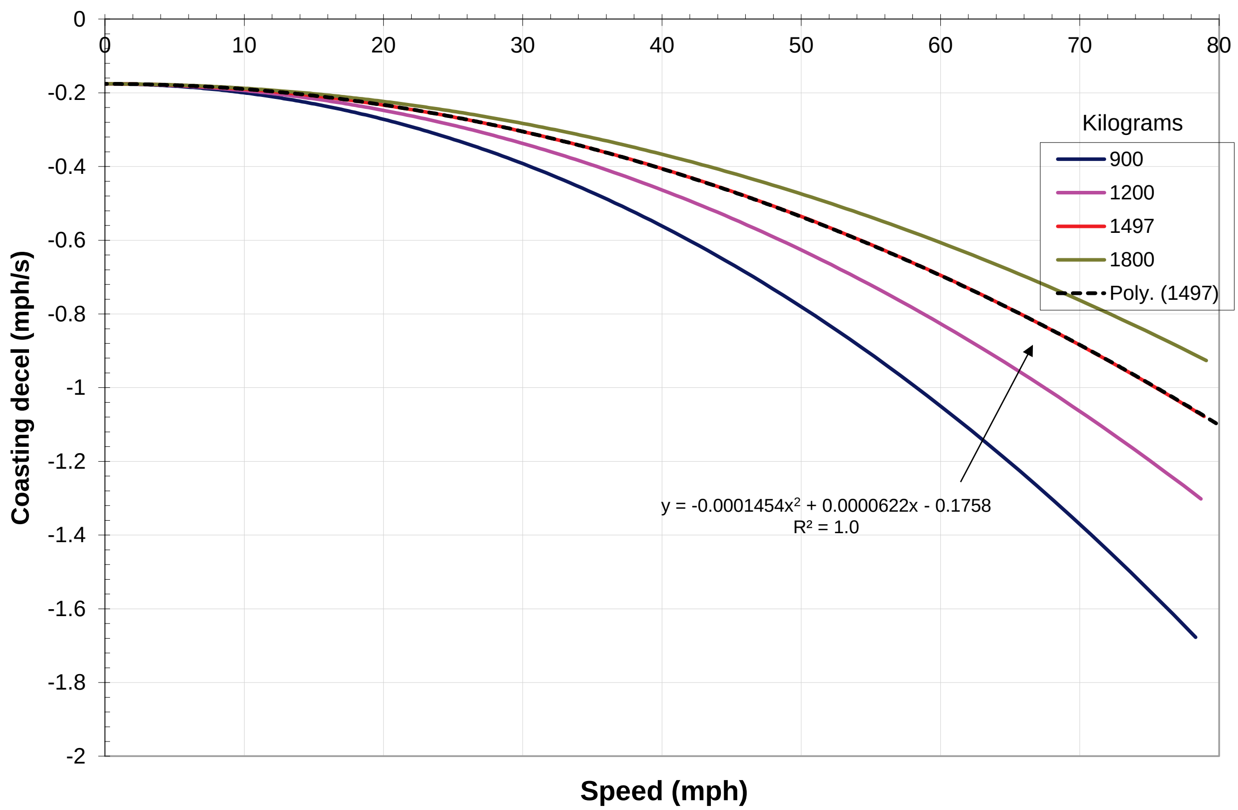


Figure A-2. Coast down Curves as a Function of Vehicle Mass

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

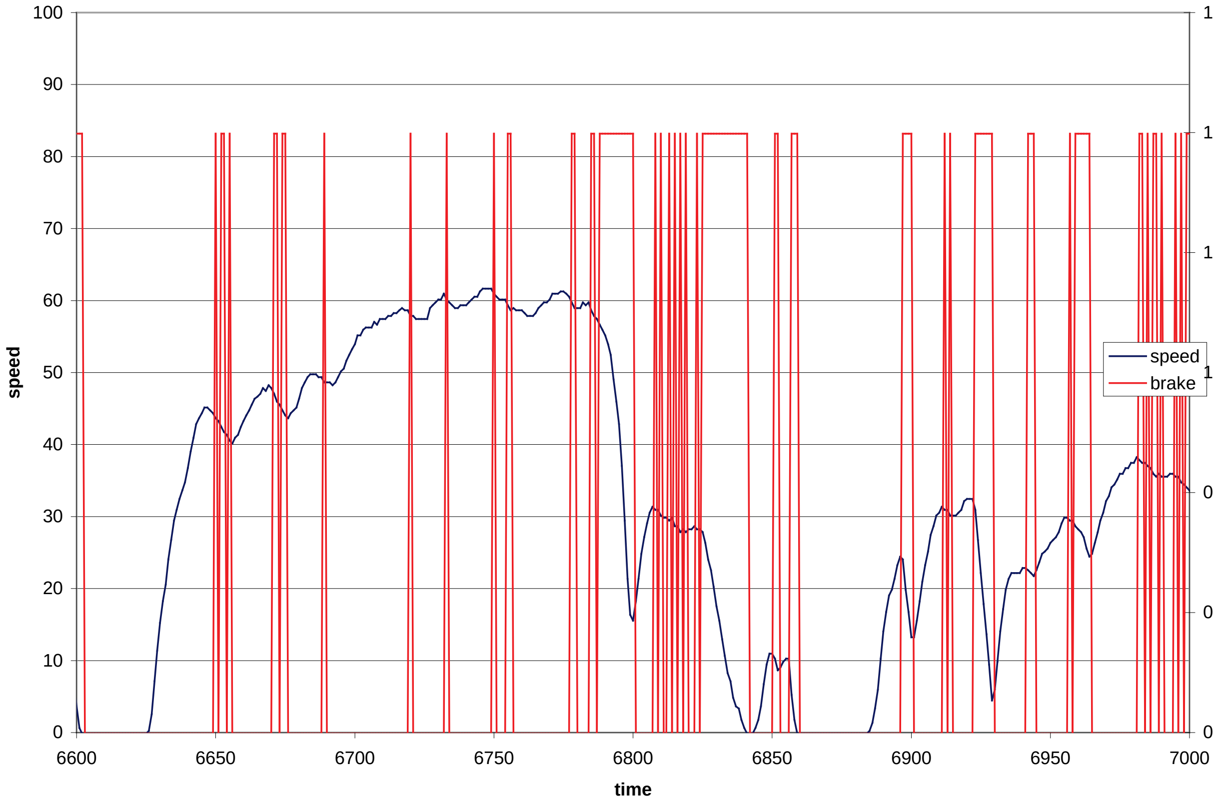


Figure A-3 Braking Episodes over the FTP cycle

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 MOVES emissionrate table.

