Emissions **from Brake Lining Wear in the San Francisco Bay Area**

Contents:

1 Introduction

Brake lining materials are released into the environment every time the contact surfaces of brakes meet. Some of the lining material is released directly to the air, some sticks to the vehicle, and some falls to the ground. Of the portion that sticks to the vehicle, some might be washed off by rain or by car washing in a driveway, or it might be rinsed to the road after the vehicle is driven through standing water, in which case it enters the storm drains. Some might be washed off in a commercial carwash that discharges to the sewer. This distribution of releases is called partitioning.

The size of the particles that are released to air is important because it determines to a large extent what the fate of the air emissions is. This report provides particle size distribution information.

One of the common components of brake lining material is copper. The quantity of copper that is released from brake lining wear is not well understood.

The overall approach taken in this study for estimating copper from brake lining wear was to apply emission factors. In the case of copper releases from break lining wear, emission factors are expressed as mass of copper per distance traveled. Several emission factors based on different methodologies were developed for 1) passenger cars and light-duty trucks, 2) medium-duty vehicles, and 3) heavy-duty vehicles.

One emission factor methodology was selected for use in conducting the inventory of copper releases from brake lining materials, based on its current applicability in the San Francisco Bay area. The remaining emission factors aid in determining the robustness of the inventory results.

Air emission factors for vehicle brake lining wear have been studied more extensively than emission factors to other environmental compartments. Because of this, perhaps the best way to develop emission factors for copper released directly to the roadway to vehicles is to first develop the air emission factor and then use information on partitioning to develop emission factors for releases to the road and releases that adhere to the vehicle.

Once emission factors are developed, they can be multiplied by vehicle distance traveled per unit time to estimate releases from brake lining wear.

Estimating copper releases from brake lining wear is a difficult undertaking. Different brake lining materials wear at different rates, and there are a multitude of brake lining formulations in use. Data on the copper content of brake lining materials is incomplete, and data on market shares for various brake lining materials is virtually nonexistent. Thus, even if wear rates for each material were available, it would not be helpful. Data from dynamometer tests must be used with caution because driving conditions have a huge impact on brake lining wear rates. In fact, one researcher has reported that for semi-metallic brakes, four brake stops from 100 mph produced as much lining wear as over 500 brake stops at 30, 40, 60, and 80 mph.

Note that the copper emitted from brake lining wear for an individual vehicle would not be expected to be accurately estimated using an emission factor because of the variation in brake lining materials from one vehicle to the next. The copper content of brake lining materials varies from little or no copper to copper mass fractions near 20%. However, copper emissions from brake lining wear in the aggregate can be estimated using emission factors.

A number of assumptions were made in order to conduct this inventory of environmental releases. These assumptions are clearly stated in the sections on value assignments to variables. When there was more than one source of data for a given value, the value judged to be superior in terms of factors including peer-review of the reference, geography, sample size, and timeliness were used. If several values were available in different references that were determined to be of equal quality, a value that was representative of all of them was chosen.

Standard uncertainties were estimated for each of the values obtained, following the strategies outlined in NIST, 2005. In a few cases, a standard deviation was calculated and used as the standard uncertainty. However, in most cases, it was possible to determine only a potential range of possible values for a given variable, where the true value was equally likely to be anywhere in the range (a uniform distribution). In these cases, the point value was calculated to be the midpoint of the range and the standard uncertainty was estimated as being equal to half of the range divided by the square root of three. This is a means of estimating the standard deviation of a uniform distribution.

Developing a standard uncertainty for each variable was onerous, but it was necessary so that the uncertainties in each intermediate value could be combined in order to develop a sense for the standard uncertainty in the final calculated results. One way to estimate the standard uncertainty in a value that is calculated using the function $f(x_1, x_2, \ldots, x_n)$ is to apply the Kline-McClintock equation to that function. The Kline-McClintock equation is the first term in the Taylor series approximation for the propagation of uncertainty and can be used when variables are not co-related. It is

$$u_R = \sqrt{\left(u_1 \frac{\partial f}{\partial x_1}\right)^2 + \left(u_2 \frac{\partial f}{\partial x_2}\right)^2 + \cdots + \left(u_n \frac{\partial f}{\partial x_n}\right)^2} \; ,$$

where u is uncertainty, R is the resulting value, and n is the number of variables in the function. The Kline-McClintock equation was used to estimate the uncertainty in calculated results for this project.

Standard uncertainties are also useful in that they can be used to provide a range of values that apply to a desired confidence interval. If a 95% confidence interval is desired, that means that it is desired that the range of values provided for the final result are 95% likely to contain the true (actual) value. This 95% confidence interval would be described as a point value plus or minus two times the standard uncertainty for that value. A 67% confidence interval is one that includes the point value plus or minus the standard uncertainty. (This assumes that the probability distribution characterized by a function's result and its standard uncertainty is approximately normal, and the uncertainty result is a reliable estimate of the standard deviation of the result.)

2 Air Emission Factors for Copper from Brake Lining Wear

Wherever possible, three categories of information were used to derive air emission factors for copper from brake lining wear:

1) tunnel studies
2) brake lining composition coupled with existing brake lining air emission factors (this is referred to as the composition/existing emission factor approach)
3) brake lining composition combined with information on the wear rate of brake linings and partitioning information (this is referred to as the composition/wear approach)

2.1 Passenger Cars and Light-Duty Trucks

2.1a *Summary of Values Assigned to Variables*

Passenger vehicles can be equipped with drum brakes or a combination of drum and disc brakes. These two types of brake systems have different wear characteristics and use different friction materials. Perhaps the most important difference between disc and drum brakes with respect to environmental releases is that drum brakes accumulate much more dust from brake lining wear than disc brakes, and release a much smaller proportion of their brake lining wear to air.

Aftermarket brakes and in some cases even original equipment service brakes tend to contain less copper than factory brakes because copper is a relatively expensive material. Because of this, vehicle age has an important effect on the concentration of copper in brake linings for passenger vehicles, and information on mass fractions of copper in brake lining materials in factory-equipped passenger vehicles was collected separately from information on mass fractions of copper in passenger vehicles that are not factory equipped. New-disc passenger vehicles still have the brake pads they were equipped with at the factory, and old-disc passenger vehicles are those that have replaced their factory disc brakes.

For the purposes of the inventory, whether a vehicle is equipped with factory disc brakes was determined based on

- the average distance traveled before lining replacement, or d_{pass}, which is estimated to be 35,000 miles (Garg, 2000) with a standard uncertainty of 3500 miles for disc brakes (see Table 2.1-1 for details concerning this choice);

- vehicle registration data by year first registered for California, from Table 2.1-2; and
- the number of miles driven per year for the average vehicle in the Bay area (11,234 mi/yr, based on regional vehicle registration of 5,432,514 vehicles in 2002 (Metropolitan Transportation Commission, 2004) and 167.2 million miles traveled per day in the region in 2003 (BAAQMD, 2004).

The fraction of passenger vehicles equipped with factory disc brakes (assigned the variable $R_{new\text{-}disc}$) thus includes vehicles that are less than three years old, or 0.34 with a standard uncertainty of 0.03.

Finding a value for $R_{new\text{-}drum}$ was not necessary (it would be near 0.55).

The average total mass of copper per vehicle and the average concentration of copper in the most popular models of factory-equipped vehicles have been collected for the Brake Pad Partnership based on manufacturer surveys. These data were used to develop the mass fraction of copper in brake lining materials on passenger vehicles that have yet to replace their factory-equipped brake linings. The data are provided as an annual average that includes both disc and drum brake linings for almost half of the vehicles sold. As of this writing, Brake Pad Partnership data are available for the years 1998 through 2003. Typically, only cars less than three years old are equipped with factory brakes, so only the values for years 2001-2003 are of interest. The average friction material per vehicle and the average copper per vehicle for the vehicles that were included in the Brake Pad Partnership's survey are given in Table 2.1-3.

Information on the portion of passenger vehicle brakes that are disc and drum was obtained from Ward's Automotive Yearbook. Disc brakes have been found on nearly 100% of US cars since 1976 (Ward's, 2004). According to Table 2.1-2, 97% of vehicles registered today were first registered within the last 25 years. This means that nearly every passenger vehicle is equipped with disc brakes on either the front axle or both axles.

Table 2.1-4 contains information about the number of vehicles that were equipped with rear drum brakes for the model year 2003 (all vehicles) and 2002 (imports only). Information in Ward's for years prior to this is only available for non-ABS vehicles equipped with drum brakes on the rear axle, and all ABS-equipped vehicles are combined, making it impossible to determine from the data given the fraction of vehicles equipped with drum brakes on the rear axle in prior years.

Originally, it was planned that standard equipment on the last ten years of high-sales vehicles would be gathered from on-line databases such as www.autotrader.com. However, comparison of these data with information in Ward's indicated that non-standard equipment could comprise a large portion of sales, so the usefulness of standard equipment data is questionable. It is probably more accurate to assume that the overall value from Table 2.1-4 represents passenger vehicles on the road today, so that the average number of axles per vehicle that are disc-equipped is

$$\begin{aligned} B_{\text{disc}} &= B_{\text{new-disc}} = B_{\text{old-disc}} \\ &= 1 \text{ (front) axle/vehicle} + (1 \text{ (rear) axle/vehicle} - 0.344 \text{ (rear) axle/vehicle}), \\ &= 1.66 \text{ axle/vehicle} \end{aligned}$$

and the average number of axles per vehicle that are drum-equipped is

$$B_{\text{drum}} = B_{\text{new-drum}} = B_{\text{old-drum}} = 0.34\,.$$

A standard uncertainty of 0.06 will apply to both of these values. This standard uncertainty is based on an assumption that for the population of vehicles in the Bay area, the true value of B_{disc} falls between 1.56 and 1.76, and the true value for B_{drum} would fall between 0.24 and 0.44, so that the standard uncertainty is 0.1 divided by the square root of three, or 0.06.

Because of the way Brake Pad Partnership mass fraction of copper data are collected, a value for the average number of axles that are factory disc brake-equipped on the subset of passenger vehicles included in the survey is also needed. This value, calculated using the values shown in Table 2.1-5, turns out to be the same as the value for the general population, or

$$B_{\text{BPP-disc}} = 1\text{ axle} + (1\text{ axle} - 0.34\text{ axle}) = 1.66\text{ axles}$$

The average drum and disc mass fraction of copper for new-disc/new-drum vehicles from Partnership data is assigned the variable $C_{\text{Cu, pass, new-disc+drum}}$ and is

$$C_{\text{Cu, pass, new-disc+drum}} = \frac{13.34\left(\dfrac{0.0769}{1.161}\right) + (24.44 - 13.34)\left(\dfrac{0.0766}{1.183}\right) + (34.44 - 24.44)\left(\dfrac{0.0561}{1.238}\right)}{34.44}$$

$$= 0.06\ (6\%)$$

Drum brakes are expected to have lower concentrations of copper than disc brakes, so this value represents a lower bound for the value of $C_{\text{Cu, pass, new-disc}}$ for surveyed vehicles. An upper bound can be found by assuming that the mass fraction of copper in drum brakes is zero and using the value for $B_{\text{BPP-disc}}$, as follows:

$$\text{(upper bound; surveyed vehicles only) } C_{\text{Cu, pass, new-disc}} = \left(\frac{2 \text{ axles}}{B_{\text{BPP-disc}}}\right) C_{\text{Cu, pass, new-disc+drum}}$$
$$= \left(\frac{2 \text{ axles}}{1.66 \text{ axles}}\right) 0.06 = 0.07$$

Another source of uncertainty in using the surveyed value to represent all factory-equipped passenger vehicles is that the population of surveyed vehicles represents less than half of the total sales in the US. The surveyed vehicles from 2001-2003 represent 40% of the registered vehicles that have factory brakes installed (i.e. that are less than three years old). The maximum mass fraction of copper found in brake pads is 0.2, and the minimum mass fraction is zero (Armstrong, 1994; Westerlund, 2001). An upper bound for the copper in factory disc brakes is found by assuming that the 60% of vehicles that were not included in the survey were 20% copper. Similarly, a lower bound is found by assuming that the 60% of vehicles that were not included in the survey were 0% copper. The values for the upper and lower bounds are

$$\text{(upper bound) } C_{\text{Cu, pass, new-disc}} = 0.6(0.2) + 0.4(0.07) = 0.15$$
$$\text{(lower bound) } C_{\text{Cu, pass, new-disc}} = 0.6(0) + 0.4(0.06) = 0.024$$

The midpoint of these two values is 0.09 and the standard uncertainty is half of the range divided by the square root of three, or 0.04.

