Copper Released from Brake Lining Wear in the San Francisco Bay Area

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Executive Summary

Many human activities result in the release of copper to the environment. The Brake Pad Partnership is conducting a study whose purpose is to gain a better understanding of the sources of elevated copper concentrations in the San Francisco Bay. The overall effort includes assessing the magnitude of copper released in the Bay area, followed by modeling of the environmental fate and transport of these estimated releases. The primary objective of this report is to provide estimates of releases of copper from brake lining wear in the Bay area for use in the Brake Pad Partnership's modeling effort. This report also presents the methodology for preparing the estimates. Copper releases from non-brake sources are the subject of a separate report.

In order to estimate the releases of copper from brake lining wear, emission factors based on vehicle distance traveled were developed. Air emission factors were created first, using several independent methodologies, and the most appropriate methodology was selected for preparing the estimates of copper releases. Emission factors for releases to roadway are based on the air emission factors coupled with brake wear partitioning information.

The emission factors prepared in this study are shown in Table ES-1. This table gives the emission factors, the standard uncertainty for each emission factor, and the 95% confidence interval for each emission factor. Separate air emission factors were calculated for passenger vehicles, medium-duty vehicles, and heavy-duty vehicles using both a brake lining composition/brake lining wear rate approach and a brake lining composition/brake lining air emission factor approach. An air emission factor based on the results of a tunnel study is also given. The tunnel study's air emission factor, which was selected for estimating copper releases, applies to all vehicles, regardless of vehicle category. The emission factor for releases to roadways was derived from the tunnel study air emission factor, along with information on the fate of brake wear debris.

Note that the uncertainty in the emission factors is large, particularly the uncertainty in the emission factor for releases to roadway.

This report also provides information on the particle size distribution of copper-containing particles released in brake wear debris. The particle size distribution that will be used by the air modeling team as the study progresses is given in Table ES-2.

The boundaries of the sub-watersheds to be modeled in this project were developed so that they suit the requirements of the models. As a result, the sub-watersheds discussed in this report may be subdivisions or aggregations of actual physical watersheds. References to sub-watersheds or Bay area sub-watersheds throughout this report indicate sub-watersheds as defined for this

project. It is important to remember that the goal of the overall project is to estimate total loads to the San Francisco Bay and not to the individual sub-watersheds.

Separate estimates of copper releases from brake wear were prepared for each of the 23 sub-watersheds in the San Francisco Bay watershed. Data on vehicle miles traveled are available by county and the emissions were apportioned to the sub-watersheds using population as a measure of traffic density. In addition, emissions based on traffic count data in the Castro Valley watershed were calculated separately for Interstate 580 (which will be treated as a line source during air modeling) and for surface streets (which will be treated as an area source). Estimated releases of copper from brake lining wear for the year 2003 are presented in Tables ES-3 and ES-4. These tables also give the standard uncertainty in each sub-watershed's estimated releases and the 95% confidence interval for estimated releases within each sub-watershed.

The first section of this report provides background information on copper releases from brake lining wear, along with a discussion of the methodology for assessing uncertainty in the results. Section 2 discusses the methodologies for preparing air emission factors of copper from brake lining materials for passenger vehicles, medium-duty vehicles, and heavy-duty vehicles. Section 3 presents the particle size distribution information for brake lining wear debris, and Section 4 presents partitioning data, along with emission factors for releases of copper to roadways from brake lining material. Section 5 contains the release estimates of copper from brake lining material for 2003. Section 6 is a list of nomenclature used in the report and Section 7 lists references.

Table ES-1 Emission factors for copper from brake lining wear. Emission factors selected for preparing the inventory are highlighted in bold.

Release Category	Vehicle Category	Emission Factor Estimation Approach	Calculated result (mg Cu/km)	Standard uncertainty in calculated result (mg Cu/km)	95% confidence interval (mg Cu/km)	
					Low	High
Airborne emission factor						
	Passenger vehicles					
		Composition/wear	0.5	0.2	0.0	0.9
		Composition/emission factor	0.4	0.2	-0.1	0.8
	Medium-duty vehicles					
		Composition/wear	0.7	0.4	0.0	1.5
		Composition/emission factor	0.48	0.09	0.30	0.66
	Heavy-duty vehicles					
		Composition/wear	0.3	0.2	0.0	0.7
		Composition/emission factor	0.2	0.1	-0.1	0.5
	All	**Tunnel study**	**0.58**	**0.07**	**0.44**	**0.72**
Roadway emission factor						
	All	**Partitioning/airborne emission factor**	**0.5**	**0.2**	**0.1**	**1.0**

Table ES-2 Particle size distribution for use in modeling (Haselden et al, 2004; standard errors are from Schlautman, 2005).

Particle Size Cutoff, µm	% of total particulate mass	% of total particulate copper mass
all particles	100.00 ± 5.39	100.00 ± 8.47
< 18	93.80 ± 5.20	94.76 ± 7.91
< 10	88.65 ± 5.02	91.18 ± 7.73
< 5.6	70.88 ± 4.46	74.66 ± 6.72
< 3.2	44.48 ± 3.45	46.23 ± 5.00
< 1.8	24.74 ± 2.87	31.97 ± 3.99
< 1	12.11 ± 2.37	15.76 ± 2.87
< 0.56	6.84 ± 1.76	9.42 ± 1.80
< 0.32	2.62 ± 1.60	4.62 ± 1.55
< 0.18	0.77 ± 1.25	2.01 ± 1.39
< 0.1	0.50 ± 0.73	0.25 ± 1.02
< 0.056	0.50 ± 0.42	0.05 ± 0.61

Table ES-3 Estimated copper releases from brake lining materials in the Castro Valley watershed in 2003. Amounts are in kg Cu/y.

Release to	Value		Interstate 580	Surface Streets
Air				
	Estimated releases		170	100
	Uncertainty		30	10
	95% Confidence interval	Low	110	70
		High	230	120
Roadway				
	Estimated releases		160	90
	Uncertainty		60	30
	95% Confidence interval	Low	30	20
		High	290	130

Table ES-4 Estimated copper releases from brake lining wear in 2003 in the sub-watersheds in the San Francisco Bay area. Amounts are in kg Cu/y.

Watershed	Airborne copper released	Standard uncertainty in airborne copper releases	95% Confidence Interval		Copper released to roadways	Standard uncertainty in copper releases to roadways	95% Confidence Interval	
			From	To			From	To
Upper Alameda	1,772	360	1,051	2,493	1,661	685	291	3,032
Santa Clara Valley Central	2,953	601	1,752	4,154	2,768	1,142	485	5,052
Castro Valley	282	57	167	397	264	109	46	483
East Bay North	1,969	401	1,168	2,771	1,846	762	323	3,369
Upper Colma	801	163	475	1,127	751	310	131	1,370
Marin South	1,183	241	702	1,664	1,109	457	194	2,024
Coyote	4,851	987	2,878	6,824	4,548	1,876	796	8,299
East Bay Central	7,052	1,434	4,184	9,921	6,612	2,727	1,158	12,065
East Bay South	1,494	304	886	2,102	1,401	578	245	2,556
Solano West	1,359	276	806	1,912	1,274	526	223	2,326
Napa	1,618	329	960	2,277	1,517	626	266	2,769
North Napa	201	41	119	283	189	78	33	344
North Sonoma	75	15	44	105	70	29	12	128
Marin North	761	155	452	1,071	714	294	125	1,303
Contra Costa Central	3,823	778	2,268	5,378	3,584	1,478	628	6,540
Petaluma	528	107	313	743	495	204	87	904
Santa Clara Valley West	6,111	1,243	3,625	8,597	5,729	2,363	1,003	10,455
Upper San Lorenzo	280	57	166	393	262	108	46	478
Contra Costa West	1,369	278	812	1,926	1,283	529	225	2,342
Peninsula Central	4,344	884	2,577	6,111	4,073	1,680	713	7,432
Sonoma	247	50	147	347	232	96	41	423
Upper San Francisquito	106	21	63	149	99	41	17	181
Upper Corte Madera	240	49	142	338	225	93	39	411
City of San Francisco	3,614	735	2,144	5,084	3,388	1,397	593	6,183
Watershed Total (Parts of 8 Counties)	43,420	8,831	25,758	61,082	40,706	16,789	7,128	74,284
9-County Total	53,839	10,950	31,939	75,740	50,474	20,818	8,839	92,110