Table B-1 PM2.5 Brake Emission Rates by Regulatory Class and Operating Mode (g/hr)

regclassID	regClassName	opModeID	opModeName	MeanBaseRate (g/hr)
10	MC	0	Braking	0.055664
10	MC	1	Idling	0.0024472
10	MC	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0.054488
10	MC	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0.03584
10	MC	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.0056
20	LDV	0	Braking	0.55846
20	LDV	1	Idling	0.024472
20	LDV	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0.546
20	LDV	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0.35896
20	LDV	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.0644
30	LDT	0	Braking	0.940406
30	LDT	1	Idling	0.0412091
30	LDT	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0.919425
30	LDT	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0.623323
30	LDT	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.115046
40	LHD <= 10k	0	Braking	0.865
40	LHD <= 10k	1	Idling	0.027334
40	LHD <= 10k	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0.789745
40	LHD <= 10k	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0.642695
40	LHD <= 10k	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.10899
41	LHD <= 14k	0	Braking	0.865
41	LHD <= 14k	1	Idling	0.027334
41	LHD <= 14k	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0.789745
41	LHD <= 14k	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0.642695
41	LHD <= 14k	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.10899
42	LHD45	0	Braking	1.44
42	LHD45	1	Idling	0.045504
42	LHD45	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	1.31472
42	LHD45	21	Moderate Speed Coasting; VSP< 0;	1.06848

			25<=Speed<50	
42	LHD45	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.18576
46	MHD67	0	Braking	2.09
46	MHD67	1	Idling	0.066044
46	MHD67	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	1.9019
46	MHD67	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	1.51525
46	MHD67	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.25289
47	HHD8	0	Braking	4.16
47	HHD8	1	Idling	0.06656
47	HHD8	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	4.16
47	HHD8	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	2.66656
47	HHD8	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.28288
48	Urban Bus	0	Braking	2.1
48	Urban Bus	1	Idling	0.0336
48	Urban Bus	11	Low Speed Coasting; VSP< 0; 1<=Speed<25	2.1
48	Urban Bus	21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	1.3461
48	Urban Bus	33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.1428

Table B-2 PM2.5 Tire Emission Rates by Regulatory Class and Operating Mode (g/hr)

regclassID	regClassName	opModeID	opModeName	MeanBaseRate (g/hr)
10	MC	400	idle	0
10	MC	401	speed < 2.5mph	0.0031775
10	MC	402	2.5mph <= speed < 7.5mph	0.00601
10	MC	403	7.5mph <= speed < 12.5mph	0.01116
10	MC	404	12.5mph <= speed < 17.5mph	0.015525
10	MC	405	17.5mph <= speed <22.5mph	0.01922
10	MC	406	22.5mph <= speed < 27.5mph	0.0223
10	MC	407	27.5mph <= speed < 32.5mph	0.02484
10	MC	408	32.5mph <= speed < 37.5mph	0.026915
10	MC	409	37.5mph <= speed < 42.5mph	0.02852
10	MC	410	42.5mph <= speed < 47.5mph	0.02979
10	MC	411	47.5mph <= speed < 52.5mph	0.03075
10	MC	412	52.5mph <= speed < 57.5mph	0.031405
10	MC	413	57.5mph <= speed < 62.5mph	0.0318
10	MC	414	62.5mph <= speed < 67.5mph	0.03198
10	MC	415	67.5mph <= speed < 72.5mph	0.03192
10	MC	416	72.5mph <= speed	0.0318
20	LDV	400	idle	0
20	LDV	401	speed < 2.5mph	0.006355
20	LDV	402	2.5mph <= speed < 7.5mph	0.01202
20	LDV	403	7.5mph <= speed < 12.5mph	0.02231
20	LDV	404	12.5mph <= speed < 17.5mph	0.031065
20	LDV	405	17.5mph <= speed <22.5mph	0.03844
20	LDV	406	22.5mph <= speed < 27.5mph	0.0446
20	LDV	407	27.5mph <= speed < 32.5mph	0.04968
20	LDV	408	32.5mph <= speed < 37.5mph	0.053795
20	LDV	409	37.5mph <= speed < 42.5mph	0.05708
20	LDV	410	42.5mph <= speed < 47.5mph	0.05958
20	LDV	411	47.5mph <= speed < 52.5mph	0.06145
20	LDV	412	52.5mph <= speed < 57.5mph	0.062755
20	LDV	413	57.5mph <= speed < 62.5mph	0.06354
20	LDV	414	62.5mph <= speed < 67.5mph	0.063895
20	LDV	415	67.5mph <= speed < 72.5mph	0.06391
20	LDV	416	72.5mph <= speed	0.063525
30	LDT	400	idle	0
30	LDT	401	speed < 2.5mph	0.006355
30	LDT	402	2.5mph <= speed < 7.5mph	0.01202
30	LDT	403	7.5mph <= speed < 12.5mph	0.02231

30	LDT	404	12.5mph <= speed < 17.5mph	0.031065
30	LDT	405	17.5mph <= speed <22.5mph	0.03844
30	LDT	406	22.5mph <= speed < 27.5mph	0.0446
30	LDT	407	27.5mph <= speed < 32.5mph	0.04968
30	LDT	408	32.5mph <= speed < 37.5mph	0.053795
30	LDT	409	37.5mph <= speed < 42.5mph	0.05708
30	LDT	410	42.5mph <= speed < 47.5mph	0.05958
30	LDT	411	47.5mph <= speed < 52.5mph	0.06145
30	LDT	412	52.5mph <= speed < 57.5mph	0.062755
30	LDT	413	57.5mph <= speed < 62.5mph	0.06354
30	LDT	414	62.5mph <= speed < 67.5mph	0.063895
30	LDT	415	67.5mph <= speed < 72.5mph	0.06391
30	LDT	416	72.5mph <= speed	0.063525
40	LHD <= 10k	400	idle	0
40	LHD <= 10k	401	speed < 2.5mph	0.0087725
40	LHD <= 10k	402	2.5mph <= speed < 7.5mph	0.016595
40	LHD <= 10k	403	7.5mph <= speed < 12.5mph	0.0308
40	LHD <= 10k	404	12.5mph <= speed < 17.5mph	0.042885
40	LHD <= 10k	405	17.5mph <= speed <22.5mph	0.05308
40	LHD <= 10k	406	22.5mph <= speed < 27.5mph	0.061575
40	LHD <= 10k	407	27.5mph <= speed < 32.5mph	0.06861
40	LHD <= 10k	408	32.5mph <= speed < 37.5mph	0.07427
40	LHD <= 10k	409	37.5mph <= speed < 42.5mph	0.0788
40	LHD <= 10k	410	42.5mph <= speed < 47.5mph	0.082305
40	LHD <= 10k	411	47.5mph <= speed < 52.5mph	0.08485
40	LHD <= 10k	412	52.5mph <= speed < 57.5mph	0.086625
40	LHD <= 10k	413	57.5mph <= speed < 62.5mph	0.08772
40	LHD <= 10k	414	62.5mph <= speed < 67.5mph	0.088205
40	LHD <= 10k	415	67.5mph <= speed < 72.5mph	0.0882
40	LHD <= 10k	416	72.5mph <= speed	0.087675
41	LHD <= 14k	400	idle	0
41	LHD <= 14k	401	speed < 2.5mph	0.0087725
41	LHD <= 14k	402	2.5mph <= speed < 7.5mph	0.016595
41	LHD <= 14k	403	7.5mph <= speed < 12.5mph	0.0308
41	LHD <= 14k	404	12.5mph <= speed < 17.5mph	0.042885
41	LHD <= 14k	405	17.5mph <= speed <22.5mph	0.05308
41	LHD <= 14k	406	22.5mph <= speed < 27.5mph	0.061575
41	LHD <= 14k	407	27.5mph <= speed < 32.5mph	0.06861
41	LHD <= 14k	408	32.5mph <= speed < 37.5mph	0.07427
41	LHD <= 14k	409	37.5mph <= speed < 42.5mph	0.0788
41	LHD <= 14k	410	42.5mph <= speed < 47.5mph	0.082305