Table 2.1-1 contains details concerning the choice of the following variables and their estimated standard uncertainties. The mass fraction of copper in non-factory disc brake pads, $C_{\text{Cu, pass, new-disc}}$, is assumed to be 0.05 (Armstrong, 1994), with a standard uncertainty of 0.03. The mass of disc brake lining material for a passenger vehicle axle that is disc-equipped, $M_{\text{pass, disc}}$ is 660 g/axle with a standard uncertainty of 30 g/axle (Brake Pad Partnership, 2004). The fraction of material that is worn off when the linings are replaced, f_{pass}, is 0.80 (Garg, 2000) with a standard uncertainty of 0.08.

2.1b Emission Factor Calculations

This section presents the calculated and reported values for the emission factors based on all three estimation methodologies.

<u>The Composition/Wear Approach:</u> In this method, the rate of overall brake lining wear is estimated by multiplying the mass of brake lining material on the vehicle by the fraction of material that is worn off when the lining is replaced, then divide that value by the number of miles driven between lining replacements. This value can then be multiplied by the concentration of copper in the brake lining material and by the fraction of material that becomes airborne in order to determine the emission factor for copper from brake lining materials.

The airborne copper from drum brakes contributes very little to the total airborne copper because some of the brake lining material is trapped in the drum, because drum brakes are less common than disc brakes, and because the copper concentration in drum brakes tends to be less than the copper concentration in disc brakes. Therefore, only the contributions from disc brakes must be included and the equation for the emission factor is

$$\begin{aligned}
\text{EF}_{\text{air, Cu, pass}} &= \frac{AR_{\text{new-disc}} B_{\text{new-disc}} M_{\text{pass, disc}}\, f_{\text{pass}} C_{\text{Cu, pass, new-disc}}}{d_{\text{pass, disc}}} \\
&\quad + \frac{A\left(1 - R_{\text{new-disc}}\right) B_{\text{old-disc}} M_{\text{pass, disc}}\, f_{\text{pass}} C_{\text{Cu, pass, old-disc}}}{d_{\text{pass, disc}}} \\
&= \frac{AB_{\text{disc}} M_{\text{pass, disc}}\, f_{\text{pass}}}{d_{\text{pass, disc}}} \left(R_{\text{new-disc}} C_{\text{Cu, pass, new-disc}} + \left(1 - R_{\text{new-disc}}\right) C_{\text{Cu, pass, old-disc}} \right)
\end{aligned}$$

Note that there is an error in the equation for this value in the work plan (the copper mass fraction terms were inadvertently left out).

Details concerning the chosen value for *A*, the fraction of disc brake lining debris that is released to air, are contained in the section on partitioning. For now, it is enough to know that *A* is given as 0.50 with a standard uncertainty of 0.09.

The calculated value for the emission factor for copper releases to air from brake lining wear in passenger vehicles using the composition/wear approach is

$$\mathrm{EF}_{\text{air, Cu, pass}} = \frac{(0.5)(1.66\text{ axles})(600\text{ g/axle})(0.8)}{56{,}000\text{ km}}\left(0.34(0.09)+(1-0.34)(0.05)\right)\left(\frac{1000\text{ mg}}{\text{g}}\right)$$
$$= 0.5\text{ mg/km}$$

The standard uncertainty for this value is 0.2 mg/km. As shown in Table 2.1-6, the largest contributor to this uncertainty is the uncertainty in the value for $C_{\text{Cu, pass, old-disc}}$, and the next largest contributor to the uncertainty is the uncertainty in the value for $C_{\text{Cu, pass, old-disc}}$. The 95% confidence interval for this emission factor is 0.04 mg/km to 0.9 mg/km.

<u>The Composition/Existing Emission Factor Approach:</u> An emission factor for air releases from brake lining wear was also developed by applying information on mass fractions of copper to measured brake wear air emission factors. As with the composition/wear approach, the airborne copper from drum brakes contributes very little to the total airborne copper because some of the brake lining material is trapped in the drum, because drum brakes are less common than disc brakes, and because the copper concentration in drum brakes tends to be less than the copper

concentration in disc brakes. Therefore, only the contributions from disc brakes must be included and the equation for the emission factor is

$$\begin{aligned}
\mathrm{EF}_{\text{air, Cu, pass}} &= \mathrm{EF}_{\text{air, pass}} F_{\text{pass}} \left(\frac{R_{\text{new-disc}} B_{\text{new-disc}} C_{\text{Cu, pass, new-disc}} + \left(1 - R_{\text{new-disc}}\right) B_{\text{old-disc}} C_{\text{Cu, pass, old-disc}}}{R_{\text{new-disc}} B_{\text{new-disc}} + \left(1 - R_{\text{new-disc}}\right) B_{\text{old-disc}}} \right) \\
&= \mathrm{EF}_{\text{air, pass}} F_{\text{pass}} \left(R_{\text{new-disc}} C_{\text{Cu, pass, new-disc}} + \left(1 - R_{\text{new-disc}}\right) C_{\text{Cu, pass, old-disc}} \right) \\
&= 8 \frac{\text{mg}}{\text{km}} (0.84) \left(0.34 (0.09) + (1 - 0.34) 0.05\right) \\
&= 0.4 \text{ mg/km}
\end{aligned}$$

The standard uncertainty for this value is 0.2 mg/km. As with the composition/wear approach, the largest contributor to this uncertainty is the uncertainty in the value for $C_{\text{Cu, pass, old-disc}}$, and the next largest contributor to the uncertainty is the uncertainty in the value for $C_{\text{Cu, pass, old-disc}}$. The 95% confidence interval for this emission factor is 0 mg/km to 0.8 mg/km. Intermediate values for calculating the standard uncertainty in this result can be found in Table 2.1-6.

<u>Tunnel Studies:</u> Tunnel studies are expected to be a strong possible means of determining emission factors because they survey emissions from actual fleets in service, as opposed to a small selection of brake lining materials. Three US tunnel studies that developed emission factors for copper were found. One (Gertler et al, 2002) developed emission factors for PM2.5 only. Another (Lough, 2004) was a study of two tunnels where braking rarely occurred. The third (Gillies et al, 2001) was a study of the Sepulveda Tunnel in Los Angeles and is most representative of urban driving. This emission factor is for PM10 only, does not separate passenger vehicles from medium-duty or heavy-duty vehicles (so it would be applied to vehicle miles traveled for all vehicles), and does not correct for re-suspended road dust. The emission factor is 0.53 mg/km with an (author-reported) uncertainty of 0.06 mg/km. A 95% confidence interval for this value is 0.41 mg/km to 0.65 mg/km. (Note that using the standard deviation for

the copper emission factors for the ten runs as the standard uncertainty would be preferable. Gillies has been contacted to see if he can share the values for the individual runs so that this standard deviation can be calculated.)

2.1c Final Result

It is surprising how well the three independently calculated emission factors (0.5 mg/km, 0.4 mg/km, and 0.53 mg/km) agree with each other. The tunnel study result will be used because it has the least amount of uncertainty and because it falls entirely within both of the results for the other methodologies.

FINAL RESULT

$EF_{air,\ Cu,\ pass}$ = 0.53 mg/km; range 0.41 mg/km to 0.65 mg/km (95% confidence interval)

Table 2.1-1 Summary of values and standard uncertainties in values for passenger vehicles.

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Emission factor for airborne brake lining debris from passenger vehicles ($EF_{air, pass}$)	Sanders, 2003.	airborne emissions 8.2-8.3 mg/stop/brake for low-met brakes used on mid-sized car, 2-2 mg/stop/brake for semimet brakes on full-sized truck, 1.8-2.4 mg/stop/brake for NAO brakes used on a full-sized car; 24 stops per 11 miles	8	mg/km	4	US	c 2002	measured dynamometer losses for three brake pad formulations	Sanders has about 84.5% becoming airborne using a wtd average from the SAE paper and he includes rotor loss. If I correct for these, I get 5.4 mg/km	2 "brakes"/car (have to have something for rear brakes -- I don't know if Sanders means /axle or /pad and I'm assuming he means /axle); assume 75% of brakes are semi-met, 12.5% are NAO, and 12.5% are low-met; multiply wtd average airborne releases by the number of stops per mile = 24/11	Kline-McClintock assuming range of 0.65 to 0.85 for cars using semi-mets, range of 6.25-10.25 mg/stop/brake for the airborne from low-mets, 0.025-0.225 for the range of cars using NAOs, range of 1.5-2.5 mg/stop/brake for airborne from semi-mets, range of 1.6-2.6 mg/stop/brake for the airborne from NAOs, range of 1.5-2.9 for stops/mile, range of 2-4 for number of half-axles per car	tested a range of brake pad materials; recent; US-based; good mass balance; driving cycle emulates urban driving; good agreement with other US researchers (Cha, ; Trainor, 2001; Abu-Allaban, 2003)
Mass of brake lining material on a disc-equipped passenger vehicle axle ($M_{pass, disc}$)	Brake Pad Partnership, 2004; and State of California, 2003.	mass of friction material per vehicle in kg per year: 1.406 in 1998, 1.314 in 1999, 1.256 in 2000, 1.238 in 2001, 1.183 in 2002, and 1.161 in 2003	660	g/axle	60	US	1998-2003	survey of BMC members for roughly 40% of cars sold in US	brake pad material per vehicle declining over the six years in the study	assumed that mass was the 1998 value for years 1998 and earlier and calculated a weighted average using the percent of vehicles first registered; divided by 2 to get mass per axle and multiply by 1000 to convert units	estimated that 67% of samples of cars would be within 60 g of this value	US-based; within one standard deviation of other researcher's results (Garg, 2000; Armstrong, 1994).

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Fraction of passenger vehicle brake lining material worn off at replacement (f_{pass})	Garg et al, 2000.	0.8	0.80	no units	0.08	US	1998	not explained		no calculation necessary	This is my estimate -- I figure 2/3 of cars would have within 10% of given value left at replacement.	US-based; agrees with another sourcee for US values (Miller, 2004)
Distance traveled between disc brake lining replacements in passenger vehicles, ($d_{pass, disc}$)	Garg et al, 2000.	35000 mi for front brakes	56,000	km	6000	US	1998	not explained		Divided by .621 to convert mi to km.	Standard uncertainty is based on the assumption that two-thirds of vehicles would be serviced within 10% of the given value.	This value was chosen because it is US-based and agrees with other sources for US values (Miller, 2004; Armstrong, 1994).