1 Introduction

Many human activities result in the release of copper to the environment. The Brake Pad Partnership is conducting a study whose purpose is to gain a better understanding of the sources of elevated copper concentrations in the San Francisco Bay. The overall effort includes assessing the magnitude of copper released in the Bay area, followed by modeling of the environmental fate and transport of these estimated releases. The primary objective of this report is to provide estimates of releases of copper from brake lining wear in the Bay area for use in the Brake Pad Partnership's modeling effort. This report also presents the methodology for preparing the estimates. Copper releases from non-brake sources are the subject of a separate report.

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. Figure 1-1 illustrates this distribution of releases, which 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. This study's approach to estimating copper releases from brake lining wear was to develop several values for emission factors based on independent methodologies. These emission factors are expressed in terms of mass of copper released per vehicle distance traveled. Separate emission factors were created for 1) passenger cars and light-duty trucks, 2) medium-duty vehicles, and 3) heavy-duty vehicles.

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

Air emissions from vehicle brake lining wear have been studied more extensively than releases to other environmental compartments. Because of this, an air emission factor was developed first, and emission factors for copper released directly to the roadway were based on this air emission factor coupled with information on partitioning.

Once the emission factors were developed, they were multiplied by vehicle distance traveled per unit time to estimate releases of copper 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, they would not be helpful. Data from dynamometer tests must be used with caution because driving conditions have a significant 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 (Anderson, 1992).

A report titled "Work Plan for Estimating Copper Emissions from Brake Lining Wear in Alameda County" contains supplementary information about the methodology pursued in the creation of the estimates of releases presented in this report. Interested readers can access this document at
www.suscon.org/brakepad/pdfs/FINALBrakeSources_emission_factor_rev5Work Plan02-Dec-04.pdf

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 describing the values that were assigned 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 was 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 of a sample 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 estimate of the standard uncertainty was set at half of the range divided by the square root of three. (Half of the range divided by the square root of three corresponds to the square root of the variance, or the second central moment, of a uniform distribution, and the square root of the variance is, by definition, the standard deviation in statistical terms.)

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 $R = f(x_1, x_2,\ldots,x_n)$ 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

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

where u is uncertainty, R is the resulting value, and n is the number of variables in the function. For example, if

$$f(x, y, z) = R = axyz$$

where a is a constant, then

$$\frac{\partial R}{\partial x} = ayz$$

$$\frac{\partial R}{\partial y} = axz$$

$$\frac{\partial R}{\partial z} = axy$$

and

$$u_R = \sqrt{\left(ayzu_x\right)^2 + \left(axzu_y\right)^2 + \left(axyu_z\right)^2}$$

If

$$f(x, y, z) = R = ax + by + cz$$

where a, b, and c are constants, then

$$\frac{\partial R}{\partial x} = a$$

$$\frac{\partial R}{\partial y} = b$$

$$\frac{\partial R}{\partial z} = c$$

and

$$u_R = \sqrt{\left(au_x\right)^2 + \left(bu_y\right)^2 + \left(cu_z\right)^2}$$

The Kline-McClintock equation was used to estimate the uncertainty in calculated results for this project.

Standard uncertainties are also useful because they can be used to provide a range of values that apply to a desired confidence interval. For example, a 95% confidence interval is one where the range of values provided for the final result has a 95% probability of containing 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.)

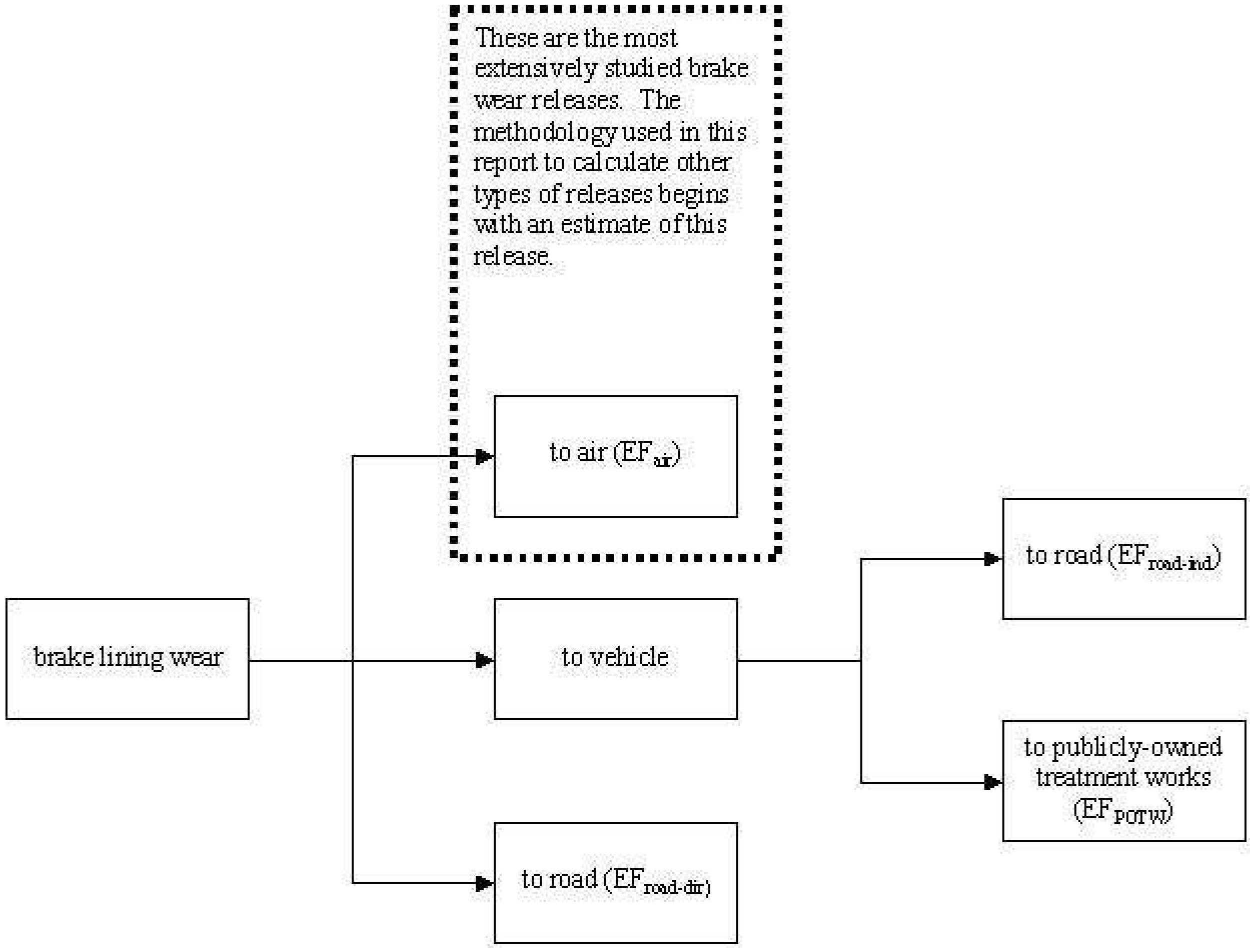

Figure 1-1 Partitioning of brake lining releases.