41	LHD <= 14k	411	47.5mph <= speed < 52.5mph	0.08485
41	LHD <= 14k	412	52.5mph <= speed < 57.5mph	0.086625
41	LHD <= 14k	413	57.5mph <= speed < 62.5mph	0.08772
41	LHD <= 14k	414	62.5mph <= speed < 67.5mph	0.088205
41	LHD <= 14k	415	67.5mph <= speed < 72.5mph	0.0882
41	LHD <= 14k	416	72.5mph <= speed	0.087675
42	LHD45	400	idle	0
42	LHD45	401	speed < 2.5mph	0.0095
42	LHD45	402	2.5mph <= speed < 7.5mph	0.017965
42	LHD45	403	7.5mph <= speed < 12.5mph	0.03335
42	LHD45	404	12.5mph <= speed < 17.5mph	0.04644
42	LHD45	405	17.5mph <= speed <22.5mph	0.05748
42	LHD45	406	22.5mph <= speed < 27.5mph	0.066675
42	LHD45	407	27.5mph <= speed < 32.5mph	0.07428
42	LHD45	408	32.5mph <= speed < 37.5mph	0.08043
42	LHD45	409	37.5mph <= speed < 42.5mph	0.08532
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	0.09383
42	LHD45	413	57.5mph <= speed < 62.5mph	0.09498
42	LHD45	414	62.5mph <= speed < 67.5mph	0.09555
42	LHD45	415	67.5mph <= speed < 72.5mph	0.09548
42	LHD45	416	72.5mph <= speed	0.09495
46	MHD67	400	idle	0
46	MHD67	401	speed < 2.5mph	0.011045
46	MHD67	402	2.5mph <= speed < 7.5mph	0.02089
46	MHD67	403	7.5mph <= speed < 12.5mph	0.03878
46	MHD67	404	12.5mph <= speed < 17.5mph	0.054
46	MHD67	405	17.5mph <= speed <22.5mph	0.06682
46	MHD67	406	22.5mph <= speed < 27.5mph	0.077525
46	MHD67	407	27.5mph <= speed < 32.5mph	0.08637
46	MHD67	408	32.5mph <= speed < 37.5mph	0.09352
46	MHD67	409	37.5mph <= speed < 42.5mph	0.0992
46	MHD67	410	42.5mph <= speed < 47.5mph	0.10359
46	MHD67	411	47.5mph <= speed < 52.5mph	0.10685
46	MHD67	412	52.5mph <= speed < 57.5mph	0.109065
46	MHD67	413	57.5mph <= speed < 62.5mph	0.11046
46	MHD67	414	62.5mph <= speed < 67.5mph	0.111085
46	MHD67	415	67.5mph <= speed < 72.5mph	0.11102
46	MHD67	416	72.5mph <= speed	0.1104
47	HHD8	400	idle	0

47	HHD8	401	speed < 2.5mph	0.023655
47	HHD8	402	2.5mph <= speed < 7.5mph	0.04474
47	HHD8	403	7.5mph <= speed < 12.5mph	0.08305
47	HHD8	404	12.5mph <= speed < 17.5mph	0.115635
47	HHD8	405	17.5mph <= speed <22.5mph	0.14312
47	HHD8	406	22.5mph <= speed < 27.5mph	0.16605
47	HHD8	407	27.5mph <= speed < 32.5mph	0.18495
47	HHD8	408	32.5mph <= speed < 37.5mph	0.200305
47	HHD8	409	37.5mph <= speed < 42.5mph	0.21248
47	HHD8	410	42.5mph <= speed < 47.5mph	0.22185
47	HHD8	411	47.5mph <= speed < 52.5mph	0.2288
47	HHD8	412	52.5mph <= speed < 57.5mph	0.23364
47	HHD8	413	57.5mph <= speed < 62.5mph	0.23658
47	HHD8	414	62.5mph <= speed < 67.5mph	0.2379
47	HHD8	415	67.5mph <= speed < 72.5mph	0.23779
47	HHD8	416	72.5mph <= speed	0.236475
48	Urban Bus	400	idle	0
48	Urban Bus	401	speed < 2.5mph	0.01271
48	Urban Bus	402	2.5mph <= speed < 7.5mph	0.024035
48	Urban Bus	403	7.5mph <= speed < 12.5mph	0.04462
48	Urban Bus	404	12.5mph <= speed < 17.5mph	0.06213
48	Urban Bus	405	17.5mph <= speed <22.5mph	0.0769
48	Urban Bus	406	22.5mph <= speed < 27.5mph	0.089225
48	Urban Bus	407	27.5mph <= speed < 32.5mph	0.09936
48	Urban Bus	408	32.5mph <= speed < 37.5mph	0.107625
48	Urban Bus	409	37.5mph <= speed < 42.5mph	0.11416
48	Urban Bus	410	42.5mph <= speed < 47.5mph	0.119205
48	Urban Bus	411	47.5mph <= speed < 52.5mph	0.12295
48	Urban Bus	412	52.5mph <= speed < 57.5mph	0.12551
48	Urban Bus	413	57.5mph <= speed < 62.5mph	0.12708
48	Urban Bus	414	62.5mph <= speed < 67.5mph	0.12779
48	Urban Bus	415	67.5mph <= speed < 72.5mph	0.12775
48	Urban Bus	416	72.5mph <= speed	0.12705

Appendix C Literature Review

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 break 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-matallic 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 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 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.

Appendix D Responses to Peer-Review Comments

This section provides a verbatim list of peer reviewer comments submitted in response to the charge questions for the Brake and Tire Wear Emissions/Temperature Effects Report.

D.1 Adequacy of Selected Data Sources

Does the presentation give a description of selected data sources sufficient to allow the reader to form a general view of the quantity, quality and representativeness of data used in the development of emission rates? Are you able to recommend alternate data sources might better allow the model to estimate national or regional default values?