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Copper concentration in passenger vehicle factory brake pads, mass fraction ($C_{Cu, pass, new-disc}$)	Brake Pad Partnership, 2004.	40% of vehicles surveyed; average mass of brake lining material per car by year in kg: 2003 - 1.161; 2002 - 1.183; 2001 - 1.238; average mass of copper in brakes per car by year in kg: 2003 - .0769, 2002 - 0.0766, 2001 - .0561	0.09	no units	0.04	US	2002-2004	based on BMC member survey of brakes used on 40% of passenger vehicles		value is the midpoint of a range of possible values; 13.34%, 11.1%, and 10% of cars registered were first registered less than one, less than 2, and less than 3 years ago, respectively; used this to get a wtd mass fraction average that represents the last three years of vehicles which represents a lower bound on surveyed mass fraction in pads because it assumes shoes have the same concentration, multiplied by 40% of cars to get a lower bound on possible mass fraction of copper because this assumes the unsurveyed 60% of cars has no copper; upper bound on surveyed mass fraction in pads was found by assuming drums have no copper and multipying wtd mass fraction average by 2/BBPP-disc, multiplied by 40% because 40% of cars were included in the survey and added 60% times 0.2 to get upper bound on possible mass fraction of copper in pads because some pads have 20% copper	estimated as half of the possible range of values divided by the square root of three	best available concentration data on copper in factory brake pads

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Copper concentration in passenger vehicle non-factory brake pads, mass fraction ($C_{Cu, pass, old-disc}$)	Armstrong, 1994.	4.5% vmt wtd average of 18 pads (Mercedes was OE so didn't include here, VMT weights given as # of brake pads used, concentration measured more than once for some pads and average value taken in this case): '91 Accord, 8.0-8.7-4.3% w/45636 pds; '86-'89 Accord, 13.2-14.9% w/61584 pads; '91 Escort, 8.5-9.3% w/11184 pads; '93 Taurus, .26-.24% w/ 0 miles so not inc.; NAPAS-7345, 2.3% w/ 0 miles so not inc; Toyota 20800, 0.012% w/22232 pads; Masterstop d465, 2.5% w/ 0 miles so not inc.; Toyota 20860, 10% w/ 3400 pads, Nissan 410160-1E590, 16-7.3% w/ 7412 pads; Nissan D1060-50Y090, 0.022% w/ 4896 pads ; VW 191689151G, 21-9.1% w/ 19632 pads; Honda 45022-SR3-L00, 14% w/ 4244 pads; Ford F3ZZ-2001-A, ND, used 0.00625% because it is ND value w/ 71688 pads; Ford F2DZ-2001-A, 0.021-0.028 w/ 79408 pads; GM 12510030, ND, used 0.00625% because it is ND value w/ 8788 pads; GM 12510008, 0.018-0.0098% w/ 8788 pads; GM 12510029, 0.013 w/ 8788 pads; GM 12510005, 0.0063 w/ 1044 pads; GM 12510001, 0.022 w/1788 pads; GM 12321455, 0.0067 w/ 15884 pads	0.05	mass fraction	0.03	US	1993	Method 6010	The cars using the brake pads analyzed represent 80% of the cars in the county but they only used manufacturer's replacement parts so the concentration may be higher than reality -- usually the black box pads have very little copper.	took the sum of the number of pads multiplied by the average concentration measured for that pad, and divided that sum by the number of pads	Took the standard deviation of the samples, wtd by the number of cars using the sample pads (see brake pad spreadsheet.xls)	US-based; survey of large number of pads
Fraction of wear debris that is brake lining material, (F_{pass})	Link, 11/2/04-11/4/04.	losses from pads, in g: 4.6+4.6+7.3+7.1+2.5+3; losses from rotor, in g: 1.7+3.3+.9	0.83	mass fraction	0.04	US	2004	This is only three pads but they were selected to be representative of passenger car pads.		sum of the brake pad losses over the sum of the rotor plus brake pad losses	estimate that 2/3 of the car population would fall within .04 of the given value -- the lowest ratio for the three pads was 0.72 and the highest was 0.86	taken from a sample of brakepads designed to be representative; agrees with other researchers (Link, 2004a; Sanders, 2003), disagrees slightly with Trainor, 2001

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Average number of axles per vehicle equipped with disc brakes, B_{disc}	Ward's, 2004.	vehicles equipped with drum brakes on rear axle, for 2003: 49.3% of 6432180 domestic cars; 25.3% of 8538668 domestic lt trucks; 30% of 2076711 import cars; 26.4% of 1153783 import lt trucks	1.66	axle	0.06	US	2003	not described		2 axles per car (one front and one rear) minus the weighted average of 2003 vehicles with rear drum brakes	assumed that actual value is within 0.1 of estimated value, standard uncertainty is 0.1/sqrt(3)	best available data for US vehicles, even though only 2003 was available
Average number of axles per vehicle with disc brakes for vehicles included in BMC survey, $B_{BPP\text{-}disc}$	Ward's, 2004.	listed in Table 2.1-5	1.66	axle	not found	US	2003	0		2 axles minus weighted average of cars in survey with drum brakes on rear axle	not calculated	Ward's values are the best available, even though they are only for 2003 models
Fraction of vehicles in service that are equipped with factory disc brakes, $R_{new\text{-}disc}$	BAAQMD, 2004; Garg et al, 2000; and State of California, 2003.	35000 between pad replacements with a standard uncertainty of 3500 (from Garg); 34.4% of cars were registered for the first time in the last three years (from State of California); 167.2 million miles traveled per day by 5432514 vehicles registered in Bay area counties driving	0.34	no units	0.03	Bay area/US	2002, c 2000	0		first found the number of years on average before pad replacement which is 5432514*35000/(167.2e6*365), which comes to 3.1 years; cumulative total for cars registered less than three years ago is 34.4%	estimated that true value lies within 0.05 of estimated value so that standard uncertainty is 0.05 divided by the square root of 3	0

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Tunnel study emission factors for copper from passenger vehicles ($EF_{air, Cu, pass}$)	Gillies et al, 2001.	.53+-.06 mg/km; no breakdown of resuspended vs. direct; this is for PM10	0.53	ug/km	0.06	Sepulveda Tunnel, Los Angeles, California	1996	Ten runs, one hour each, two PM10 samples per run; XRF of Teflon membrane filters; vehicles videotaped and speed determined with radar gun	Asked Gillies if I could get copper emissionf factors for the ten runs for copper so I could see what the standard deviation is for copper in the different runs. No distinction made betweeen HDV, MDV, and passenger vehicles. No correction for resuspended road dust. PM10 only.	Multiplied by 1000 to convert mg to ug.	given; author states that uncertainty was calculated by propagating the combined uncertainty of the inlet and outlet sum of species concentrations using the measured tunnel airflow volume and vehicle kilometers traveled	Sepulveda tunnel is more likely to have braking events and is a closer model for urban driving than the other two studies

Table 2.1-2. Distribution of fee-paid registrations by type and year first registered California, 2003[a] (State of California, 2003).

Vehicle Age: Less than	Auto	Commer-cial	Trailers	Motor-cycles
1 year	13.34	11.33	8.34	17.64
2 years	24.44	21.47	15.35	31.16
3 years	34.44	30.78	21.77	41.33
4 years	42.74	38.44	27.80	48.52
5 years	49.54	44.60	32.86	53.82
6 years	55.32	49.76	37.34	58.27
7 years	60.45	54.45	41.34	62.06
8 years	65.03	58.53	45.32	65.29
9 years	69.24	62.43	49.23	68.17
10 years	72.86	65.78	52.34	70.71
11 years	76.08	68.72	55.83	72.96
12 years	79.13	71.50	58.55	75.19
13 years	82.36	74.67	61.50	77.33
14 years	85.30	77.87	64.48	79.10
15 years	87.76	80.57	67.86	80.81
16 years	89.78	83.04	71.13	82.73
17 years	91.72	85.60	74.00	84.76
18 years	93.19	87.75	76.32	86.79
19 years	94.26	89.33	78.37	88.64
20 years	95.01	90.38	79.86	90.24
21 years	95.48	91.15	81.09	91.44
22 years	95.85	91.80	82.39	92.62
23 years	96.15	92.44	83.63	93.71
24 years	96.49	93.20	85.12	94.84
25 years	96.83	93.95	86.59	95.59
All Years	100.00	100.00	100.00	100.00

a Not necessarily the manufactured model year. Includes all registered vehicles which paid dues regardless of the model year used to determine fees.

Table 2.1-3. Friction material copper content monitoring results from survey of vehicles in the top 20 in US sales (2001 and 2002) and for vehicles in a sample of 20 vehicles (2003) (Brake Pad Partnership, 2004).

Mass, kg	2001	2002	2003
Friction material per vehicle	1.238	1.183	1.161
Copper per vehicle	0.0561	0.0766	0.0769

Table 2.1-4 Fraction of vehicles equipped with drum brakes on rear axle (from Ward's, 2004, unless otherwise noted).

Category	Model Year	% of Vehicles with Drum Brakes on Rear Axle	Total Number of Vehicles
Domestic Cars	2003	49.3	6,432,180
Domestic Light Trucks	2003	25.3	8,538,668
Import Cars	2002*	35.7	2,099,390
	2003	30	2,076,711
Import Light Trucks	2002*	58.8	1,048,691
	2003	26.4	1,153,783
Model Year 2003 Totals		34.4	18,201,342

*Ward's, 2003.

Table 2.1-5 Fraction of vehicles surveyed that were equipped with drum brakes on rear axle.

Make	Model	Sales (Brake Pad Partnership, 2004)	% of Vehicles with Drum Brakes on Rear Axle (Ward's, 2004)
Chevrolet	Cavalier	256,550	64.1
Ford	Focus	229,353	98.1
Toyota	Corolla	265,449	93
Honda	Civic	260,632	91
Chevrolet	Malibu	173,263	100
Ford	Taurus	361,838	94
Mercury	Sable		
Honda	Accord	325,465	0
Toyota	Camry	367,394	55
Nissan	Altima	201,240	0
PT Cruiser		227,860	81
Dodge	Neon		
Plymouth	Neon		
Ford	Explorer	422,810	0
Mercury	Mountaineer		
Jeep	Grand Cherokee	207,479	0
Ford	Expedition	220,289	0
Lincoln	Navigator		
GMC	Tahoe, Suburban, other large SUVs	527,033	0
Chevrolet	Trailblazer	397,168	0
Oldsmobile	Bravada		
GMC	Envoy		
Ford	Escape	217,190	100
Mazda	Tribute		
Jeep	Liberty	162,987	0
Dodge	Caravan/Voyager/Town&Country	374,494	59
Plymouth	Caravan/Voyager/Town&Country		
Chrysler	Caravan/Voyager/Town&Country		
GMC	Sonoma	171,613	100
Chevrolet	S10		
Ford	Ranger	224,087	100
Mazda	Pickup		
Chevrolet	Silverado	880,318	0
GMC	Sierra		
Dodge	Ram	449,371	0
Ford	F-Series	806,887	0
TOTAL		7,730,770	33.7

Table 2.1-6 Intermediate values for calculating the uncertainty for emission factor results for passenger cars.