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)

This section is divided into subsections on passenger vehicles, medium-duty vehicles, heavy-duty vehicles, buses, and motorcycles. Air emission factors for copper from brake lining wear from the first three of these vehicle categories were calculated, and the methodology and results are summarized here.

2.1 Passenger Cars and Light-Duty Trucks

This vehicle category includes passenger cars and trucks weighing less than 5,750 lb.

2.1.a 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 replacement brake lining materials tend to contain less copper than factory-installed brake lining materials because copper is a relatively expensive material. As a result, 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 was estimated to be 35,000 miles (Garg et al, 2000) with a standard uncertainty of 3500 miles for disc brakes (see Table A-1 in Appendix A for details concerning this choice);
- vehicle registration data by year first registered for California, from Table 2.1-1; 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 $R_{\text{new-disc}}$) thus includes vehicles that are less than three years old and was assigned a value of 0.34 with a standard uncertainty of 0.03.

Finding a value for $R_{\text{new-drum}}$ 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 2.1-2.

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). As shown in Table 2.1-1, 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 2.1-3 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 was 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

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

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

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

A standard uncertainty of 0.06 axles applies to both of these values. This standard uncertainty was 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 axles, and the true value for B_{drum} would fall between 0.24 and 0.44 axles, so that the standard uncertainty was 0.1 axles divided by the square root of three, or 0.06 axles.

Because of the data on the mass fraction of copper are collected for the Brake Pad Partnership, a value for the average number of axles that are factory disc brake-equipped on the subset of passenger vehicles included in the survey was also needed. This value, calculated using the values shown in Table 2.1-4, 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 mass fraction of copper for new-disc/new-drum vehicles from Brake Pad Partnership data was assigned the variable $C_{\text{Cu, pass, new-disc+drum}}$ and is

$$C_{\text{Cu, pass, new-disc+drum}} = \frac{13.34\left(\frac{0.0769}{1.161}\right) + (24.44 - 13.34)\left(\frac{0.0766}{1.183}\right) + (34.44 - 24.44)\left(\frac{0.0561}{1.238}\right)}{34.44}$$
$$= 0.06\ (6\%)$$

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 was 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 was 0.2, and the minimum mass fraction is zero (Armstrong, 1994; Westerlund, 2001). An upper bound for the copper in factory disc brakes was found by assuming that brake lining materials in the 60% of vehicles that were not included in the survey were 20% copper. Similarly, a lower bound was found by assuming that brake lining materials in 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 A-1 in Appendix A 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, $C_{\text{Cu, pass, old-disc}}$, was 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, $M_{\text{pass, disc}}$ was estimated to be 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}, was estimated to be 0.80 (Garg et al, 2000) with a standard uncertainty of 0.08.

2.1.b Emission Factor Calculations

This section presents the values for air emission factors that were calculated using all three estimation methodologies.

The Composition/Wear Approach: In this method, the rate of overall brake lining wear was 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. This value, divided by the distance driven between lining replacements and adjusted for the mass fraction of brake lining material that is copper and the fraction of material that becomes airborne, determined this methodology's air 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

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

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 was estimated to be

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

The standard uncertainty for this value is 0.2 mg/km. As shown in Table 2.1-5, the largest contributor to this uncertainty was the uncertainty in the value for $C_{\text{Cu, pass, old-disc}}$, and the next largest contributor to the uncertainty was the uncertainty in the value for $C_{\text{Cu, pass, old-disc}}$. The final column in this table is a measure of the variable's contribution to uncertainty in the calculated result. The 95% confidence interval for this emission factor is 0.04 mg/km to 0.9 mg/km.

The Composition/Existing Emission Factor Approach: 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 calculating the emission factor is

$$\begin{aligned}
\text{EF}_{\text{air, Cu, pass}} &= \text{EF}_{\text{air, pass}} F_{\text{pass}} \left(\frac{R_{\text{new-disc}} B_{\text{new-disc}} C_{\text{Cu, pass, new-disc}} + \left(1 - R_{\text{new-disc}}\right) B_{\text{old-disc}} C_{\text{Cu, pass, old-disc}}}{R_{\text{new-disc}} B_{\text{new-disc}} + \left(1 - R_{\text{new-disc}}\right) B_{\text{old-disc}}} \right) \\
&= \text{EF}_{\text{air, pass}} F_{\text{pass}} \left(R_{\text{new-disc}} C_{\text{Cu, pass, new-disc}} + \left(1 - R_{\text{new-disc}}\right) C_{\text{Cu, pass, old-disc}} \right) \\
&= 8 \frac{\text{mg}}{\text{km}} (0.83) \left(0.34 (0.09) + (1 - 0.34) 0.05 \right) \\
&= 0.4 \text{ mg/km}
\end{aligned}$$

The standard uncertainty for this value is 0.2 mg/km. As with the composition/wear approach, the largest contributor to this uncertainty was the uncertainty in the value for $C_{\text{Cu, pass, old-disc}}$, and the next largest contributor to the uncertainty was 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 2.1-5. The final column in this table is a measure of the variable's contribution to uncertainty in the calculated result.

Tunnel Studies: Tunnel studies are expected to be a strong possible means of determining emission factors because they represent 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 $PM_{2.5}$ only. Another (Lough, 2005a) 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. More braking occurs in the Sepulveda Tunnel than in other tunnels that were studied (Lough, 2005b; Gertler, 2005a), and because of this, the results of Gillies et al are most representative of urban driving. This emission factor is for PM_{10} 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. In addition, heavy-duty and medium-duty vehicles contribute a larger fraction of total vehicle miles traveled in the Bay area than in the Sepulveda Tunnel. More details concerning this tunnel study can be found in Appendix B of this report, which contains the abstract for the reference. A discussion of the differences in vehicle miles traveled by vehicle category can be found in Appendix C.

The emission factor as stated in the reference is 0.53 mg Cu/km with an author-reported uncertainty of 0.06 mg Cu/km. This emission factor must be adjusted upwards to account for copper contained in particles larger than 10 μm. The fraction of brake lining particles that is 10 μm and smaller ranges from 0.8 to 0.98 (Garg et al, 2000; Cha et al, 1983; Sanders et al, 2003; Haselden et al, 2004). (Note that particle size distributions from brake lining wear are discussed in more detail in Section 3 of this report.) In order to adjust the tunnel study's airborne copper emission factor to include copper contained in particles larger than 10 μm, Haselden et al's value for PM_{10} fraction was used. This value is 0.91 with a standard uncertainty of 0.04. Thus, the adjusted emission factor for airborne copper emissions from brake linings is 0.58 mg Cu/km with a standard uncertainty of 0.07 mg Cu/km. The 95% confidence interval for this value is 0.44 to 0.72 mg Cu/km. Intermediate values for calculating the standard uncertainty can be found in Table 2.1-5.

2.1.c Final Result

The three independently calculated air emission factors for copper released from brake lining wear in passenger vehicles (0.5 mg Cu/km, 0.4 mg Cu/km, and 0.58 mg Cu/km) are in surprisingly good agreement. The tunnel study result was used in this inventory effort because it has the least amount of uncertainty and because its 95% confidence interval range falls entirely within the 95% confidence interval ranges for both of the other methodologies.

FINAL RESULT

$EF_{air, Cu, pass}$ = 0.58 mg Cu/km; range 0.44 to 0.72 mg Cu/km (95% confidence interval)

Table 2.1-1 Distribution of fee-paid registrations by type and year first registered for 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 that paid dues regardless of the model year used to determine fees.