D.1.1 Dr. Chris Frey

Table 2-1 of the report is a helpful summary of data sources that were reviewed by EPA as a possible basis for estimating brake wear emission rates. EPA chose to base the brake wear emission rates for light duty vehicles mostly on a study by Sanders et al. (2003). The brake wear emission rates for heavy duty vehicles are based mostly on a study by Moahmoud Abu-Allabah et al. (2003). The tire wear emission rates are based mostly on a study by Lahuna et al. (2004).

There is a need for more critical discussion of the representativeness of the data from these studies for the U.S. onroad fleet. Since all three of these key studies are approximately a decade old, a question naturally emerges in the reader's mind as to whether the brake lining, brake shoe, or tire materials that were the basis of these studies are representative of materials currently in use. Furthermore, are the vehicles measured representative of vehicles currently in use in terms of the most relevant characteristics, such as vehicle weight, and factors such as the ratio of brake pad or brake shoe area to vehicle weight, and tire tread dimensions to vehicle weight, and so on. If these questions are not answerable, then explain why they cannot be answered. However, it is important to indicate that these issues were at least considered, even if there is not a quantitative basis upon which to make a judgment.

> *RESPONSE: An explanation was added to the paper, which describes that the paper was originally drafted in 2006, and the literature review was current at the time. The MOVES team had not the resources to update this paper in time for MOVES2014 due to the many other updates required. A Next Steps section was also added to the report describing what a future study could update. As to whether the papers are representative, this is a difficult question to answer, as these are the only papers that could be found at the time, there simply is not a large amount of research conducted on airborne tire and brake wear particulate matter emissions. The author of the report attempted to analytically adjust the data to be as representative as practicable.*

D.1.2 Dr. Joe Zietsman

The literature used as the basis for this work is sufficient. I am not aware of any other literature that has been overlooked. The only concern is that the literature is quite old (newest study is from 2004 for brake wear and 2005 for tire wear).

On Table 2-1, the vehicle type classification for the Warner et al study refers to both "passenger cars" as well as "light duty". I am not sure what the distinction is or whether it is a typo. In the Sanders work, UDS, UDP, and AMS should be defined. On looking at the source reference looks like UDS may be a typo. It seems as though the description of the Sanders study on page 3 needs to be corrected – for example, -7.9m/s should be -7.9m/s2; specify what g is in the context of the decelerations, etc.

> *RESPONSE: These issues have been addressed in the report. The table has also been shortened to only include papers with measurements; the papers with brake emissions estimates based on models and literature reviews have been omitted.*

On page 7 – first sentence should refer to accelerations if referring to Figure 2.5.

> *RESPONSE: This has been clarified in the report.*

On page 15, effect of horizontal curvature is discussed. It is assumed vertical curvature or grade could have an effect on tire wear, but it was not mentioned in this work.

> *RESPONSE: Agreed: thank you for the suggestion, this has been added to the report.*

In Table 3-1 – there is no mention of the Luhana study

> *RESPONSE: We added the Luhana et al. (2003) study to Table 3-1.*

In Table 3-3 and related text– it should be better clarified how total weight loss is calculated.

> *RESPONSE: the table description now includes the information that the tires were weighed.*

On Page 20, Table 5 is referred to as "above", and it is actually below; Table 6 is referred to, but it doesn't exist.

> *RESPONSE: this has been corrected.*

D.2 Clarity of Analytical Methods and Procedures

Is the description of analytic methods and procedures clear and detailed enough to allow the reader to develop an adequate understanding of the steps taken and assumptions made by EPA *to develop the model inputs? Are examples selected for tables and figures well chosen and designed to assist the reader in understanding approaches and methods?*

D.2.1 Dr. Chris Frey

No.

Consider Figure 2-1. This is apparently an excel worksheet that was copied into the report. The figure is labeled as "UDP results." What is UDP? Spell it out. Results for what, exactly? The table reports "PM10 emiss." for "filter" and "ELPI" (again, always make tables and figures self-documenting – what is ELPI?). I looked in Sanders et al. (2003) to try to figure out where these reported numbers come from. For UDP, low metallic, I find in Table 5 that "filter" results are reported for "total mass" in mg/stop/brake. However, the numbers in the draft report are not the same as from Sanders et al. (2003). For example, the low metallic filter PM10 emiss. is reported as 6.9 (are the units mg/stop-brake? – not very clear given that units are not given for each column of data). Let's assume that this is 6.9 mg/stop-brake. In Table 5 of Sanders et al. (2003), I find that the individual tests range from 6.2 mg/stop-brake to 11.7 mg/stop-brake, with an average of 8.3 mg/stop-brake. Thus, as a reader, I cannot figure out either why did EPA choose one test from among the multiple reported by Sanders et al. (2003), or what adjustment did EPA make from the average of 8.3 mg/stop-brake to arrive at 6.9 mg/stop-brake? On the other hand, for the ELPI results, EPA seems to be reporting the same values as shown by Sanders et al. (2003) for the average of all reported tests for each of the three types of brake pad linings.

> *RESPONSE: All of these have been clarified in the section 2.1. For example, the acronyms have been spelled out and the units are more clear. Describing what exactly these instruments do is beyond the scope of this report. We also removed UDP from the heading of Figure 2-1. As for the reason why the paper's UDP number doesn't match Sanders et al.: We calculated 6.9 mg/stop/brake from the 8.2 mg/stop/brake. The filter number reported in Sanders is TOTAL PM Mass. In order to get the PM10 mass, the ELPI ratios were used, thus 8.2 * (7/8.3). Likewise, 1.7 was determined from 1.7 * (1.7/2) etc. A footnote was added with an example calculation.*

Also unclear: how does EPA go from average/stop/brake (what is this… isn't this average emission rate in mg/stop-brake) to "Avg./veh" (again, what is this – always report units). It would help to show an example calculation. The ratio of avg./veh to 'average/stop/brake" is approximately 3, which may be based on an assumption that the non-drive wheels have ½ the brake wear of the drive wheels. This could be more clear.

> *RESPONSE: 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 and 1/3 from the rear brakes. Footnote has been added.*

As far as the deceleration in Figure 2-1, where does this come from? Is this an average of all decelerations from all stops during the UDP? This could be more clear. Is the value of 0.0012 km/s2 reported by Sanders et al. (2003) or was this inferred by EPA. If the latter, how?Similarly, what is the basis for the "average brake time in secs" that is reported in Figure 2-1?

Similarly, what is the basis for the "avg . emissions in mg/ stop" that is reported in Figure 2-1?

> *RESPONSE: The following footnote was added below the table (f). 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 bottom of Figure 2-1 includes "emission rate for the UDP test" of 2.65 gms/hr. Since the previous lines indicate that time is for braking or per stop, clarification is needed as to the time basis for 2.65 g/hr. Is this based only on braking time? Is this based on total travel or trip time?

> RESPONSE: Yes, the emission rate is only during braking events and times as clarified in the text near the figure.

Similar comments apply to Figures 2-2, 2-3, and 2-4.