Composition/Wear Approach					
	Variables	Value	Uncertainty, $u_{variable}$	*df/d*(variable), evaluated at value	*df/d*(variable)^2 x $u_{variable}^2$
	A	0.50	0.09	0.9137	0.007
	B_{disc}	1.66	0.06	0.2759	0.0003
	$M_{pass, disc}$	660	60	0.0007	0.002
	f_{pass}	0.80	0.08	0.5711	0.002
	$d_{pass, disc}$	60,000	6000	0.00001	0.002
	$R_{new\text{-}disc}$	0.34	0.03	0.3186	0.0001
	$C_{Cu, pass, new\text{-}disc}$	0.09	0.04	2.6545	0.009
	$C_{Cu, pass, old\text{-}disc}$	0.05	0.03	5.0621	0.02
	Calculated result (mg/km)				0.5
	Standard uncertainty in calculated result (mg/km)				0.2
	95% confidence interval (mg/km)			0.04	0.9
Composition/Emission Factor Approach					
	$EF_{air, pass}$	8	4	0.049195659	0.03
	F_{pass}	0.83	0.04	0.448210371	0.0003
	$R_{new\text{-}disc}$	0.34	0.03	0.259756036	0.0001
	$C_{Cu, pass, new\text{-}disc}$	0.09	0.04	2.164007225	0.006
	$C_{Cu, pass, old\text{-}disc}$	0.05	0.03	4.126711452	0.01
	Calculated result (mg/km)				0.4
	Standard uncertainty in calculated result (mg/km)				0.2
	95% confidence interval (mg/km)			-0.1	0.8

2.2 Medium-Duty Vehicles

2.2a Summary of Values Assigned to Variables

One of the important variables that must be assessed when determining copper releases from medium-duty vehicles is the amount of brake lining debris that is not trapped in the drum. This value, assigned the variable T, could not be found in the literature. It will be assumed that this value can be represented by a uniform distribution that ranges from 0.5 to 0.1, so that the point value is 0.3 with a standard uncertainty of 0.1.

Medium-duty vehicles have two axles. It was necessary to estimate the number of disc-brake equipped axles per medium-duty vehicle, $B_{\mathrm{MDV,\ disc}}$. This value could not be found in literature, either. It was estimated to be 0.5 (i.e., half of medium-duty vehicles are equipped with disc brakes in front). A uniform distribution from 0.3 axle to 0.7 axle is assumed for this value, so that it has a standard uncertainty of 0.1 axle.

Table 2.2-1 contains details concerning the choice of the following variables and their estimated standard uncertainties. In nearly every case, data specific to medium-duty vehicles were not available and data on heavy-duty vehicles were used. Because information on the copper content in medium-duty vehicle brake linings was not available, the mass fraction of copper in disc brakes on medium-duty vehicles, $C_{\mathrm{Cu,\ MDV,\ disc}}$ was set at the value found for heavy-duty vehicles by a European researcher. This value is 0.05 (von Euxkull, 2002) with a standard uncertainty of 0.02. This value is notable in that it is similar to the copper concentration in passenger cars in the US for non-factory brake pads. Another European study of heavy-duty vehicles provides the value for the mass of disc brake lining material per axle, $M_{\text{MDV, disc}}$. This value is 4800 g/axle (Westerlund, 2001) with a standard uncertainty of 300 g/axle. That same European study provides a heavy-duty vehicle substitute for the value of the fraction of brake lining material worn off at replacement, f_{MDV}. This value is 0.7 (Westerlund, 2001) with a standard uncertainty of 0.07. That European study of heavy-duty vehicles also provides the value for the distance traveled between disc brake lining replacements, $d_{\text{MDV, disc}}$. This value was found to be 60,000 km (Westerlund, 2001) with a standard uncertainty of 5000 km. The fraction of wear debris that is brake lining material (as opposed to disc material), F_{MDV}, could not be found specifically for medium-duty vehicles and was assumed to be the same value as was measured for passenger vehicles. That value (see previous section on passenger vehicles) is 0.83 with a standard uncertainty of 0.04. The emission factor for air releases from medium-duty brakes developed for the UN, $\text{EF}_{\text{air, MDV}}$, is 12 mg/km (Ntziachristos, 2004), with a standard uncertainty of 2 mg/km.

2.2b Emission Factor Calculations

<u>The Composition/Wear Approach</u>: In this method, the rate of overall brake lining wear is determined by multiplying the mass of brake lining material on the vehicle by the fraction of material that is worn off when the lining is replaced, then dividing that value by the number of miles driven between lining replacements.

Details concerning the chosen value for *A*, the fraction of disc brake lining debris that is released to air, are contained in the section on partitioning. For now, it is enough to know that *A* is given as 0.50 with a standard uncertainty of 0.09.

These emission factors can then be used to calculate an emission factor for copper releases to air from brake lining wear in medium-duty vehicles:

$$\begin{aligned}\mathrm{EF}_{\text{air, Cu, MDV}} &= \frac{AB_{\text{MDV, disc}} M_{\text{MDV, disc}} f_{\text{MDV}}}{d_{\text{MDV, disc}}} C_{\text{Cu, MDV, disc}} \\ &= \frac{(0.5)(0.5\text{ axles})\left(4.8\times10^{6}\ \frac{\text{mg}}{\text{axle}}\right)(0.7)(0.05)}{60{,}000\text{ km}} \\ &= 0.7\text{ mg/km}\end{aligned}$$

The standard uncertainty for this value is 0.4 mg/km. The intermediate values for calculating the standard uncertainty in this value are given in Table 2.2-2. This table shows that the largest contributor to the uncertainty is the value for the concentration of copper in the brake lining materials (both shoes and pads contribute equally to the uncertainty). The next most important sources of uncertainty are in the values for the fraction of debris that becomes airborne (A) and the number of axles equipped with disc brakes per vehicle. The 95% confidence interval for this emission factor is 0 mg/km to 1 mg/km.

<u>The Composition/Existing Emission Factor Approach:</u> An emission factor for air releases from brake lining wear was also developed by applying information on mass fractions of copper to reported brake wear air emission factors. As with the composition/wear approach, the airborne copper from drum brakes contributes very little to the total airborne copper. Therefore, only the contributions from disc brakes must be included and the equation for the emission factor is

$$\begin{aligned}\mathrm{EF}_{\text{air, Cu, MDV}} &= \mathrm{EF}_{\text{air, MDV}} F_{\text{MDV}} C_{\text{Cu, MDV, disc}} \\ &= \left(11\frac{\text{mg}}{\text{km}}\right)(0.83)(0.05) \\ &= 0.48 \text{ mg/km}\end{aligned}$$

An estimate of the standard uncertainty for this value is 0.09 mg/km. The intermediate values for calculating the standard uncertainty in this value are given in Table 2.3-2. This table shows that the largest contributor to the uncertainty, again, is the value for the concentration of copper in the linings. The 95% confidence interval for this emission factor is 0.3 mg/km to 0.7 mg/km.

Tunnel Studies: There are no tunnel studies in the US with copper air emission factors specifically for medium-duty vehicles. However, the Gillies et al, 2001 study of the Sepulveda Tunnel in Los Angeles does not separate passenger vehicles from medium-duty or heavy-duty vehicles (so it would be applied to vehicle miles traveled for all vehicles), and does not correct for re-suspended road dust. The emission factor is 0.53 mg/km with an (author-reported) uncertainty of 0.06 mg/km. A 95% confidence interval for this value is 0.41 mg/km to 0.65 mg/km. (Note that using the standard deviation for the copper emission factors for the ten runs as the standard uncertainty would be preferable. Gillies has been contacted to see if he can share the values for the individual runs so that this standard deviation can be calculated.)

2.2c Final Result

Again, the emission factors from the three methodologies are in fairly good agreement (0.7 mg/km, 0.48 mg/km, and 0.53 mg/km) are in good agreement. The tunnel study result will be used because it has the least amount of uncertainty, because it applies to all vehicle categories, and because it falls entirely within both of the results for the other methodologies.

FINAL RESULT

$EF_{air,\ Cu,\ pass}$ = 0.53 mg/km; range 0.41 mg/km to 0.65 mg/km (95% confidence interval)

Table 2.2-1 Summary of values and standard uncertainties in values for medium-duty vehicles.

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty
Emission factor for airborne brake lining debris from MDVs, lb brake lining/mi ($EF_{air, MDV}$)	Ntziachristos, L, P Boulter. Automobile tyre and brake wear, web-site supporting the development of chapter B770 (SNAP 0707) of the EMEP/Corinair Emission Inventory Guidebook. 7/31/2004.	11.7 mg/vkm	11.7	mg/km	1.645448267	global	taken from multiple studies	taken from multiple studies	0	no calculation necessary	Range is given as 8.8-14.5 mg/vkm, with a point value of 11.7. Assuming a uniform distribution over the range, standard uncertainty is (14.5-8.8)/2/sqrt(3).
Mass of brake lining material on a disc-equipped MDV axle, lb brake lining/axle ($M_{MDV, disc}$)	Westerlund, K-G. Metal emissions from Stockholm traffic -- wear of brake linings. The Stockholm Environment and Health Protection Administration. 2001.	2.4 kg in front per wheel; 3.5 kg in rear per wheel; doesn't specify pad or shoe	4800000	mg	288675.1346	Sweden	c 2001	He got this from a personal communication with R Hedlund of the BBA Friction Sweden AB.	He doesn't say whether these are disc or drum	assumed front wheels are disc and multiplied by 2 to get amount per axle, then multiplied by 1000000 to convert units	Assume the point value has a uniform distribution between 1900 g to 2900 g (this is an plus or minus 0.5 kg of the high and low values per wheel) to get standard uncertainty of half the range divided by the square root of three
Fraction of brake lining material worn off at replacement (f_{MDV})	Westerlund, K-G. Metal emissions from Stockholm traffic -- wear of brake linings. The Stockholm Environment and Health Protection Administration. 2001.	70% of total before being replaced	0.7	no units	0.07	Sweden	c 2001	not explained	0	no calculation necessary	estimated that 2/3 of trucks would have within 10% of given value left at replacement

Copper concentration in MDV brake pads, mass fraction ($C_{Cu, MDV, disc}$)	von Uexkull, O. Antimony in brake pads -- a carcinogenic component? For submission to Journal of Cleaner Production. 2002.	mixed dust from 45 disc formulations = 61000 mg/kg, mixed dust from 15 formulations = 27,000 mg/kg, three other pads have concentration of 18000, 14000, and 27000	0.050936508	mass fraction	0.021688599	Sweden	c 2002	concentrations measured using XRF, two samples from filters on dynamometers used to test brakes plus three samples direct from pads	0	Weighted average of two dust samples and three pad samples, divided by 1e6 to convert units.	Used Kline-McClintock on equation for calculating weighted average of three average values. Stdev was calculated for the three separate samples, and assumed to be 1/2 of value for the other two.
Distance traveled between disc brake lining replacements, mi ($d_{MDV, disc}$)	Ntziachristos, L. Road vehicle tyre & brake wear. Emission Inventory Guidebook. August 2003.	60000 km	60000	km	5000	unknown	2000	unknown	0	no calculation necessary	used the same fraction as the drum brake distance
Fraction of wear debris that is brake lining material, (F_{MDV})	Sanders, PG, N Xu, TM Dalka, MM Maricq. Airborne brake wear debris: size distributions, composition, and a comparison of dynanometer and vehicle tests. Environ. Sci. Technol. 37: 4060-4069. 2003.	60% of wear debris comes from the rotor when low metallic linings are used; 70% is from lining material when NAO brakes are used; 90% is from linings when semi-mets are used	0.8	no units	0.057735027	US	c 2003	not described	Went with the value slightly lower than semi-mets because semi-met is the most common formulation. The highest this value could be is 0.9. The values given in the SAE paper are a little different from these.	no calculation necessary	This is my assessment, the range for all passenger cars must lie between 0.7 and 0.9 so I took half of the difference and divided by the square root of three.