Table 2.1-2 Copper content of friction material from a survey of 2001 and 2002 vehicle models in the top 20 in US sales and for a sample of twenty 2003 vehicle models (Brake Pad Partnership, 2004).

Material	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 2.1-3 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 2.1-4 Fraction of surveyed vehicles 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 2.1-5 Air emission factors for copper from brake lining material in passenger vehicles.

	Variables	Value	Uncertainty, $u_{variable}$	df/d(variable), evaluated at value	$df/d(\text{variable})^2 \times u_{variable}^2$
Airborne Emission Factor from Composition/Wear Approach					
	A	0.50	0.09	0.91	0.006
	B_{disc}	1.66 axle	0.06 axle	0.28	0.0003
	$M_{pass, disc}$	657 g/axle	60 g/axle	0.00070	0.002
	f_{pass}	0.80	0.08	0.57	0.002
	$d_{pass, disc}$	56,361 km	5,636 km	0.0000081	0.002
	$R_{new\text{-}disc}$	0.34	0.03	0.32	0.00008
	$C_{Cu, pass, new\text{-}disc}$	0.09	0.04	2.7	0.009
	$C_{Cu, pass, old\text{-}disc}$	0.05	0.03	5.1	0.02
	Calculated result (mg Cu/km)				0.5
	Standard uncertainty in calculated result (mg Cu/km)				0.2
	95% confidence interval (mg Cu/km)			0.0	0.9
Airborne Emission Factor from Composition/Emission Factor Approach					
	$EF_{air, pass}$	8 mg/km	4 mg/km	0.049	0.03
	F_{pass}	0.83	0.04	0.45	0.0003
	$R_{new\text{-}disc}$	0.34	0.03	0.26	0.00006
	$C_{Cu, pass, new\text{-}disc}$	0.09	0.04	2.2	0.006
	$C_{Cu, pass, old\text{-}disc}$	0.05	0.03	4.1	0.01
	Calculated result (mg Cu/km)				0.4
	Standard uncertainty in calculated result (mg Cu/km)				0.2
	95% confidence interval (mg Cu/km)			-0.1	0.8
Airborne Emission Factor from Tunnel Study Approach					
	$EF_{air, Cu, all\ vehicles}$	0.53 mg Cu/km	0.06 mg Cu/km	1.1	0.004
	PM_{10} correction	0.91	0.04	0.64	0.0006
	Calculated result (mg Cu/km)				0.58
	Standard uncertainty in calculated result (mg Cu/km)				0.07
	95% confidence interval (mg Cu/km)			0.44	0.72

2.2 Medium-Duty Vehicles

A medium-duty vehicle is one that weights 5,750 to 8500 lb.

2.2.a Summary of Values Assigned to Variables

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 to 0.7 axle was assumed for this value, so that it has a standard uncertainty of 0.1 axle.

Table A-2 in Appendix A 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, $M_{\mathrm{MDV,\ disc}}$. This value is 4,800 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. Another value from the same study was used for the distance traveled between disc brake lining replacements, $d_{\mathrm{MDV,\ disc}}$. This value was found to be 60,000 km (Westerlund, 2001) with a standard uncertainty of 5,000 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 as was measured for passenger vehicles. That value (see previous section on passenger vehicles) is 0.83 with a standard uncertainty of 0.04. An emission factor for air releases from medium-duty brakes developed for the UN, $\mathrm{EF}_{\mathrm{air,\ MDV}}$, was used. This value is 12 mg/km (Ntziachristos and Boulter, 2004), with a standard uncertainty of 2 mg/km.

2.2.b Emission Factor Calculations

This section presents the values for air emission factors that were calculated using all three estimation methodologies.

<u>The Composition/Wear Approach</u>: In this method, the rate of overall brake lining wear was 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. This value, divided by the distance driven between lining replacements and adjusted for the mass fraction of brake lining material that is copper and the fraction of material that becomes airborne, determined this methodology's air emission factor for copper from brake lining materials.

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 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

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

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 2.2-1. The final column in this table is a measure of the variable's contribution to uncertainty in the calculated result. This table shows that the largest contributor to the uncertainty is the value for the concentration of copper in the brake lining materials. 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 1.5 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 on medium-duty vehicles 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 2.2-1. The final column in this table is a measure of the variable's contribution to uncertainty in the calculated result. 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.

<u>Tunnel Studies:</u> There are no US tunnel studies in that provide copper air emission factors specifically for medium-duty vehicles. 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). This study does not correct for re-suspended road dust. In addition, heavy-duty and medium-duty vehicles contribute a larger fraction of total vehicle miles traveled in the Bay area than in the Sepulveda Tunnel. More braking occurs in the Sepulveda Tunnel than in other tunnel studies that provided copper emission factors (Lough, 2005b; Gertler, 2005a), and because of this, the results of Gillies et al are most representative of urban driving. More details concerning this tunnel study can be found in Appendix B of this report, which contains the abstract for the reference. A discussion of the differences in vehicle miles traveled by vehicle category can be found in Appendix C.

The emission factor as stated in the reference is 0.53 mg Cu/km with an author-reported uncertainty of 0.06 mg Cu/km. This emission factor must be adjusted upwards to account for copper contained in particles larger than 10 μm. The fraction of brake lining particles that is 10 μm and smaller ranges from 0.8 to 0.98 (Garg et al, 2000; Cha et al, 1983; Sanders et al, 2003; Haselden et al, 2004). (Note that particle size distributions from brake lining wear are discussed in more detail in Section 3 of this report.) In order to adjust the tunnel study's airborne copper emission factor to include copper contained in particles larger than 10 μm, Haselden et al's value for PM_{10} fraction was used. This value is 0.91 with a standard uncertainty of 0.04. The adjusted emission factor for airborne copper emissions from brake linings is thus 0.58 mg Cu/km with a standard uncertainty of 0.07 mg Cu/km. The 95% confidence interval for this value is 0.44 to 0.72 mg Cu/km. Intermediate values for calculating the standard uncertainty can be found in Table 2.2-1.

2.2.c Final Result

Again, the emission factors from the three methodologies are in fairly good agreement (0.7 mg Cu/km, 0.48 mg Cu/km, and 0.58 mg Cu/km). The tunnel study result was used in this inventory effort because it has the least amount of uncertainty, because it applies to all vehicle categories, and because its 95% confidence interval range falls nearly entirely within the 95% confidence interval range for the results for the other two methodologies.

FINAL RESULT

$EF_{air, Cu, MDV}$ = 0.58 mg Cu/km; range 0.44 to 0.72 mg Cu/km (95% confidence interval)

Table 2.2-1 Air emission factors for copper from brake lining material in medium-duty vehicles.

	Variables	Value	Uncertainty, $u_{variable}$	df/d(variable), evaluated at value	$df/d(\text{variable})^2 \times u_{variable}^2$
Airborne Emission Factor from Composition/Wear Approach					
	A	0.50	0.09	1.4	0.02
	$B_{MDV, disc}$	0.5 axle	0.1 axle	1.4	0.03
	$M_{MDV, disc}$	4,800,000 mg/axle	288,675 mg/axle	0.00000015	0.002
	f_{MDV}	0.70	0.07	1.0	0.005
	$d_{MDV, disc}$	60,000 km	5,000 km	0.000012	0.004
	$C_{Cu, MDV, disc}$	0.05	0.02	14	0.09
	Calculated result (mg Cu/km)				0.7
	Standard uncertainty in calculated result (mg Cu/km)				0.4
	95% confidence interval (mg Cu/km)			0.0	1.5
Airborne Emission Factor from Composition/Emission Factor Approach					
	$EF_{air, MDV}$	12 mg/km	2 mg/km	0.017	0.0008
	F_{MDV}	0.80	0.06	0.25	0.0002
	$C_{Cu, MDV, disc}$	0.05	0.02	3.9	0.007
	Calculated result (mg Cu/km)				0.48
	Standard uncertainty in calculated result (mg Cu/km)				0.09
	95% confidence interval (mg Cu/km)			0.30	0.66
Airborne Emission Factor from Tunnel Study Approach					
	$EF_{air, Cu, all vehicles}$	0.53 mg Cu/km	0.06 mg Cu/km	1.1	0.004
	PM_{10} correction	0.91	0.04	0.64	0.0006
	Calculated result (mg Cu/km)				0.58
	Standard uncertainty in calculated result (mg Cu/km)				0.07
	95% confidence interval (mg Cu/km)			0.44	0.72

2.3 Heavy-Duty Vehicles

Heavy-duty vehicles are those that weigh 8,500 lb or more.