Without clear documentation of how the emission rates were estimated, it is not possible to comment on whether the curve fit in Figure 2-5 is reasonable. The fit shown is reasonable given the numbers used in fitting the curve, but the basis for, and meaning of, the numbers is unclear.

Additional comments regarding needs for improved communication of the data and methods are given in detail in a section on "Specific Comments"

D.2.2 Dr. Joe Zietsman

The methods and approaches are adequate. It is not clear in this report how the exact measurement (of the PM emissions) was conducted in the source studies, as well as the basis for assumptions/measurements regarding apportionment (of what gets emitted into the air as PM10) and what percentage of PM10 is PM2.5. For example, on Page 20 (last sentence) – 8% of tire wear as PM10 assumption is not referenced.

RESPONSE: these have been addressed throughout the document. For example the 8% text is made more clear on page 22.

D.3 Appropriateness of Technical Approach

Are the methods and procedures employed technically appropriate and reasonable, with respect to the relevant disciplines, including physics, chemistry, engineering, mathematics and statistics?

Are you able to suggest or recommend alternate approaches that might better achieve the goal of developing accurate and representative model inputs? In making recommendations please distinguish between cases involving reasonable disagreement in adoption of methods as opposed to cases where you conclude that current methods involve specific technical errors.

D.3.1 Dr. Chris Frey

EPA is making use of data collected by others and reported in the literature. The selected references generally seem to be reasonable.

The methods and procedures employed by EPA include judgments about the representativeness and appropriateness of the selected data sets for use as a basis for developing MOVES inputs, and regarding the statistical analyses conducted based on the selected data. Given lack of sufficient data from which to develop more detailed models, EPA has developed relatively simply models. The general approach is reasonable. However, the communication of what was done could and should be more clear and complete. Ideally, sufficient information should be communicated regarding the underlying data and inference approaches such that an independent investigator can reproduce the results and obtain the same answer. Many of the detailed comments given below under "specific comments" are aimed at this objective.

> *RESPONSE: These comments have been addressed throughout the report as described in greater detail in the more detailed comments.*

D.3.2 Dr. Joe Zietsman

No response.

D.4 Appropriateness of Assumptions

In areas where EPA has concluded that applicable data is meager or unavailable, and consequently has made assumptions to frame approaches and arrive at solutions, do you agree that the assumptions made are appropriate and reasonable? If not, and you are so able, please suggest alternative sets of assumptions that might lead to more reasonable or accurate model inputs while allowing a reasonable margin of environmental protection.

D.4.1 Dr. Chris Frey

In general, I agree that EPA has done a reasonable job with a very limited data set to make inferences and develop data and fitted models for use with MOVES.

D.4.2 Dr. Joe Zietsman

No response.

D.5 Consistency with Existing Body of Data and Literature

Are the resulting model inputs appropriate, and to the best of your knowledge and experience, reasonably consistent with physical and chemical processes involved in exhaust emissions *formation and control? Are the resulting model inputs empirically consistent with the body of data and literature that has come to your attention?*

D.5.1 Dr. Chris Frey

Yes.

D.5.2 Dr. Joe Zietsman

With regard to the above three questions, based on the available data the methods are appropriate and reasonable. I concur with what is noted in the report regarding improvements with more data, for example allocating tire wear by VSP bin, etc. I am not aware of any current datasets or methods that can enhance this work.

D.6 Tire and Brakewear PM2.5 and PM10 Emission Rates and Speciation

MOVES2014 estimates total PM2.5 and PM10 emission rates from brake and tire wear. Additional PM2.5 speciation capabilities have been incorporated in MOVES2014 for exhaust emission processes. What recommendations do you have for EPA for incorporating the PM2.5 and PM10 speciation of tire and brakewear for future versions of MOVES?

D.6.1 Dr. Chris Frey

Clearly, it will be desirable to include speciation of PM10 and PM2.5 into future versions of MOVES for brake and tire where when sufficient data are available to support such estimates. In the current report, EPA could provide at least a paragraph summarizing what is known about the PM composition of brake wear debris, to expand upon some text on page 3. To the extent that there is or isn't information on PM composition of tire wear, EPA should add at least a paragraph to discuss this and, if applicable, summarize available information. Of particular interest is what are the key indicator species or components of brake wear and of tire wear, and are these sensitive to the materials used, or is there insufficient information to address these points? There is no information offered in the section on tire wear regarding the chemical composition of tear wear debris or emissions. Is this because no information is available?

> *RESPONSE: The literature had very limited discussion of PM speciation. There were some measurements of this, however, it was beyond the scope of this current modeling exercise. We added discussion in Section 4 Next Steps, that we would like to do more work on PM speciation of brake and tire wear.*

D.6.2 Dr. Joe Zietsman

While the additional PM2.5 speciation capabilities in MOVES 2013/2014 (in terms of added species, as relevant) will be useful, a first step for brake and tire wear emissions would be to better estimate and justify the following factors: a) PM-10 to PM2.5 ratio; b) percentage of brake and tire wear that is actually emitted as PM-10 and PM2.5.

RESPONSE: We hope to improve on these emission factors as we become aware of new literature and data. We have added a statement that we would like to improve the information on size distributions in the Next Steps Section.

D.7 General/Catch-All Review

Please provide any additional thoughts or review of the material you feel important to note that is not captured by the preceding questions.

D.7.1 Dr. Chris Frey

This is a significant report that documents an important part of the MOVES emission factor model, which is used nationally for a wide variety of regulatory and other analyses. As such, it is critically important that the report be well written and very clear. While the current draft of the report is good in many respects, it comes across as a draft and is not in final form in terms of the critical thinking needed to make sure that it clearly communicates information to the reader.

For each of the major sections on brake and tire wear, it will help the reader to have clearly labeled sections that deal with light duty vehicles and with all other vehicle source categories. It will also help to clearly define and consistently use terms and concepts. For example, it is critically important to have a clear quantitative definition of break wear and of tire wear, and to be clear as to whether these are rates per wheel, per vehicle, or other (specify).

RESPONSE: We added Light- Duty to Section 2.23, and Heavy-duty and Other Vehicles to Section 2.2.5.

Since this is a formal technical report, the use of first person should be avoided. Statements regarding how an analysis was done, or regarding judgments that were made, can be made without self-reference.

In general, be careful about significant figures. It is pretty rare in this type of work that data are known with more than 3 significant figures. However, in various places, numbers are reported with 5 or 6 significant figures, and often with 4. Even if the original data might be known with many significant figures, its adoption for use in representing a national fleet introduces uncertainty, since the original data may not represent the U.S. national fleet as it exists today.

RESPONSE: Significant figures for intermediate numbers were largely maintained. The final numbers were appropriately adjusted. Some of the figures/tables have reduced sig figs now as well.

Many specific comments are given below that elaborate on responses given above in response to the charge questions.