Table 2.2-2 Intermediate values for calculating the uncertainty for emission factor results for medium-duty vehicles.

Composition/Wear Approach					
	Variables	Value	Uncertainty, $u_{variable}$	*df/d*(variable), evaluated at value	*df/d*(variable)^2 × $u_{variable}^2$
	A	0.50	0.09	1.4262	0.02
	$B_{MDV, disc}$	0.5	0.1	1.4262	0.03
	$M_{MDV, disc}$	4,800,000	300,000	0.0000001	0.002
	f_{MDV}	0.70	0.07	1.0187	0.005
	$d_{MDV, disc}$	60,000	5000	0.00001	0.004
	$C_{Cu, MDV, disc}$	0.05	0.02	14.0000	0.09
	Calculated result (mg/km)				0.7
	Standard uncertainty in calculated result (mg/km)				0.4
	95% confidence interval (mg/km)			-0.1	1
Composition/Emission Factor Approach					
	$EF_{air, MDV}$	12	2	0.016995297	0.0008
	F_{MDV}	0.80	0.06	0.248556219	0.0002
	$C_{Cu, MDV, disc}$	0.05	0.02	3.903781059	0.007
	Calculated result (mg/km)				0.48
	Standard uncertainty in calculated result (mg/km)				0.09
	95% confidence interval (mg/km)			0.3	0.7

2.3 Heavy-Duty Vehicles

Heavy-duty vehicles are not large contributors to copper releases from brake lining wear. This is in part due to the fact that they do not comprise a substantial portion of vehicle miles traveled. In addition, more than 95% of heavy-duty vehicle brakes are drum brakes (Lawrence, 2004) and much of the brake lining material that is worn during braking remains trapped in the drum. Also, the reported copper concentration of lining material in drum brakes in heavy-duty vehicles is lower than the copper concentration in disc brake linings.

2.3a Summary of Values Assigned to Variables

One of the important variables that must be assessed when determining copper releases from heavy-duty vehicles is the amount of brake lining debris that is not trapped in the drum. This value, assigned the variable *T*, could not be found in the literature. It will be assumed that this value can be represented by a uniform distribution that ranges from 0.5 to 0.1, so that the point value is 0.3 with a standard uncertainty of 0.1.

Another variable important for estimating copper releases from heavy-duty vehicle brakes is the number of axles per heavy-duty vehicle, N_{HDV}. Again, information on this value could not be obtained. It will be assumed that this value can be represented by a uniform distribution from 4 axles to 8 axles, so that the point value is 6 axles with a standard uncertainty of 1 axle.

It was also necessary to estimate the number of disc-brake equipped axles per heavy-duty vehicle, $B_{\mathrm{HDV,\ disc}}$. This number is small; less than 5% of heavy-duty truck brakes are disc brakes (Lawrence, 2004). This value was estimated by multiplying the number of axles per heavy-duty vehicle by 3%, or

$$N_{\mathrm{HDV}} = 6 \text{ axles}(0.03) = 0.18 \text{ axles}$$

A uniform distribution from 0.15 axle to 0.03 axle is assumed for this value, so that it has a standard uncertainty of 0.06 axle.

Table 2.3-1 contains details concerning the choice of the following variables and their estimated standard uncertainties. Information on the copper content in heavy-duty vehicle brake linings in the Unites States was not available. The mass fraction of copper in heavy-duty vehicle drum brakes, $C_{\mathrm{Cu,\ HDV,\ drum}}$, was found in a European study to be 0.002 (von Euxkull, 2002), with a standard uncertainty of 0.002. The mass fraction of copper in disc brakes on heavy-duty vehicles, $C_{\mathrm{Cu,\ HDV,\ disc}}$ was found by the same researcher to be 0.05 (von Euxkull, 2002) with a standard uncertainty of 0.02. This value is notable in that it is similar to the copper concentration in passenger cars in the US for non-factory brake pads. In another European study, the mass of drum brake lining material per axle in heavy-duty vehicles, $M_{\mathrm{HDV,\ drum}}$, was found to be 7000 g/axle (Westerlund, 2001) with a standard uncertainty of 300 g/axle. The same researcher found the mass of disc brake lining material per axle, $M_{\mathrm{HDV,\ disc}}$, to be 4800 g/axle (Westerlund, 2001) with a standard uncertainty of 300 g/axle. The fraction of brake lining material worn off at replacement, f_{HDV}, was found in the same European study to be 0.7 (Westerlund, 2001) with a standard uncertainty of 0.07. Again, in that European study, the distance traveled between drum brake lining replacements, $d_{\mathrm{HDV,\ drum}}$, was found to be 100,000 km (Westerlund, 2001) with a standard uncertainty of 20,000 km and the distance traveled between disc brake lining replacements, $d_{HDV,\ disc}$, was found to be 60,000 km (Westerlund, 2001) with a standard uncertainty of 5000 km. The fraction of wear debris that is brake lining material (as opposed to drum material), F_{HDV}, could not be found specifically for heavy-duty vehicles and was assumed to be the same value as was measured for passenger vehicles. That value (see previous section on passenger vehicles) is 0.83 with a standard uncertainty of 0.04. The emission factor for air releases from heavy-duty brakes developed by the UN, $EF_{air,\ HDV}$, is 33 mg/km (Ntziachristos, 2004), with a standard uncertainty of 5 mg/km.

2.3b Emission Factor Calculations

<u>The Composition/Wear Approach</u>: In this method, the rate of overall brake lining wear is determined by multiplying the mass of brake lining material on the vehicle by the fraction of material that is worn off when the lining is replaced, then dividing that value by the number of miles driven between lining replacements. In the case of drum brakes, this value has to also be adjusted for the amount of brake wear debris that is trapped in the drum.

Details concerning the chosen value for A, the fraction of disc brake lining debris that is released to air, are contained in the section on partitioning. For now, it is enough to know that A is given as 0.50 with a standard uncertainty of 0.09.

These emission factors can then be used to calculate an emission factor for copper releases to air from brake lining wear in heavy-duty vehicles:

$$\mathrm{EF}_{\text{air, Cu, HDV}} = \frac{TA\left(N_{\text{HDV}} - B_{\text{HDV, disc}}\right)M_{\text{HDV, drum}}\, f_{\text{HDV}} C_{\text{Cu, HDV, drum}}}{d_{\text{HDV, drum}}} + \frac{AB_{\text{HDV, disc}} M_{\text{HDV, disc}}\, f_{\text{HDV}}}{d_{\text{HDV, disc}}} C_{\text{Cu, HDV, disc}}$$

$$= \frac{(0.3)(0.5)(6 \text{ axles} - 0.18 \text{ axles})\left(7\times10^{6} \ \frac{\text{mg}}{\text{axle}}\right)(0.7)(0.002)}{100{,}000 \text{ km}}$$

$$+ \frac{(0.5)(0.18 \text{ axles})\left(4.8\times10^{6} \ \frac{\text{mg}}{\text{axle}}\right)(0.7)(0.05)}{60{,}000 \text{ km}}$$

$$= 0.3 \text{ mg/km}$$

The standard uncertainty for this value is 0.2 mg/km. The intermediate values for calculating the standard uncertainty in this value are given in Table 2.3-2. This table shows that the largest contributor to the uncertainty, by far, is the value for the concentration of copper in the brake lining materials (both shoes and pads contribute equally to the uncertainty). The 95% confidence interval for this emission factor is 0 mg/km to 0.8 mg/km. The contribution by drum brakes to the emission factor is only one-quarter of the total, even though drum brakes are more than 95% of brakes. This verifies the validity of neglecting the drum brake terms for passenger and medium-duty vehicles.

<u>The Composition/Existing Emission Factor Approach:</u> An emission factor for air releases from brake lining wear was also developed by applying information on mass fractions of copper to reported brake wear air emission factors. As with the composition/wear approach, the airborne copper from disc brakes contributes very little to the total airborne copper because disc brakes are infrequently used in heavy-duty vehicles. Therefore, only the contributions from drum brakes must be included and the equation for the emission factor is

$$
\begin{aligned}
&\mathrm{EF}_{\text{air, Cu, HDV}} \\
&= \mathrm{EF}_{\text{air, HDV}} F_{\text{HDV}} \left(\frac{\dfrac{B_{\text{HDV, disc}} M_{\text{HDV, disc}} C_{\text{Cu, HDV, disc}}}{d_{\text{HDV, disc}}} + \dfrac{T\left(N_{\text{HDV}} - B_{\text{HDV, disc}}\right) M_{\text{HDV, drum}} C_{\text{Cu, HDV, drum}}}{d_{\text{HDV, drum}}}}{\dfrac{B_{\text{HDV, disc}} M_{\text{HDV, disc}}}{d_{\text{HDV, disc}}} + \dfrac{T\left(N_{\text{HDV}} - B_{\text{HDV, disc}}\right) M_{\text{HDV, drum}}}{d_{\text{HDV, drum}}}} \right) \\
&= \left(33 \frac{\text{mg}}{\text{km}}\right)(0.83) \\
&\times \left(\frac{\dfrac{(0.18)\left(4.8\times 10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)(0.05)}{60{,}000\ \text{km}} + \dfrac{(0.3)(6\ \text{axle} - 0.18\ \text{axle})\left(7.0\times 10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)(0.002)}{100{,}000\ \text{km}}}{\dfrac{(0.18)\left(4.8\times 10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)}{60{,}000\ \text{km}} + \dfrac{(0.3)(6\ \text{axle} - 0.18\ \text{axle})\left(7.0\times 10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)}{100{,}000\ \text{km}}} \right) \\
&= 0.2\ \text{mg/km}
\end{aligned}
$$

An estimate of the standard uncertainty for this value is 0.1 mg/km. (Note that the partial derivatives for the equation for the average concentration of copper are unwieldy. In order to estimate the uncertainty, the denominator was set equal to a variable and the standard uncertainty for the denominator and numerator were found separately and then combined. This does not provide as good of an assessment of the standard uncertainty because they are co-related.) The intermediate values for calculating the standard uncertainty in this value are given in Table 2.3-2. This table shows that the largest contributor to the uncertainty, again, is the value for the concentration of copper in the shoes. The 95% confidence interval for this emission factor is 0 mg/km to 0.2 mg/km.

<u>Tunnel Studies:</u> There are no tunnel studies in the US with copper air emission factors specifically for heavy-duty vehicles. However, the Gillies et al, 2001 study of the Sepulveda Tunnel in Los Angeles does not separate passenger vehicles from medium-duty or heavy-duty

vehicles (so it would be applied to vehicle miles traveled for all vehicles), and does not correct for re-suspended road dust. The emission factor is 0.53 mg/km with an (author-reported) uncertainty of 0.06 mg/km. A 95% confidence interval for this value is 0.41 mg/km to 0.65 mg/km. (Note that using the standard deviation for the copper emission factors for the ten runs as the standard uncertainty would be preferable. Gillies has been contacted to see if he can share the values for the individual runs so that this standard deviation can be calculated.)