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.

2.3.a 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 is assumed that this value can be represented by a uniform distribution that ranges from 0.1 to 0.5, 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 is 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

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

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 A-3 in Appendix A contains details concerning the choice of the following variables and their estimated standard uncertainties. Information on the copper content of heavy-duty vehicle brake linings in the Unites States was not available. Neither was information on the potential differences between copper concentrations of linings in factory-equipped brakes and aftermarket brake linings. 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 7,000 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 4,800 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, $d_{\text{HDV, drum}}$, 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, $d_{\text{HDV, disc}}$, was found to be 60,000 km (Westerlund, 2001) with a standard uncertainty of 5,000 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, $\text{EF}_{\text{air, HDV}}$, is 33 mg/km (Ntziachristos and Boulter, 2004), with a standard uncertainty of 5 mg/km.

2.3.b Emission Factor Calculations

This section presents the values for air emission factors that were calculated using all three estimation methodologies.

<u>The Composition/Wear Approach</u>: In this method, the rate of overall brake lining wear was 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. This value, divided by the distance driven between lining replacements and adjusted for the mass fraction of brake lining material that is copper and the fraction of material that becomes airborne, determined this methodology's air emission factor for copper from brake lining materials. 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.

The equation for the emission factor is

$$\begin{aligned}\text{EF}_{\text{air, Cu, HDV}} &= \frac{TA\left(N_{\text{HDV}} - B_{\text{HDV, disc}}\right)M_{\text{HDV, drum}}\,f_{\text{HDV}}\,C_{\text{Cu, HDV, drum}}}{d_{\text{HDV, drum}}} + \frac{AB_{\text{HDV, disc}}M_{\text{HDV, disc}}\,f_{\text{HDV}}}{d_{\text{HDV, disc}}}C_{\text{Cu, HDV, disc}} \\ &= \frac{(0.3)(0.5)(6\text{ axles} - 0.18\text{ axles})\left(7\times10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)(0.7)(0.002)}{100{,}000\text{ km}} \\ &\quad + \frac{(0.5)(0.18\text{ axles})\left(4.8\times10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)(0.7)(0.05)}{60{,}000\text{ km}} \\ &= 0.3\text{ mg/km}\end{aligned}$$

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 2.3-1. The final column in this table is a measure of the variable's contribution to uncertainty in the calculated result. This table shows that the largest contributors to the uncertainty, by far, are the values for the concentration of copper in the brake lining materials (both shoes and pads contribute equally to the uncertainty) and the value for the number of axles equipped with disc brakes. 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.

The Composition/Existing Emission Factor Approach: 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. The equation for the emission factor is

$$\begin{aligned}
&\mathrm{EF}_{\text{air, Cu, HDV}} \\
&= \mathrm{EF}_{\text{air, HDV}} F_{\text{HDV}} \left(\frac{ \dfrac{B_{\text{HDV, disc}} M_{\text{HDV, disc}} C_{\text{Cu, HDV, disc}}}{d_{\text{HDV, disc}}} + \dfrac{T\left(N_{\text{HDV}} - B_{\text{HDV, disc}}\right) M_{\text{HDV, drum}} C_{\text{Cu, HDV, drum}}}{d_{\text{HDV, drum}}} }{ \dfrac{B_{\text{HDV, disc}} M_{\text{HDV, disc}}}{d_{\text{HDV, disc}}} + \dfrac{T\left(N_{\text{HDV}} - B_{\text{HDV, disc}}\right) M_{\text{HDV, drum}}}{d_{\text{HDV, drum}}} } \right) \\
&= \left(33 \frac{\text{mg}}{\text{km}}\right)(0.83) \\
&\times \left(\frac{ \dfrac{(0.18)\left(4.8\times10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)(0.05)}{60{,}000\ \text{km}} + \dfrac{(0.3)(6\ \text{axle} - 0.18\ \text{axle})\left(7.0\times10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)(0.002)}{100{,}000\ \text{km}} }{ \dfrac{(0.18)\left(4.8\times10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)}{60{,}000\ \text{km}} + \dfrac{(0.3)(6\ \text{axle} - 0.18\ \text{axle})\left(7.0\times10^{6}\ \dfrac{\text{mg}}{\text{axle}}\right)}{100{,}000\ \text{km}} } \right) \\
&= 0.2\ \text{mg/km}
\end{aligned}$$

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 2.3-1. The final column in this table is a measure of the variable's contribution to uncertainty in the calculated result. This table shows that the largest contributor to the uncertainty is the value for the concentration of copper in the brake lining materials. The 95% confidence interval for this emission factor is 0 mg/km to 0.5 mg/km.

Tunnel Studies: 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). Values in this study are not corrected for re-suspended road dust. In addition, heavy-duty and medium-duty vehicles contribute a larger fraction of total vehicle miles traveled in the Bay area than in the Sepulveda Tunnel. However, more braking occurs in the Sepulveda Tunnel than in other tunnel studies that were used to develop copper air emission factors (Lough, 2005b; Gertler, 2005a), and because of this, the results of Gillies et al are most representative of urban driving. More details concerning this tunnel study can be found in Appendix B of this report, which contains the abstract for the reference. A discussion of the differences in vehicle miles traveled by vehicle category can be found in Appendix C.

The emission factor as stated in the reference is 0.53 mg Cu/km with an author-reported)uncertainty of 0.06 mg Cu/km. The 95% confidence interval for this value is 0.41 mg Cu/km to 0.65 mg Cu/km. This emission factor must be adjusted upwards to account for copper contained in particles larger than 10 μm. The fraction of brake lining particles that is 10 μm and smaller ranges from 0.8 to 0.98 (Garg et al, 2000; Cha et al, 1983; Sanders et al, 2003; Haselden et al, 2004). (Note that particle size distributions from brake lining wear are discussed in more detail in Section 3 of this report.) In order to adjust the tunnel study's airborne copper emission factor to include copper contained in particles larger than 10 μm, Haselden et al's value for PM_{10} fraction was used. This value is 0.91 with a standard uncertainty of 0.04. The adjusted emission factor for airborne copper emissions from brake linings is thus 0.58 mg Cu/km with a standard uncertainty of 0.07 mg Cu/km. The 95% confidence interval for this value is 0.44 to 0.72 mg Cu/km. Intermediate values for calculating the standard uncertainty can be found in Table 2.3-1.

2.3.c Final Result

Again, the emission factors from the three methodologies are in fairly good agreement (0.2 mg/km, 0.3 mg/km, and 0.58 mg/km). The tunnel study result is used in this effort because it has the least amount of uncertainty, because it applies to all vehicle categories, and because it encompasses a large part of the 95% confidence interval for both of the results from 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

$EF_{air, Cu, HDV}$ = 0.58 mg Cu/km; range 0.44 to 0.72 mg Cu/km (95% confidence interval)

Table 2.3-1 Air emission factors for copper from brake lining material in heavy-duty vehicles.