Specific Comments (numbers refer to page/paragraph/line … e.g., 3/3/1 means page 3, paragraph 3, line 1)

> *RESPONSE: Unless otherwise noted, all minor comments have been addressed in the report in the relevant sections. Responses are provided to the major comments.*

Given that this report will be finalized perhaps in 2013 or 2014, explanation is needed for the reader as why the literature review starts off with information from 2004. Is this because more recent data are not available?

Page 2, 3rd paragraph in Section 2.1, next to last line "is acceptable" does not fit here.

Page 2, 4th paragraph in Section 2.1: while these statements seem intuitively reasonable, they are stated as if they are known facts. However, no references are cited. How do the authors know that these are accepted facts? Or are these the author's hypotheses or opinions? If factual, then cite reference(s). If these are hypotheses, then say so.

> *RESPONSE: we believe that these statements in this particular paragraph are obvious to anyone with a basic knowledge of vehicle brakes. While not all readers of this paper may have knowledge of brakes, some of the text in this paper are meant to be include basic instructive material as well. As such, we do not believe that relatively "basic" statements like this require references. However, the subsequent statements in the following 2 paragraphs are more specific. We've added a parenthetical when the Garg paper is first mentioned that much of the basic PM information comes from this paper. This paper is very important in the list of this study's references.*

Please carefully define what is meant by "wear" and then use the definition consistently. Does "wear" refer to a mass rate of emissions or loss per tire per braking episode, or is it a time-based rate for a tire (or a vehicle), or a mileage-based rate? If this is not defined, then readers will make their own assumptions as to what this means. Does "greater wear" mean greater rate of wear, or more accumulative lost mass regardless of time period?

> *RESPONSE: the definition of wear versus airborne PM has been differentiated in various points in the paper. Wear means slightly different things in the literature, but in this paper it is generally, the mass of material lost, whether in the brake pads or the tires. A fraction of that wear is airborne PM. Some studies look at both wear and airborne PM, others look at one or the other. We added discussion providing a definition of brake wear, and airborne PM in Section 2.1.*

3/2/1: Page 3, 2nd paragraph, a 2000 study is not "recent" in 2013… delete "In recent studies,"

3/2/6: "ranged from 3.4 mg/mile to 4.6 mg/mile" is the correct way to write the range at the end of the same paragraph.

3/3/1: "currently used" – refers to 2003 or to now?

3/3/7: this list is hard to read because apparently not all brake linings were measured in all types of tests, but the reader has to reread this a few times to really figure this out.

3/3/9: -7.9 m/s is not an acceleration. Is this supposed to be -7.9 m/s2?

3/3 – near end of paragraph… it would help to give a summary of how the PM composition varies by brake type.

RESPONSE: We added as much information as we could, but we do not have perfect information.

End of page 3 – why is there no discussion of other references, particular ones published shortly before or after Sanders et al. (2003), such as Warner et al. (2002), Abu-Allaban et al. (2002), and others. From Table 2-1, the reader infers that some of these could also be useful. If EPA judged that they are not useful, a rationale should be given.

RESPONSE: a paragraph was added to the paper here.

Related to page 3 – is the current market share of each brake lining type known? If so, please summarize. If not, then say so.

RESPONSE: We added a sentence saying that this is not known in this section.

4/1/1: "is based on the average of the" is better than "averages"

4/3: why are only results from Sanders et al. (2003) used here… give an explanation.

5/1/1: how sensitive are results to the assumption regarding equal mix of brake types?

RESPONSE: this is answered indirectly earlier in the report where there is a summary provided from the paper regarding the differing results from the varying materials.

5/1/2: is there some basis for the assumption that 2/3 of braking power is in the front brakes? Actually, the assumption made here is that the rate of brake lining wear is twice that for front drive wheels than for rear nondrive wheels. Is the assumption really based on "power"?

RESPONSE: this information was provided by Matti Mariq from Ford who is a co-author on the Sanders paper and helped us with the data and information like this in this report. This is a "rule of thumb" in the industry. It is also consistent with what is written in Garg and that is now added to the footnote.

5/1/4: what is meant by "total PM"? is this total suspended particulate matter?

Page 8 – include definitions of opmode bins 0 and 1.

8/1: to reader it is unclear as to why 1,497 kg is used. Explain that this is a typical weight of a sedan passenger car. Is this the only selected weight? Why not others? What about larger vehicles?

RESPONSE: this is the average weight of passenger cars in MOVES. Other vehicle type weights are provided elsewhere in the report. We added this to the report.

Page 9, figure 2-7: "coastdown curves" for what, based on what data sources? Figure and table captions generally need to be more specific throughout the report. Also, the number of significant figures given for the equation borders on the absurd.

RESPONSE: PERE is a vehicle simulation model, that has undergone separate peer review. A complete description of how these plots were developed would be lengthy and distract from the focus of the report. We do not believe that it is required for what is a minor part of the quantification of the braking emissions. However, more detail was added with three figures on the PERE coast down and braking estimates in Appendix A.

9/1/3: "Eastern" not "Easter"

9/2/2: it is very unclear as to how the distribution of braking activity across speed and deceleration can be determined from the numbers given in Table 2-7.

9/2/2: "vast majority of braking" – how is this known? What is a "minor slowdown"? (give quantitative criteria for this).

RESPONSE: The following table quantitatively shows deceleration frequencies drop as braking becomes more severe. We disagree that an actual quantitative definition of mild and full decelerations is required here. This is not a distinction that is made in the MOVES model.

11: Table 2-8: in text or footnote, show the equations that define or use the constants given such as "wgt", "Cr0", "Cd", "A"… and preferably use mathematical nomenclature. Also, do not report "m^2". This should be "m2" Please use source bin terminology and please define what the columns are in this table… i.e. the last 5 columns should have a superheader of "Vehicle Type." Does MOVES have source ids for "Compact," "Mid-size," "SUV," "mddt," and "tractor"?. If these are assumptions that are meant to apply to source bin ids in MOVES, then use proper MOVES terminology to avoid confusion.

RESPONSE: MOVES does not have source types for compact, mid-size or SUV. These source type definitions are typical for vehicle simulation models like PERE. These models are capable of greater precision than MOVES, and an attempt is made here to model greater detail first, then aggregate the results up to MOVES source bins.

Table 2-8 has some definition problems, in that the first four rows of numbers are not fractions and thus should not be defined as such, and yet the last 7 rows are in a sense undefined, because there is no header in the table that defines what they are. There is inconsistency in the number of decimal places given. Also, the basis for these numbers is unclear – where do they come from and how exactly where they derived?

RESPONSE: The table has been cleaned up. Also more information has been included in the text near this table as well as appendix.

11/1: it would help to have an example calculation showing how these emission rates were estimated.

13/1: please give some rationale as to why this study was used and/or why others were not. Was this the only relevant study? The most recent study? The best study? Just stating that it was used is not sufficient to explain to the reader why it was used. Also, please indicate what type of instruments were used and at least some summary of how the sampling was done, and how it was possible to associate the measurements with a per vehicle emission rate specific to brake wear.