2.3c Final Result

Again, the emission factors from the three methodologies are in fairly good agreement (0.2 mg/km, 0.3 mg/km, and 0.53 mg/km) are in good agreement. The tunnel study result will be used because it has the least amount of uncertainty, because it applies to all vehicle categories, and because it falls entirely within both of the results for the other methodologies.

Note that heavy-duty vehicles comprise a small proportion of the vehicle miles traveled in the Bay area and their contribution to copper air emissions from brake pads is negligible.

FINAL RESULT

$EF_{air, Cu, pass}$ = 0.53 mg/km; range 0.41 mg/km to 0.65 mg/km (95% confidence interval)

Table 2.3-1 Summary of values and standard uncertainties in values for heavy-duty vehicles.

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Emission factor for airborne brake lining debris from HDVs ($EF_{air, HDV}$)	Ntziachristos, L, P Boulter. Automobile tyre and brake wear, web-site supporting the development of chapter B770 (SNAP 0707) of the EMEP/Corinair Emission Inventory Guidebook. 7/31/2004.	32.7 mg/vkm	33	mg/km	5	global	taken from multiple studies	taken from multiple studies	0	no calculation necessary	Range is given as 23.5-42 mg/vkm, with a point value of 32.7. Assuming a uniform distribution over the range, standard uncertainty is (42-23.5)/2/sqrt(3).	this value is taken from a compilation of other values for heavy-duty vehicles
Average number of heavy-duty vehicle axles that are disc brake-equipped ($B_{HDV, disc}$)	Lawrence, J. Personal communication. ?,?,?. 2004.	Class D and higher (>26K lb) would be air braked and these are 95+% drum brakes	0.18	axles	0.07	US	2004	personal communication	0	took the midpoint of a range from 100%-95% to 100%-99% multiplied by the average number of axles per HDV	half of the range divided by the square root of three	this is the only available value

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Mass of brake lining material on a drum-equipped HDV axle ($M_{HDV, drum}$)	Westerlund, K-G. Metal emissions from Stockholm traffic -- wear of brake linings. The Stockholm Environment and Health Protection Administration. 2001.	2.4 kg in front per wheel; 3.5 kg in rear per wheel; doesn't specify pad or shoe	7,000,000	mg	300,000	Sweden	c 2001	He got this from a personal communication with R Hedlund of the BBA Friction Sweden AB.	He doesn't say whether these are disc or drum	assumed rear wheels are drum and multiplied by 2 to get amount per axle, then multiplied by 1,000,000 to convert units	Assume the point value has a uniform distribution between 6500 g to 7500 g (this is an plus or minus 0.5 kg of the high and low values per wheel) to get standard uncertainty of half the range divided by the square root of three	this is the only available value
Mass of brake lining material on a disc-equipped HDV axle ($M_{HDV, disc}$)	Westerlund, K-G. Metal emissions from Stockholm traffic -- wear of brake linings. The Stockholm Environment and Health Protection Administration. 2001.	2.4 kg in front per wheel; 3.5 kg in rear per wheel; doesn't specify pad or shoe	4800000	mg	300,000	Sweden	c 2001	He got this from a personal communication with R Hedlund of the BBA Friction Sweden AB.	He doesn't say whether these are disc or drum	assumed front wheels are disc and multiplied by 2 to get amount per axle, then multiplied by 1,000,000 to convert units	Assume the point value has a uniform distribution between 1900 g to 2900 g (this is an plus or minus 0.5 kg of the high and low values per wheel) to get standard uncertainty of half the range divided by the square root of three	this is the only available value

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Fraction of brake lining material worn off at replacement (f_{HDV})	Westerlund, K-G. Metal emissions from Stockholm traffic -- wear of brake linings. The Stockholm Environment and Health Protection Administration. 2001.	70% of total before being replaced	0.70	no units	0.07	Sweden	c 2001	not explained	0	no calculation necessary	estimated that 2/3 of trucks would have within 10% of given value left at replacement	this is the only available value
Distance traveled between drum brake lining replacements ($d_{HDV, drum}$)	Westerlund, K-G. Metal emissions from Stockholm traffic -- wear of brake linings. The Stockholm Environment and Health Protection Administration. 2001.	80,000 to 120,000 km, doesn't specify pad or shoe	100,000	km	20,000	Sweden	c 2001	He got this from a personal communications with M Asen of Bilia Lastbilar AB and P Ramen of Scania-Bilar I Stockholm, AB	0	picked midpoint of range	used range provided; this is normal range, not total possible range, so did not divide by sqrt(3)	this is the only available value
Distance traveled between disc brake lining replacements ($d_{HDV, disc}$)	Ntziachristos, L. Road vehicle tyre & brake wear. Emission Inventory Guidebook. August 2003.	60000 km	60,000	km	5000	unknown	2000	unknown	0	no calculation necessary	used the same fraction as the drum brake distance	this is the only available value
Copper concentration in HDV brake shoes, mass fraction ($C_{Cu, HDV, drum}$)	von Uexkull, O. Antimony in brake pads -- a carcinogenic component? For submission to Journal of Cleaner Production. 2002.	dust from drums measured at 1500, 390, 5500, 820, 6700, 580, 520, 5400, 8100, 530, 920, 1900, 700, 980, 680, 2100, 1200, 700 mg/kg	0.002	mass fraction	0.002	Sweden	c. 2002	concentrations measured using XRF, samples taken from drums of trucks and tractors	0	average of 18 values, divided by 1e6 to convert units	standard deviation of 18 values, divided by 1e6 to convert units	large sample, known to be specific to drum brakes

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Copper concentration in HDV brake pads, mass fraction ($C_{Cu, HDV, disc}$)	von Uexkull, O. Antimony in brake pads -- a carcinogenic component? For submission to Journal of Cleaner Production. 2002.	mixed dust from 45 disc formulations = 61000 mg/kg, mixed dust from 15 formulations = 27,000 mg/kg, three other pads have concentration of 18000, 14000, and 27000	0.05	mass fraction	0.02	Sweden	c 2002	concentrations measured using XRF, two samples from filters on dynamometers used to test brakes plus three samples direct from pads	0	Weighted average of two dust samples and three pad samples, divided by 1e6 to convert units.	Used Kline-McClintock on equation for calculating weighted average of three average values. Stdev was calculated for the three separate samples, and assumed to be 1/2 of value for the other two.	this is the only available value
Fraction of wear debris that is brake lining material (F_{HDV})	Link Testing Laboratories, Inc. Brake dynamometer test report. Prepared for Mark Schlautman, Brake Manufacturers Council. 11/2/04-11/4/04.	losses from pads, in g: 4.6+4.6+7.3+7.1+2.5+3; losses from rotor, in g: 1.7+3.3+.9	0.83	mass fraction	0.04	US	2004	This is only three pads but they were selected to be representative of passenger car pads.	0	sum of the brake pad losses over the sum of the rotor plus brake pad losses	estimate that 2/3 of the car population would fall within .04 of the given value -- the lowest ratio for the three pads was 0.72 and the highest was 0.86	taken from a sample of brakepads designed to be representative; agrees with other researchers (Link, 2004a; Sanders, 2003), disagrees slightly with Trainor, 2001

Variable	Source	Reported Value	Value	Units of Value	Standard Uncertainty (in Same Units as Value)	Geographic Factors	Year	Experimental Factors	Other Notes	Calculation for Converting Reported Value to Value	Rationale for Standard Uncertainty	Reasons for Choosing this Value
Tunnel study emission factors for copper from HDVs, lb Cu/mi ($EF_{air, Cu, HDV}$)	Gillies, JA, AW Gertler, JC Sagebiel, WA Dippel. On-road particulate matter (PM2.5 and PM10) emissions in the Sepulveda Tunnel, Los Angeles, CA. Environ. Sci. Technol. 35, 1054-1063. 2001.	.53+-.06 mg/km; no breakdown of resuspended vs. direct; this is for PM10	530	ug/km	60	Sepulveda Tunnel, Los Angeles, California	1996	Ten runs, one hour each, two PM10 samples per run; XRF of Teflon membrane filters; vehicles videotaped and speed determined with radar gun	Asked Gillies if I could get copper emissionf factors for the ten runs for copper so I could see what the standard deviation is for copper in the different runs. No distinction made betweeen HDV, MDV, and passenger vehicles. No correction for resuspended road dust. PM10 only.	Multiplied by 1000 to convert mg to ug.	given; author states that uncertainty was calculated by propagating the combined uncertainty of the inlet and outlet sum of species concentrations using the measured tunnel airflow volume and vehicle kilometers traveled	Sepulveda tunnel is more likely to have braking events and is a closer model for urban driving than the other two studies

Table 2.3-2 Intermediate values for calculating the uncertainty for emission factor results for heavy-duty vehicles.

Composition/Wear Approach					
	Variables	Value	Uncertainty, $u_{variable}$	*df*/*d*(variable), evaluated at value	$df/d(\text{variable})^2 \times u_{variable}^2$
	A	0.50	0.09	0.6999	0.004
	T	0.3	0.1	0.3107	0.001
	$B_{HDV, disc}$	0.18	0.07	1.4260	0.01
	$M_{HDV, drum}$	7,000,000	300,000	0.00000001	0.00001
	$M_{HDV, disc}$	4,800,000	300,000	0.00000005	0.0002
	f_{HDV}	0.70	0.07	0.4999	0.001
	$d_{HDV, drum}$	100,000	20,000	0.000001	0.0003
	$d_{HDV, disc}$	60,000	5000	0.000004	0.0005
	N_{HDV}	6	1	0.0160	0.0003
	$C_{Cu, HDV, drum}$	0.002	0.002	42.7770	0.01
	$C_{Cu, HDV, disc}$	0.05	0.02	5.0400	0.01
	Calculated result (mg/km)				0.3
	Standard uncertainty in calculated result (mg/km)				0.2
	95% confidence interval (mg/km)			-0.05	0.8
Composition/Emission Factor Approach					
	$EF_{air, HDV}$	33	5	0.006080886	0.001
	F_{HDV}	0.83	0.04	0.239299642	0.00009
	$C_{Cu, HDV, ave}$	0.007	0.005	27.17191977	0.02
	Calculated result (mg/km)				0.2
	Standard uncertainty in calculated result (mg/km)				0.1
	95% confidence interval (mg/km)			-0.1	0.5

2.4 Buses

Copper emissions from bus brake lining materials are insignificant compared to copper emissions from passenger vehicles. Buses account for a small fraction of vehicle miles traveled, less than heavy-duty vehicles. Also, buses are equipped with drum brakes, and the copper concentration in drum brakes is very low and has less likelihood of escaping to the environment.

2.5 Motorcycles

Motorcycles contribute negligibly to the copper emissions from brake lining materials. They are expected to have approximately 1/4th of the total airborne brake wear debris per mile releases of passenger vehicles because they weigh substantially less than passenger vehicles (total airborne brake wear debris releases correlate with curb weight). Also, they contribute a small portion of vehicle miles traveled.

3 Particle Size Distribution of Copper Releases to Air from Brake Lining Wear

A number of researchers have measured the particle size distribution of brake wear material emitted to air. A few of these particle size distributions are given in Table 3-1. (Note that the values from Haselden et al were taken from a curve fit of their data.)

The particle size distribution for this project will be taken from the dynamometer studies commissioned by the Brake Pad Partnership, and performed in November of 2004 (Haselden et al, 2004). The researchers found the particle size distribution for total particulates and for particulates containing copper. Figure 3-1 shows that the results for copper and for total particulate are very similar. Table 3-2 gives their particle bin data in full.