	Variables	Value	Uncertainty, $u_{variable}$	df/d(variable), evaluated at value	$df/d(\text{variable})^2 \times u_{variable}^2$
Airborne Emission Factor from Composition/Wear Approach					
	A	0.50	0.09	0.70	0.004
	T	0.30	0.10	0.31	0.001
	$B_{HDV,\ disc}$	0.18 axle	0.07 axle	1.4	0.01
	$M_{HDV,\ drum}$	7,000,000 mg/axle	288,000 mg/axle	0.000000013	0.00001
	$M_{HDV,\ disc}$	4,800,000 mg/axle	288,000 mg/axle	0.000000053	0.0002
	f_{HDV}	0.70	0.07	0.50	0.001
	$d_{HDV,\ drum}$	100,000 km	20,000 km	0.00000093	0.0003
	$d_{HDV,\ disc}$	60,000 km	5,000 km	0.0000043	0.0005
	N_{HDV}	6 axles	1 axle	0.016	0.0003
	$C_{Cu,\ HDV,\ drum}$	0.002	0.002	43	0.01
	$C_{Cu,\ HDV,\ disc}$	0.051	0.022	5.0	0.01
	Calculated result (mg Cu/km)				0.3
	Standard uncertainty in calculated result (mg Cu/km)				0.2
	95% confidence interval (mg Cu/km)			0.0	0.7
Airborne Emission Factor from Composition/Emission Factor Approach					
	$EF_{air,\ HDV}$	33 mg/km	5 mg/km	0.0061	0.001
	F_{HDV}	0.83	0.04	0.24	0.00009
	$C_{Cu,\ HDV,\ ave}$	0.007	0.005	27	0.02
	Calculated result (mg Cu/km)				0.2
	Standard uncertainty in calculated result (mg Cu/km)				0.1
	95% confidence interval (mg Cu/km)			-0.1	0.5
Airborne Emission Factor from Tunnel Study Approach					
	$EF_{air,\ Cu,\ all\ vehicles}$	0.53 mg Cu/km	0.06 mg Cu/km	1.1	0.004
	PM_{10} correction	0.91	0.04	0.64	0.0006
	Calculated result (mg Cu/km)				0.58
	Standard uncertainty in calculated result (mg Cu/km)				0.07
	95% confidence interval (mg Cu/km)			0.44	0.72

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 even 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 one-fourth of the total airborne brake wear debris released per mile for 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.

The particle size distribution for this project are 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.

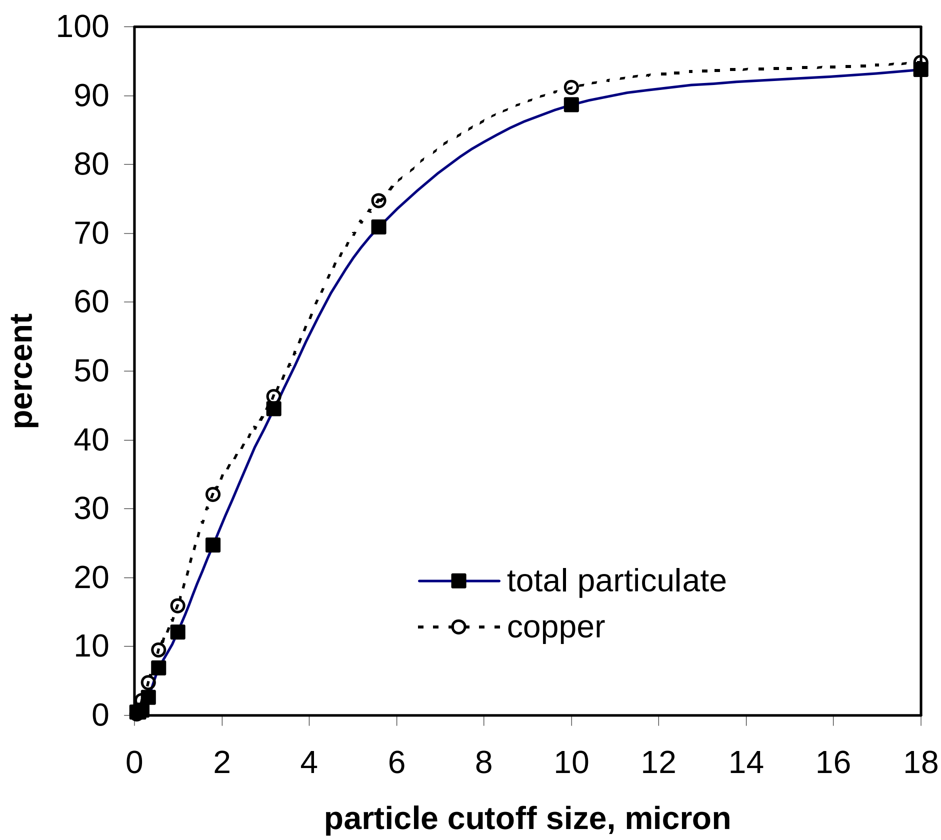

Figure 3-1 Comparison of size distributions for total brake wear and copper brake wear particles (Haselden et al, 2004).

Table 3-1 Brake wear particle size distributions from literature.

	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 PM_{10}	84	98	80	89	91
% of airborne that is PM_{7}		90	60		
% of airborne that is $PM_{4.7}$		82	35		
% of airborne that is $PM_{2.5}$	67				
% of airborne that is $PM_{1.1}$		16	2		
% of airborne that is PM_{1}				12	16
% of airborne that is $PM_{0.43}$		9			
% of airborne that is $PM_{0.1}$	35			0.5	0.25

Table 3-2 Particle size distribution for use in modeling (Haselden et al, 2004; standard errors are from Schlautman, 2005).

Particle Size Cutoff, µm	% of total particulate mass	% of total particulate copper mass
all particles	100.00 ± 5.39	100.00 ± 8.47
< 18	93.80 ± 5.20	94.76 ± 7.91
< 10	88.65 ± 5.02	91.18 ± 7.73
< 5.6	70.88 ± 4.46	74.66 ± 6.72
< 3.2	44.48 ± 3.45	46.23 ± 5.00
< 1.8	24.74 ± 2.87	31.97 ± 3.99
< 1	12.11 ± 2.37	15.76 ± 2.87
< 0.56	6.84 ± 1.76	9.42 ± 1.80
< 0.32	2.62 ± 1.60	4.62 ± 1.55
< 0.18	0.77 ± 1.25	2.01 ± 1.39
< 0.1	0.50 ± 0.73	0.25 ± 1.02
< 0.056	0.50 ± 0.42	0.05 ± 0.61

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 with 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 et al, 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 et al, 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 after initially adhering to the vehicle (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 commercial car washes 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 from vehicles 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

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

$$= 0.08$$

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*.