RESPONSE: a lengthy description has been added on page 13 and following.

13/1/7: "by ratioing"… ratio is not a verb. "by taking the ratio of…" More importantly, please explain the empirical basis for these ratios. Upon what measurements are they based, and how was it possible to distinguish among the vehicle categories – e.g., how was it possible to apportion measurements to vehicle types?

Table 2-2: the caption "scaling to other vehicle class" may mean something to the author, but lacks sufficient detail and specificity to mean much to the reader. What exactly is contained in this table and what is the source or basis of the information? Tables and figures should be self-documented to the extent possible, to make very clear as to what is the content. Please define or explain specialized terms – e.g., "regclasswt" and "regclassid" are variables used in MOVES (define them). What is the basis of the weight ratio? Is this based on weights given in MOVES (for clarity, report the weights so that the basis of the weight ratios is more clear). What is the source of the "mg/mi" and why is there no description of what this is in the column header? Similarly, "gms/hr**" has no explanatory title nor is there any explanation of whether "**" is meant to be a footnote. This type of sloppy and incomplete documentation of tables leads to long-term confusion as to the basis of data contained in MOVES, and causes a lot of problems for MOVES users for many years to come. Thus, it is essential that these reports be well documented.

RESPONSE: A paragraph has been added before Figure 2-4 in addition to a Figure 2-4 and additional tables (Tables 2-12, 2-13) to help clarify.

13/2/2: "a PM10/PM2.5 ratio" – is one ratio used regardless of opmode bin? Source category? Etc.? Needs to be more clear.

RESPONSE: this has been clarified in the report that there is one ratio used for simplification.

13/2: The PM10/PM2.5 ratio is "based on the assumption that the mass fraction of particles below PM10 is 0.80, and that the mass fraction of particles below PM2.5 is 0.1" ☐ this is suggested revised text. I do not think that the authors really mean to refer to the fraction of particle number, but rather mean to refer to fraction of particle mass, yet the text implies that these ratios are by particle number. There is a big difference. Also, explain the basis of these assumptions. Are these mass fractions of 0.8 (why 0.80 – 2 sig figs) and 0.1 (why only 1 sig fig) based on measurements, a wild guess?

> *RESPONSE: Additional clarification on the size distribution used to derive the PM10/PM2.5 fraction from Sanders et al. (2003) is provided in Section 2.2.4.*

13/2/6: what are examples of cases either in which the PM2.5 values are known, or are not known, so that the reader has some idea of how extensive is the reliance on the assumption?

13/3: could delete "Tires are an essential part of any vehicle and"

> *RESPONSE: this is a matter of style. We disagree on this deletion.*

14/2: this paragraph ("Tire wear occurs through…") needs references. Some of the points here are repetitive of previous text.

14/4 ("The key influences…") this text comes across as repetitive although it does more specifically refer to vehicle characteristics, whereas other lists given previously seem not be specifically about vehicle characteristics. However, in general, this material could be better and more clearly organized with less repetition and with citation to literature to support statements of apparent fact that presumably have an empirical basis.

14/5 "Retreads are considered…" "considered" is extremely vague. "estimated" would be better. However, the text that follows does not support this claim. It merely indicates that retreads have less tire volume than the original tread. Why does this imply more wear? And what does more wear really mean – a higher rate of wear in terms of mass per stop, mass per time, mass per mile?

> *RESPONSE: this is another issue that is commonly known. The references include some other interesting facts, however, the report now lists that modeling emissions from retreads is beyond the scope of the report in Section 3.1 .*

14/6: any statement that starts with "According to the literature" must end with one or more cited references.

> *RESPONSE the subsequent paragraphs and table have many references on the technique that is introduced in this sentence.*

Page 15: Table 3-1 appears but I cannot find anywhere in the text where it is mentioned or discussed. If it is not mentioned or discussed, why is it here, or if it is here, why isn't it mentioned or discussed? Also, clarify specifically what is meant by the tire wear rates – are these rates per vehicle and, if so, based on how many tires per vehicle? The mass reported here is for what PM size range? Why isn't Luhana et al. (2004) summarized in this table, since it is the only reference really used?

15/1/1-2: delete "that have been carried out"

15/2/2: "m9ass" should be "mass"

15/3/2: delete "That being said" (too colloquial for a formal technical report).

15/4/2: change to "with results reported either as"

16/1: there is a disconnect between stating that data are primarily from one reference and yet that reference is not included in the summary table just above.

16/1/middle – there are syntax problems here.

Table 3-2: caption is too vague. What type(s) of vehicles? What type(s) of tires? What is the source of these data? The table is not very clear either – e.g., mean tire weight loss "mg/km" – does this refer to per tire or per vehicle? The numbers reported in the table have inconsistent numbers of decimal places and/or significant figures.

17/1: does mg/vkm refer to all tires on a vehicle, or one tire? Clarify throughout.

17/2/1: "the tables below" – cite the specific table(s).

Table 3-3. The caption "Data used for the analysis" takes the prize for vagueness. I don't think there could be a more meaningless caption. The caption should specifically indicate the content of the table. The lack of thought that went into this table is frustrating for the reader. These are some examples: "Front-wheel drive vehicles only" is not a valid column header, it should be part of the caption; "units" does not describe what is in the first column, yet why not use the same labels for both Tables 3-2 and 3-3 to denote the same tests (i.e. be consistent); the average trip speed of the first data row of 90.3 km/hr is not the same as the corresponding number in Table 3-2; is the tire weight loss per tire or the sum of both wheels on the axles? i.e. are the units g/km-axle or g/km-tire?; total weight loss for all tires (could be more clear) and could have one superheader over both of the columns that contain this information. Why is average speed given in the 2nd and 7th columns, rather than in adjacent columns if the only difference is a units conversion?; where do these data come from (what reference), and why not (in the footnote) specifically state the year, make, and model of each vehicle?

RESPONSE: This and other tables throughout the report have more descriptive captions now. The table has also been reformatted and redone so that the information is more clear to the reader.

Figure 3-1 and 3-2: the caption should indicate the vehicle type and whether the g/mi is per tire or per vehicle. If per vehicle, based on the assumption of how many tires/vehicle? Also, are mean trips speeds based on a particular time period of travel? One could divide a trip arbitrarily into short segments and obtain a wider range of mean trip speeds. However, if the averaging time is something like 60 seconds, 600 seconds, or 3000 seconds, that would affect the appropriate use of these rates.

RESPONSE: The paper does not specify the trip times.

Figure 3-2 – this figure seems unnecessary. The fitted curve is in Figure 3-2. If the purpose is to show the curve extrapolated beyond the range of the observed data, this could be done in figure 3-1 by using a dashed line for the fitted curve when it is outside the range of mean trip speeds.

RESPONSE: this figure has been removed.