Haselden et al performed an analysis of the uncertainty in their results and their values will be used. They will be incorporated in this report after they are obtained in tabular form.

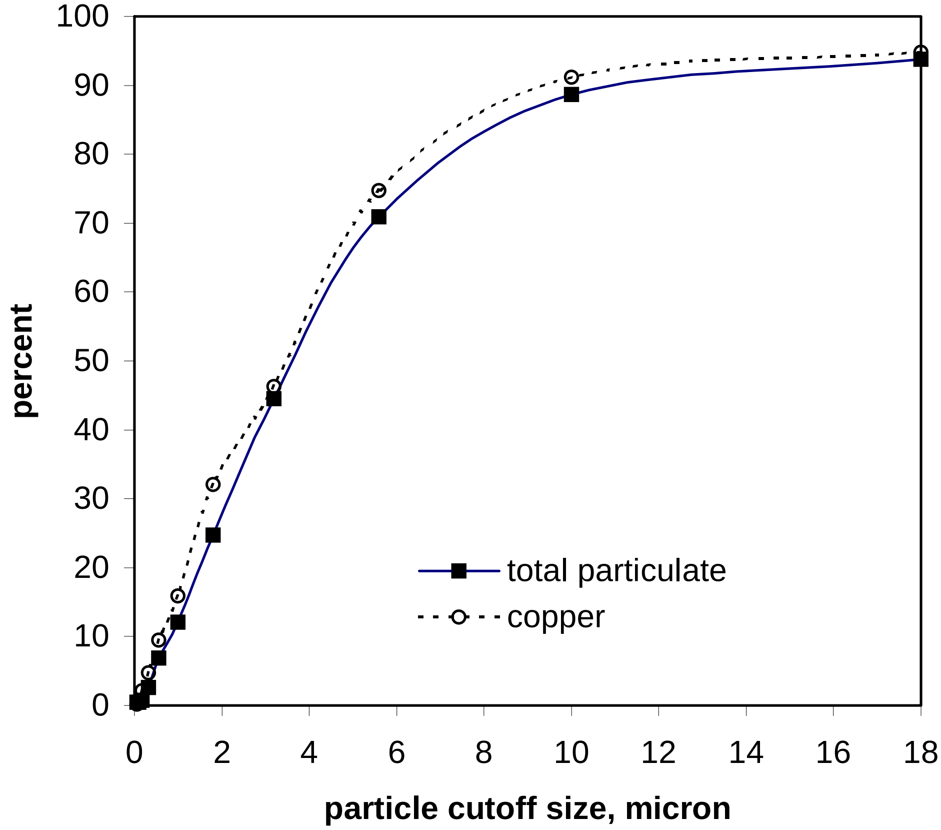

Figure 3-1. Comparison of size distribution for total and copper brake wear particulate (Haselden et al, 2004).

Table 3-1. Brake wear particulate size distributions from various researchers.

	Garg et al, 2000	Cha et al, 1983	Sanders et al, 2003	Haselden et al, 2004 (total particulate)	Haselden et al, 2004 (copper particulate)
% of airborne that is PM10	84	98	80	89	91
% of airborne that is PM7		90	60		
% of airborne that is PM4.7		82	35		
% of airborne that is PM2.5	67				
% of airborne that is PM1.1		16	2		
% of airborne that is PM1				12	16
% of airborne that is PM0.43		9			
% of airborne that is PM0.1	35			0.51	0.35

Table 3-2. Particle size distribution for use in modeling (Haselden et al, 2004).

Particle Size Cutoff, µm	% of total particulates	% of copper particulates
all particles	100	100
18	93.8	94.77
10	88.65	91.19
5.6	70.88	74.69
3.2	44.48	46.29
1.8	24.74	32.04
1	12.11	15.85
0.56	6.84	9.52
0.32	2.62	4.72
0.18	0.78	2.11
0.1	0.51	0.35
0.056	0.51	0.15

4 Partitioning of Copper Releases from Brake Lining Wear and Development of Emission Factors for Non-Air Releases of Copper from Brake Lining Wear

As brake lining material wears, some of the lining material is released directly to the air, some sticks to the vehicle, and some falls to the ground. Of the portion that sticks to the vehicle, some might be washed off by rain or by individual car washing, in which case it enters the storm drains. Some might be washed off in a commercial carwash that discharges to the sewer. This distribution of releases is called partitioning.

The value for the fraction of total brake lining wear that is emitted to air is assigned the variable *A*. This value is crucial to the entire modeling effort and is extremely difficult to measure. Generally, brake lining emissions are studied in a laboratory using a dynamometer. The experimental apparatus generally precludes including even a wheel to the brake equipment, and when a wheel is included, a great deal of debris clings to it and does not become airborne. One researcher (Garg et al, 2000), included a wheel assembly. This researcher found that 35% of the debris became airborne. Another researcher (Sanders et al, 2003), claimed that Garg's result, when corrected for sampling losses, would have been 64%. In his own dynamometer testing with a wheel, Sanders found that 69% of debris became airborne when a wheel was included, compared to 89% when no wheel was included (Sanders et al, 2002).

The best available value for airborne fraction is from a test of a vehicle in a wind tunnel (Sanders, 2003). The experiment to determine this value was conducted on one full-size vehicle and there are many factors that make a wind tunnel an imperfect model of on-road operation. However, the wind tunnel result is expected to be more realistic than dynamometer values. In the wind tunnel, the airborne fraction was 0.50. This value is reasonable when compared to the results for dynamometer testing when a wheel is included and when comparing the change in airborne fraction due to addition of a wheel. If the true value for airborne fraction has a 100% likelihood of falling between 35% and 65%, then the standard uncertainty for this value is 0.09.

Dynamometer results indicate that most of the remaining debris sticks to the vehicle. In dynamometer tests, two to six times as much debris adhered to the hardware as fell to the floor (Sanders, 2002). If this ratio holds for the non-airborne fraction during actual vehicle use, then between 8% and 17% of brake wear debris falls directly to the road. The remaining 33% to 42% either falls to the road (because it is jarred off, builds up to the point where it falls off, or is washed off in a rain event or when the vehicle drives through standing water) or is rinsed to sewer in a commercial car wash.

It is difficult to estimate the portion of brake wear debris that is removed in a commercial car wash and sent to sewer. This is the only portion of brake wear debris that escapes any possibility of becoming entrained in storm water runoff.

In one of the Brake Pad Partnership discussions, it was mentioned that brake wear debris is more likely to be rinsed off a brake caliper when a wheel splashes through a puddle than in a commercial car wash. Precipitation events are not the only causes of standing water; over-irrigation creates puddles as well.

Copper concentrations in the discharge water from commercial car washes is not helpful because they are not combined with information on the number of vehicles served. In addition, water recycling and treatment at these facilities makes it very difficult to correlate the concentration of copper with copper release rates per vehicle.

A crude estimate of the amount of brake wear debris that is removed in commercial carwashes can be obtained by assuming that all brake wear debris is removed on days with rain, and that all brake wear debris is removed when a car is washed. The ratio of commercial carwash events to the total brake wear debris removal events (days of rain plus carwash events) provides an estimate of how much brake wear debris is removed at commercial car washes.

In a 2004 survey titled "Americans Come Clean About Their Cars," the International Carwash Association reported that more than half of all car owners wash their cars less than once a month (ICWA, 2005). Another survey by the IWCA found that 44.5% of Americans preferred home car washing to commercial carwashes (Mercer, 2005). An average value for commercial carwash use might then be 0.5 times per month or six times a year. Home car washing would also occur an average of six times a year.

The average number of rainfall events in the Bay area per year is 60 (GGWS, 2005).

Therefore, of the amount of brake wear debris that sticks to the vehicle, an estimate of the amount that is likely to be washed off at a commercial carwash is

$$\text{fraction of vehicle-adhered brake wear debris to POTW} = \frac{\frac{6 \text{ commercial carwash events}}{\text{yr}}}{\frac{60 \text{ rainfall events}}{\text{yr}} + \frac{12 \text{ carwash events}}{\text{yr}}}$$
$$= 0.08$$

To get an estimate of POTW-borne copper from brake wear debris, this value must be multiplied by the estimated fraction of copper that adheres to the vehicle, which is 0.33 to 0.42. Thus, approximately 3% of the copper in brake wear debris enters a publicly-owned treatment work via commercial carwashes. This value is assigned the variable *W*.

This assumes a steady rate of carwash events and rainfall events throughout the year, and of course this is not the case. Very few precipitation events occur between May and September. However, home car washing is more common during the summer months, and this factor does not take into account vehicle debris that falls to the road because it is jarred off, builds up and falls off, or gets splashed off in a puddle that is not precipitation-related. Home car washing does not occur for medium-duty and heavy-duty vehicles. However, they would still experience brake wear debris removal during rain events and they comprise a small portion of total vehicles, so that influence is not expected to be an over-riding factor. It is assumed that 1% to 5% represents the range of possible values for the fraction of brake wear debris that enters publicly-owned treatment works, and that the standard uncertainty is 1%.

Emission factors for brake wear debris that is washed off at a commercial carwash are given by the following equations.

$$\mathrm{EF}_{\text{POTW, Cu, pass}} = \frac{\mathrm{EF}_{\text{air, Cu, pass}} W}{A} = \frac{0.53 \frac{\text{mg}}{\text{km}} (0.03)}{0.5} = 0.03 \text{ mg/km}$$

$$\mathrm{EF}_{\text{POTW, Cu, MDV}} = \frac{\mathrm{EF}_{\text{air, Cu, MDV}} W}{A} = \frac{0.53 \frac{\text{mg}}{\text{km}} (0.03)}{0.5} = 0.03 \text{ mg/km}$$

$$\mathrm{EF}_{\text{POTW, Cu, HDV}} = \frac{\mathrm{EF}_{\text{air, Cu, HDV}} W}{A} = \frac{0.53 \frac{\text{mg}}{\text{km}} (0.03)}{0.5} = 0.03 \text{ mg/km}$$

The standard uncertainty in these values is 0.01 mg/km, and the 95% confidence interval is 0 mg/km to 0.06 mg/km. The largest source of the uncertainty in these values is the uncertainty in the value for *W*, the fraction of brake wear debris that gets washed off in commercial carwashes.

Brake wear debris losses that do not become airborne or get washed off in commercial carwashes are expected to fall or be rinsed to the road. Emission factors are

$$\begin{aligned}\mathrm{EF}_{\text{road+veh, Cu, pass}} &= \frac{\mathrm{EF}_{\text{air, Cu, pass}}}{A} - \mathrm{EF}_{\text{air, Cu, pass}} - \mathrm{EF}_{\text{POTW, Cu, pass}} \\ &= \frac{0.53 \frac{\text{mg}}{\text{km}}}{0.50} - 0.53 \frac{\text{mg}}{\text{km}} - 0.03 \frac{\text{mg}}{\text{km}} \\ &= 0.5 \text{ mg/km}\end{aligned}$$

$$\begin{aligned}\mathrm{EF}_{\text{road+veh, Cu, MDV}} &= \frac{\mathrm{EF}_{\text{air, Cu, MDV}}}{A} - \mathrm{EF}_{\text{air, Cu, MDV}} - \mathrm{EF}_{\text{POTW, Cu, MDV}} \\ &= \frac{0.53 \frac{\text{mg}}{\text{km}}}{0.50} - 0.53 \frac{\text{mg}}{\text{km}} - 0.03 \frac{\text{mg}}{\text{km}} \\ &= 0.5 \text{ mg/km}\end{aligned}$$

$$\begin{aligned}\mathrm{EF}_{\text{road+veh, Cu, HDV}} &= \frac{\mathrm{EF}_{\text{air, Cu, HDV}}}{A} - \mathrm{EF}_{\text{air, Cu, HDV}} - \mathrm{EF}_{\text{POTW, Cu, HDV}} \\ &= \frac{0.53\,\frac{\text{mg}}{\text{km}}}{0.50} - 0.53\frac{\text{mg}}{\text{km}} - 0.03\frac{\text{mg}}{\text{km}} \\ &= 0.5\ \text{mg/km}\end{aligned}$$

The uncertainty for these values is 0.2 mg/km, and the 95% confidence interval is 0.1 mg/km to 0.9 mg/km. The largest source of uncertainty in these values is the uncertainty in the value for *A*, the airborne wear debris fraction.