These estimates assume 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 in the San Francisco Bay area. 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 important 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.

$$\mathrm{EF}_{\mathrm{POTW,\ Cu,\ pass}} = \frac{\mathrm{EF}_{\mathrm{air,\ Cu,\ pass}} W}{A} = \frac{0.58 \frac{\mathrm{mg\ Cu}}{\mathrm{km}}(0.03)}{0.5} = 0.04\ \mathrm{mg\ Cu/km}$$

$$\mathrm{EF}_{\mathrm{POTW,\ Cu,\ MDV}} = \frac{\mathrm{EF}_{\mathrm{air,\ Cu,\ MDV}} W}{A} = \frac{0.58 \frac{\mathrm{mg\ Cu}}{\mathrm{km}}(0.03)}{0.5} = 0.04\ \mathrm{mg\ Cu/km}$$

$$\mathrm{EF}_{\mathrm{POTW,\ Cu,\ HDV}} = \frac{\mathrm{EF}_{\mathrm{air,\ Cu,\ HDV}} W}{A} = \frac{0.58 \frac{\mathrm{mg\ Cu}}{\mathrm{km}}(0.03)}{0.5} = 0.04\ \mathrm{mg\ Cu/km}$$

The standard uncertainty in these values is 0.02 mg Cu/km, and the 95% confidence interval is 0.01 mg Cu/km to 0.07 mg Cu/km. As shown in Table 4-1, 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

$$\begin{aligned}\mathrm{EF}_{\mathrm{road+veh,\ Cu,\ pass}} &= \frac{\mathrm{EF}_{\mathrm{air,\ Cu,\ pass}}}{A} - \mathrm{EF}_{\mathrm{air,\ Cu,\ pass}} - \mathrm{EF}_{\mathrm{POTW,\ Cu,\ pass}} \\ &= \frac{0.58 \frac{\mathrm{mg\ Cu}}{\mathrm{km}}}{0.50} - 0.58 \frac{\mathrm{mg\ Cu}}{\mathrm{km}} - 0.04 \frac{\mathrm{mg\ Cu}}{\mathrm{km}} \\ &= 0.5\ \mathrm{mg\ Cu/km}\end{aligned}$$

$$\begin{aligned}\mathrm{EF}_{\mathrm{road+veh,\ Cu,\ MDV}} &= \frac{\mathrm{EF}_{\mathrm{air,\ Cu,\ MDV}}}{A} - \mathrm{EF}_{\mathrm{air,\ Cu,\ MDV}} - \mathrm{EF}_{\mathrm{POTW,\ Cu,\ MDV}} \\ &= \frac{0.58 \frac{\mathrm{mg\ Cu}}{\mathrm{km}}}{0.50} - 0.58 \frac{\mathrm{mg\ Cu}}{\mathrm{km}} - 0.04 \frac{\mathrm{mg\ Cu}}{\mathrm{km}} \\ &= 0.5\ \mathrm{mg\ Cu/km}\end{aligned}$$

$$\begin{aligned}\mathrm{EF}_{\mathrm{road+veh,\ Cu,\ HDV}} &= \frac{\mathrm{EF}_{\mathrm{air,\ Cu,\ HDV}}}{A} - \mathrm{EF}_{\mathrm{air,\ Cu,\ HDV}} - \mathrm{EF}_{\mathrm{POTW,\ Cu,\ HDV}} \\ &= \frac{0.58 \frac{\mathrm{mg\ Cu}}{\mathrm{km}}}{0.50} - 0.58 \frac{\mathrm{mg\ Cu}}{\mathrm{km}} - 0.04 \frac{\mathrm{mg\ Cu}}{\mathrm{km}} \\ &= 0.5\ \mathrm{mg\ Cu/km}\end{aligned}$$

The uncertainty for these values is 0.2 mg Cu/km, and the 95% confidence interval is 0.1 mg Cu/km to 1.0 mg Cu/km. As shown in Table 4-1, the largest source of uncertainty in these values is the uncertainty in the value for *A*, the airborne wear debris fraction.

Table 4-1 Intermediate values for calculating the uncertainty in emission factors and final emission factor results for releases to POTWs and to the road.

Variables	Value	Uncertainty, $u_{variable}$	*df/d*(variable), evaluated at value	*df/d*(variable)^2 × $u_{variable}^2$
POTW Emission Factor				
$EF_{air, Cu, all vehicles}$ (adjusted for >PM_{10})	0.58 mg Cu/km	0.07 mg Cu/km	0.063	0.00002
W	0.03	0.01	1.2	0.0002
A	0.50	0.09	0.073	0.00004
Calculated result (mg Cu/km)				0.04
Standard uncertainty in calculated result (mg Cu/km)				0.02
95% confidence interval (mg Cu/km)			0.01	0.07
Vehicle + Road Emission Factor				
$EF_{air, Cu, all vehicles}$ (adjusted for >PM_{10})	0.58 mg Cu/km	0.07 mg Cu/km	0.94	0.004
A	0.50	0.09	2.3	0.04
W	0.03	0.01	1.2	0.0002
Calculated result (mg Cu/km)				0.5
Standard uncertainty in calculated result (mg Cu/km)				0.2
95% confidence interval (mg Cu/km)			0.1	1.0

5 Estimates of Copper Releases from Vehicle Brake Pad Lining Wear in the San Francisco Bay Area

The boundaries of the sub-watersheds to be modeled in this project were developed so that they suit the requirements of the models. As a result, the sub-watersheds discussed in this report may be subdivisions or aggregations of actual physical watersheds. References to sub-watersheds or Bay area sub-watersheds throughout this report indicate sub-watersheds as defined for this project. It is important to remember that the goal of the overall project is to estimate total loads to the San Francisco Bay and not to the individual sub-watersheds.

Emissions were estimated separately for each of the 23 sub-watersheds in the Bay watershed. Data on vehicle miles traveled were available by county and the emissions were apportioned to the sub-watersheds using population (from the 2000 census) as a measure of traffic density. In addition, emissions in the Castro Valley watershed were calculated separately for Interstate 580 (which will be treated as a line source during air modeling) and for surface streets (which will be treated as an area source).

This section of the report is divided into two subsections: one on estimates of copper releases in the 23 sub-watersheds in the Bay area and one on estimates of copper releases in the Castro Valley watershed.

The applicability of the emission factor from the tunnel study to the study area depends somewhat on the similarity in the mix of vehicles observed while the tunnel study was being conducted and in the inventory area. In the tunnel study, the fleet mix averaged 97.4% light-duty vehicles and 2.6% heavy-duty vehicles. In the San Francisco Bay area, the fleet mix in 2003 was 14% heavy-duty vehicles (see Appendix C).

Note that the difference in copper emitted by the various vehicle categories is not well-understood. Larger vehicles generally emit more brake wear debris, but this is offset by the fact that larger vehicles use brake lining materials that contain a lower concentration of copper than light-duty vehicles. Larger vehicles are also more likely to be equipped with drum brakes than are light-duty vehicles, and some brake wear debris is trapped in the drum rather than being emitted.

5.1 Estimates of Releases in the Sub-Watersheds

A map of the 23 sub-watersheds contained in the San Francisco Bay watershed is shown in Figure 5.1-1. Note that San Francisco County drains almost exclusively to the ocean as opposed to the Bay and is not within the San Francisco Bay watershed. However, air emissions of copper in San Francisco County have a high potential for transport to the Bay or to portions of the Bay area that drain to the Bay and are included in the inventory. Also, a very small portion of Santa Cruz County falls within the watershed. This area was neglected when creating this inventory. Thus, the 9-county region that is referred to in this report includes the following counties: San Francisco, San Mateo, Santa Clara, Alameda, Contra Costa, Solano, Napa, Sonoma, and Marin Counties.

Vehicle miles traveled for each of the nine counties in the Bay area are given in Table 5.1-1. Two sources of data estimates are presented in this table: 1) the Bay Area Air Quality Management District (BAAQMD), and 2) the Metropolitan Transportation Commission (MTC). Total vehicle miles traveled in the 9-county area as reported by these two agencies differs by approximately 13%. However, the difference between MTC estimates and BAAQMD estimates for San Francisco County in particular is quite large. This variation provides a glimpse into the uncertainty in these values.

For the purposes of estimating copper emissions from brake lining materials, the point value for each county was the midpoint of the BAAQMD and the MTC values. The true value was assumed to have a 100% probability of lying within 20% of that point value. Thus, the standard uncertainty in vehicle miles traveled in each county is assumed to be 12% of the point value.