19/1/1: rewrite as "Based on extrapolation of the fitted curve, wear is highest at zero speed and decreases as the speed increases." Why is this counter-intuitive? Lower mean trip speed might imply more variability in speed and, hence, more acceleration/deceleration(braking) that could increase tire wear. Thus, to me, this curve is intuitive. Delete "it is important to note" which is a passive phrase that has no content. The statement that "the relationship" does not take accelerations (and turning) into account is probably false. Aren't these data based on real-world driving? If so, then the observed wear rates implicitly take into account these factors, and the curve is fitted to these data – thus, the curve implicitly accounts for these.

RESPONSE: more text is included in this section to help clarify why the authors believe why some readers may believe this to be counterintuitive.

20/1/2: how is it known that the vehicle is "braking hard"?

RESPONSE: this is a descriptive term, not scientific. We do not feel that change to the text is required.

20/1/2-4: text here is a bit awkward… could say that there is insufficient data to characterize tire wear on a second by second basis to enable binning by operating mode bins.

20/2/1: this first sentence needs to be stated up front – i.e. that this section focuses on LDVs. Tire wear rates for other than LDVs should be in a new section. The assumption that tire wear is just based on the number of tires also presumes that tire wear for larger tires is the same as for LDV tires, and that tire wear is the same regardless of the ratio of weight/number of tires on a vehicle. These assumptions should be more clearly enumerated and discussed. Might it be the case that all else being equal (e.g., weight, acceleration, speed, road surface, etc.), tires with larger tread surface in contact with the ground would have less wear, but that more weight per tire would increase wear?

RESPONSE: We added a sentence at the beginning of Section 3.2 stating that the analysis starts with light-duty, and then is extended to other vehicle types. A number of engineering assumptions were required here. There is clearly a lack of information in the literature (as of when this study was completed) that would give emission rates for a variety of regulatory classes. A paragraph was added on future work.

20/2/4: Should say "The latter data were found in the …" s

Table 3-4: does the 2002 VIUS Survey report the number of tires per truck? Or the number of axles? If the latter, then it is not valid to imply that the number of tires is from the survey.

However, in either case, the survey can be cited with appropriate explanatory text in a footnote. The report is inconsistent in how vehicle categories are defined and described. If "regclass" is actually used here, which doesn't' seem quite right (aren't these source id?), then also give the MOVES code associated with each for complete clarity. There is no way that there are 519 billion LDVs in the U.S. – something is wrong with all of the numbers in the 3rd and 4th columns of this table. Some explanation is needed of the "Tires Per Vehicle" – this must be "Average Tires Per Vehicle," since no vehicle can have 5.5 or 14.9 tires, and 7 tires would also be quite unusual. Some explanation of the basis for the number of tires per vehicle for each vehicle type is needed. The assumption that the number of tires for LDT is the same as for LDV seems reasonable, but should be explained – i.e. LDT includes SUV, minivan, and pickup trucks which are typically 4 wheels. Larger pickup trucks that might have 6 wheels are not considered or do they fall into another category?

> *RESPONSE: We added clarification in the Table heading, that the tires were calculated from the 2002 VIUS Survey axle count. We also removed the survey weighting factors that were not helpful from for the reader. We also, specify that the Tires are calculated as the averages in the Table headings, which can yield the non-integer numbers. As discussed in the MOVES2014 Population and Activity Report, trucks with 6 wheels are classified in RegClassID 41, not as LDT.*

20/3/1: text refers to "Table 5" – should this be Table 3-5? (but Table 3-5 seems to be on a different topic).

20/4: This paragraph is unclear. It starts by stating that probably less than 10% of car tire wear is emitted as PM10 based on Boulter (2005a) and then goes on to say that results of Kupiainen et al. (2005) were used by Boulter. If Kupiainen is the original source of the data/information, then this could be more clear and conveyed consistently in the paragraph. Also, here and in general throughout the report, clarify if the mg/vkm values are per tire or per vehicle.

> *RESPONSE: this sentence was removed. Kupiainen and Boulter are research collaborators and co-authors, judging from their series of publications.*

20/5: what is the basis for assuming 8% of total tire wear is PM10 and that 15% of PM10 is PM2.5 For clarity, what happens to the other 92% of tire wear? Is it assumed that none of it ever re-emitted to the atmosphere?

> *RESPONSE: References and description of how the 8%, and 15% mass fractions were selected are added in Section 3.2. We also added a footnote (h) describing how the PM10/PM2.5 ratio is derived from the PM mass fractions in Section 3.2.1.*

Table 3-5: please clarify if the g/mi tire wear is per vehicle or per tire. What is "avgbinspeed" and "RegclassID" – should define/explain in footnotes. The last 8 columns need a superheader of "Regulatory Class" and it would help if each of the individual columns included descriptive text in the header. Avebinspeed should have units. SpeedBinID and OpModeID also need to be defined/explained.

Response: The previous table is removed, and is replaced with Table 3-4, which includes output by MOVES2014 by sourcetypeID. We also specify that the tire wear emission rates are per/vehicle-mile. We also included information on the exact rates used in MOVES (g/hour), in Appendix B.

21/1: for clarity, insert information that 15% of the mass of PM10 is estimated to be emitted as PM2.5.

For the references, the reference format does not seem to follow any standard convention.

Response: We have provided information such that readers can find the sources.

D.7.2 Dr. Joe Zietsman

Overall, this report on brake and tire wear emissions in MOVES 2014 is well documented and satisfactory. Most of my comments are related to clarifications that are needed rather than methodological issues.

References

[1] Harrison, R.M., A. M. Jones, J. Gietl, J. Yin, D. C. Green, "Estimation of the Contributions of Brake Dust, Tire Wear, and Resuspension to Nonexhaust Traffic Particles Derived from Atmospheric Measurements," Environmental Science & Technology, 2012.

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

[3] Cha, S., P. Carter, R. Bradow., "Simulation of Automobile Brake Wear Dynamics and Estimation of Emissions", SAE Paper 831036. Society of Automotive Engineers, Warrendale, PA, 1983.

[4] EPA, PART5 Documentation

[5] Garg, B. D., S. H. Cadle, P. A. Mulawa, P. J. Groblicki, C. Laroo, G. A. Parr, "Brake Wear Particulate Matter Emissions", Environmental Science and Technology, 34(21), 4463-4469, 2000.

[6] Sanders, P.G., N. Xu,T. M. Dalka, M. M. Maricq, "Airborne Brake Wear Debris: Size Distributions, Composition, and a Comparison of Dynamometer and Vehicle Tests", Environmental Science & Technology,37 (18), 4060-4069, 2003.Note that 7 is missing. Maybe this will be cleaned up after all track changes are accepted.

[7] EPA, Development of Emission Rates for Light-Duty Vehicles in the Motor Vehicle Emissions Simulator (MOVES2010),198 pp, EPA-420-R-11-011, August 2011)

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