Table 4-1 gives details about the uncertainty calculations for the emission factors in this section.

Table 4-1 Intermediate values for calculating the uncertainty for emission factors for copper from brake wear debris to POTWs and to the road.

Variables	Value	Uncertainty, $u_{variable}$	*df/d*(variable), evaluated at value	*df/d*(variable)^2 x $u_{variable}^2$
POTW				
$EF_{air, Cu}$	0.53	0.06	0.06	0.00001
W	0.03	0.01	1.06	0.0001
A	0.50	0.09	0.0636	0.00003
Calculated result (mg/km)				0.03
Standard uncertainty in calculated result (mg/km)				0.01
95% confidence interval (mg/km)			0.0	0.06
vehicle + road				
$EF_{air, Cu}$	0.53	0.06	1	0.004
A	0.50	0.09	2.12	0.04
$EF_{potw, Cu}$	0.03	0.01	1	0.0002
Calculated result (mg/km)				0.5
Standard uncertainty in calculated result (mg/km)				0.2
95% confidence interval (mg/km)			0.1	0.9

5 Estimates of Copper Releases from Vehicle Brake Pad Lining Wear in the 9-County Bay Area

The emission factors described in this report will be multiplied by vehicle miles traveled for each watershed in the Bay area in order to arrive at copper releases from brake lining material. Vehicle miles traveled are available by county and will be adjusted for watershed boundaries by distributing them according to population.

Population data by county for each of the watersheds is not available at this time, but the copper releases in the 9-county Bay area can be estimated. Vehicle miles traveled in the 9-county region amount to 167.2 million miles per day. Copper releases to air due to brake wear are thus 50,000 kg/yr or 110,000 lb/yr, with a 95% confidence interval of 90,000 lb/yr to 140,000 lb/yr. Estimated copper releases to roadways are 50,000 kg/yr or 100,000 lb/yr, with a 95% confidence interval of 20,000 lb/yr to 200,000 lb/yr.

6 Nomenclature (with a Potential Set of Units)

A	Mass fraction of disc brake lining debris that is released to air
$B_{\text{HDV, disc}}$	Average number of heavy-duty vehicle axles that are disc brake-equipped
$B_{\text{MDV, disc}}$	Average number of medium-duty vehicle axles that are disc brake-equipped
$B_{\text{BPP-disc}}$	Average number of axles that are disc brake-equipped on the subset of passenger vehicles included in the Partnership survey
$B_{\text{new-disc}}$	Average number of axles that are equipped with disc brakes on new-disc passenger vehicles
$B_{\text{new-drum}}$	Average number of axles that are equipped with drum brakes on new-drum passenger vehicles
$B_{\text{old-disc}}$	Average number of axles that are equipped with disc brakes on old-disc passenger vehicles
$B_{\text{old-drum}}$	Average number of axles that are equipped with drum brakes on old-drum passenger vehicles
$C_{\text{Cu, HDV, ave}}$	Population-averaged copper concentration in heavy-duty vehicle brakes, mass fraction
$C_{\text{Cu, HDV, disc}}$	Copper concentration in heavy-duty vehicle brake pads, mass fraction
$C_{\text{Cu, HDV, drum}}$	Copper concentration in heavy-duty vehicle brake shoes, mass fraction
$C_{\text{Cu, MDV, ave}}$	Population-averaged copper concentration in medium-duty vehicle brakes, mass fraction
$C_{\text{Cu, MDV, disc}}$	Copper concentration in medium-duty vehicle brake pads, mass fraction
$C_{\text{Cu, MDV, drum}}$	Copper concentration in medium-duty vehicle brake shoes, mass fraction
$C_{\text{Cu, pass, ave}}$	Population-averaged copper concentration in passenger vehicle brakes, mass fraction
$C_{\text{Cu, pass, new-disc}}$	Copper concentration in passenger vehicle factory brake pads, mass fraction
$C_{\text{Cu, pass, new-disc+drum}}$	Average drum and disc copper concentration for new-disc/new-drum vehicles from Partnership data, mass fraction
$C_{\text{Cu, pass, new-drum}}$	Copper concentration in passenger vehicle factory brake shoes, mass fraction
$C_{\text{Cu, pass, old-disc}}$	Copper concentration in passenger vehicle non-factory brake pads, mass fraction
$C_{\text{Cu, pass, old-drum}}$	Copper concentration in passenger vehicle non-factory brake shoes, mass fraction
D_{HDV}	Average distance driven per year for a heavy-duty vehicle
$d_{\text{HDV, disc}}$	Distance traveled between disc brake lining replacements in heavy-duty vehicles
$d_{\text{HDV, drum}}$	Distance traveled between drum brake lining replacements in heavy-duty vehicles
D_{MDV}	Average distance driven per year for a medium-duty vehicle
$d_{\text{MDV, disc}}$	Distance traveled between disc brake lining replacements in medium-duty vehicles
$d_{\text{MDV, drum}}$	Distance traveled between drum brake lining replacements in medium-duty vehicles
D_{pass}	Average distance driven per year for a passenger vehicle

$d_{pass, disc}$	Distance traveled between disc brake lining replacements in passenger vehicles
$d_{pass, drum}$	Distance traveled between drum brake lining replacements in passenger vehicles
$EF_{air, Cu, HDV}$	Emission factor for air releases of copper from heavy-duty vehicles
$EF_{air, Cu, MDV}$	Emission factor for air releases of copper from medium-duty vehicles
$EF_{air, Cu, pass}$	Emission factor for air releases of copper from passenger vehicles
$EF_{air, HDV}$	Emission factor for airborne brake lining debris from heavy-duty vehicles
$EF_{air, HDV, disc}$	Air emission factor for brake lining debris from disc brakes in heavy-duty vehicles
$EF_{air, HDV, drum}$	Air emission factor for brake lining debris from drum brakes in heavy-duty vehicles
$EF_{air, MDV}$	Emission factor for airborne brake lining debris from medium-duty vehicles
$EF_{air, MDV, disc}$	Air emission factor for brake lining debris from disc brakes in medium-duty vehicles
$EF_{air, MDV, drum}$	Air emission factor for brake lining debris from drum brakes in medium-duty vehicles
$EF_{air, pass}$	Emission factor for airborne brake lining debris from passenger vehicles
$EF_{air, pass, new-disc}$	Air emission factor for brake lining debris from factory disc brakes in passenger vehicles
$EF_{air, pass, new-drum}$	Air emission factor for brake lining debris from factory drum brakes in passenger vehicles
$EF_{air, pass, old-disc}$	Air emission factor for brake lining debris from non-factory disc brakes in passenger vehicles
$EF_{air, pass, old-drum}$	Air emission factor for brake lining debris from non-factory drum brakes in passenger vehicles
$EF_{POTW, Cu, HDV}$	Emission factor for POTW discharges of copper from commercial carwashes servicing heavy-duty vehicles
$EF_{POTW, Cu, MDV}$	Emission factor for POTW discharges of copper from commercial carwashes servicing medium-duty vehicles
$EF_{POTW, Cu, pass}$	Emission factor for POTW discharges of copper from commercial carwashes servicing passenger vehicles
$EF_{road-dir, Cu, HDV}$	Emission factor for direct releases of copper to the road from heavy-duty vehicles
$EF_{road-dir, Cu, MDV}$	Emission factor for direct releases of copper to the road from medium-duty vehicles
$EF_{road-dir, Cu, pass}$	Emission factor for direct releases of copper to the road from passenger vehicles
$EF_{road-ind, Cu, HDV}$	Emission factor for copper that is released to the road after adhering to heavy-duty vehicles
$EF_{road-ind, Cu, MDV}$	Emission factor for copper that is released to the road after adhering to medium-duty vehicles
$EF_{road-ind, Cu, pass}$	Emission factor for copper that is released to the road after adhering to passenger vehicles

$EF_{road\text{-}tot,\ Cu,\ HDV}$	Emission factor for all copper released to the road from heavy-duty vehicles
$EF_{road\text{-}tot,\ Cu,\ MDV}$	Emission factor for all copper released to the road from medium-duty vehicles
$EF_{road\text{-}tot,\ Cu,\ pass}$	Emission factor for all copper released to the road from passenger vehicles
$EF_{veh,\ Cu,\ HDV}$	Emission factor for copper that adheres to the vehicle after being released from heavy-duty vehicles
$EF_{veh,\ Cu,\ MDV}$	Emission factor for copper that adheres to the vehicle after being released from medium-duty vehicles
$EF_{veh,\ Cu,\ pass}$	Emission factor for copper that adheres to the vehicle after being released from passenger vehicles
f_{HDV}	Mass fraction of heavy-duty vehicle brake lining material worn off at replacement
F_{HDV}	Mass fraction of wear debris that is brake lining material in heavy-duty vehicles
f_{MDV}	Mass fraction of medium-duty vehicle brake lining material worn off at replacement
F_{MDV}	Mass fraction of wear debris that is brake lining material in medium-duty vehicles
f_{pass}	Mass fraction of passenger vehicle brake lining material worn off at replacement
F_{pass}	Mass fraction of wear debris that is brake lining material in passenger vehicles
$M_{HDV,\ disc}$	Mass of brake lining material on a disc-equipped heavy-duty vehicle axle
$M_{HDV,\ drum}$	Mass of brake lining material on a drum-equipped heavy-duty vehicle axle
$M_{MDV,\ disc}$	Mass of brake lining material on a disc-equipped medium-duty vehicle axle
$M_{MDV,\ drum}$	Mass of brake lining material on a drum-equipped medium-duty vehicle axle
$M_{pass,\ disc}$	Mass of brake lining material on a disc-equipped passenger vehicle axle
$M_{pass,\ drum}$	Mass of brake lining material on a drum-equipped passenger vehicle axle
N_{HDV}	Average number of axles per heavy-duty vehicle
P	Average number of significant rainfall events per year
$R_{new\text{-}disc}$	Fraction of passenger vehicles equipped with factory disc brakes
$R_{new\text{-}drum}$	Fraction of passenger vehicles equipped with factory drum brakes
S	Mass fraction of total brake lining wear that is released directly to the road during use
V	Mass fraction of total brake lining wear debris that adheres to the vehicle after being released
W_{HDV}	Number of times per year that the average heavy-duty vehicle is washed at a commercial car wash
W_{MDV}	Number of times per year that the average medium-duty vehicle is washed at a commercial car wash
W_{pass}	Number of times per year that the average passenger vehicle is washed at a commercial car wash

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