Population estimates for the counties differ as well, but not as widely as estimates of vehicle miles traveled. As long as consistent data for sub-watershed and county populations are used, the uncertainty in population can be assumed to be insignificant. More important is the uncertainty introduced when assigning vehicle miles traveled based on population within the sub-watersheds. Figure 5.1-2 provides insight into the reasonableness of using per capita values within the counties to estimate vehicle miles traveled in each of the sub-watersheds in the Bay area. This figure shows that for the counties, vehicle miles traveled correlates very well with population. The only counties that do not closely follow a linear curve fit for population versus vehicle miles traveled are San Francisco County and San Mateo County. As Table 5.1-1 shows, these two counties had the highest discrepancy between the two sources of data on vehicle miles traveled.

The actual value for per capita vehicle miles traveled within each sub-watershed was assumed to have a 100% probability of falling within 20% of the per capita value for the county as a whole. Thus, the standard uncertainty in assigning vehicle miles traveled to the sub-watersheds is assumed to be 12% of each sub-watershed's per capita value.

Table 5.1-2 gives estimated vehicle miles traveled by sub-watershed in the San Francisco Bay area. These values were used to estimate airborne copper from brake lining wear, found in Table 5.1-3, and releases of copper from brake lining wear to roadways, found in Table 5.1-4. Tables 5.1-3 and 5.1-4 provide the results in English and metric units and show the values for standard uncertainty in the estimates, along with the 95% confidence intervals for each of the sub-watersheds.

Figure 5.1-1 Sub-watersheds in the San Francisco Bay watershed (URS, 2005).

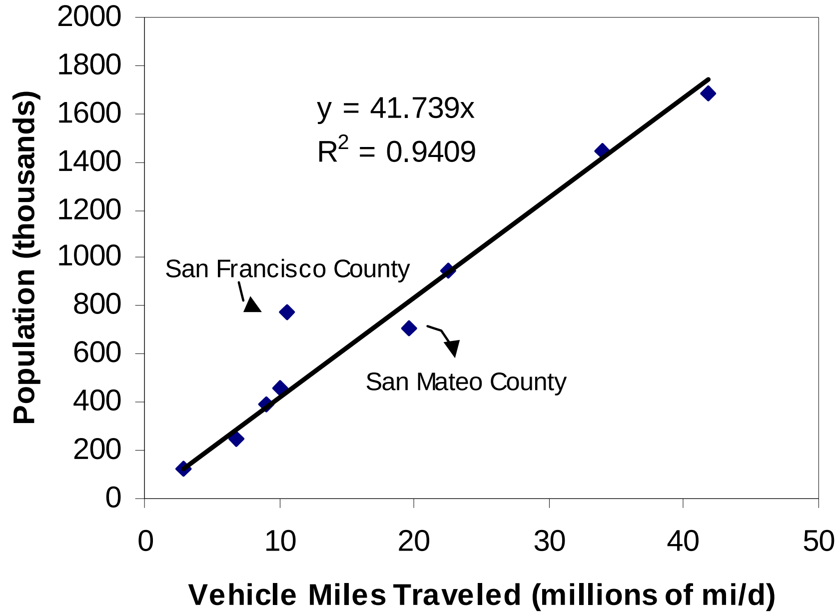

Figure 5.1-2 Vehicle miles traveled and population for each of the nine counties in the San Francisco Bay area.

Table 5.1-1 Vehicle miles traveled in the San Francisco Bay area in 2003.

County	Total Daily Vehicle Miles Traveled				
	MTC[1]	BAAQMD[2]	% Difference	Midpoint	Standard Uncertainty
Alameda	33,831,600	34,200,000	1	34,015,800	3,927,806
Contra Costa	19,638,950	25,400,000	29	22,519,475	2,600,325
Marin	6,671,350	7,000,000	5	6,835,675	789,316
Napa	2,653,150	3,200,000	21	2,926,575	337,932
San Francisco	8,145,150	13,000,000	60	10,572,575	1,220,816
San Mateo	16,797,650	22,500,000	34	19,648,825	2,268,851
Santa Clara	38,409,200	45,200,000	18	41,804,600	4,827,179
Solano	11,162,300	7,000,000	37	9,081,150	1,048,601
Sonoma	10,485,250	9,700,000	7	10,092,625	1,165,396
Total Bay Area	147,794,600	167,200,000	13	157,497,300	18,186,222

[1]MTC, 2005; values are an average of 2000 and projected 2006 weekday values.
[2]BAAQMD, 2004.

Table 5.1-2 Estimated vehicle miles traveled per day in 2003 in San Francisco Bay area sub-watersheds (based on population in the sub-watershed and vehicle miles traveled in the counties).

Watershed	Sonoma	Solano	Santa Clara	San Mateo	San Francisco	Napa	Marin	Contra Costa	Alameda	Total for Sub-Watershed
Upper Alameda	0	0	5,536	0	0	0	0	1,141,698	4,036,487	5,183,721
Santa Clara Valley Central	0	0	8,637,517	0	0	0	0	0	0	8,637,517
Castro Valley	0	0	0	0	0	0	0	0	825,162	825,162
East Bay North	0	0	0	0	0	0	0	2,018,503	3,742,683	5,761,186
Upper Colma	0	0	0	2,342,830	0	0	0	0	0	2,342,830
Marin South	0	0	0	0	0	0	3,460,252	0	0	3,460,252
Coyote	0	0	14,190,406	0	0	0	0	0	0	14,190,406
East Bay Central	0	0	0	0	0	0	0	433,977	20,196,544	20,630,521
East Bay South	0	0	43,454	0	0	0	0	0	4,327,302	4,370,756
Solano West	0	3,964,342	0	0	0	12,235	0	0	0	3,976,577
Napa	42	2,476,919	0	0	0	2,257,167	0	0	0	4,734,128
North Napa	174	0	0	0	0	588,644	0	0	0	588,818
North Sonoma	218,460	0	0	0	0	46	0	0	0	218,505
Marin North	0	0	0	0	0	0	2,227,477	0	0	2,227,477
Contra Costa Central	0	0	0	0	0	0	0	11,182,715	54	11,182,769
Petaluma	1,463,560	0	0	0	0	0	81,439	0	0	1,544,999
Santa Clara Valley West	0	0	16,639,687	1,236,781	0	0	0	0	0	17,876,469
Upper San Lorenzo	0	0	0	0	0	0	0	42	817,942	817,984
Contra Costa West	0	0	0	0	0	0	0	3,976,650	27,786	4,004,435
Peninsula Central	0	0	0	12,708,383	0	0	0	0	0	12,708,383
Sonoma	722,567	0	0	0	0	35	0	0	0	722,602
Upper San Francisquito	0	0	3,642	305,580	0	0	0	0	0	309,222
Upper Corte Madera	0	0	0	0	0	0	702,518	0	0	702,518
City of San Francisco	0	0	0	0	10,572,575	0	0	0	0	10,572,575
Watershed Total Within County	2,404,803	6,441,261	39,520,243	16,593,574	0	2,858,127	6,471,686	18,753,585	33,973,958	127,017,237
County Total	10,092,625	9,081,150	41,804,600	19,648,825	10,572,575	2,926,575	6,835,675	22,519,475	34,015,800	157,497,300

Table 5.1-3 Estimated airborne copper emissions from brake lining wear in 2003 in San Francisco Bay area sub-watersheds.

Watershed	kg/y				lb/yr			
	Airborne copper released	Standard uncertainty in airborne copper released	95% Confidence Interval		Airborne copper released	Standard uncertainty in airborne copper released	95% Confidence Interval	
			from	to			from	to
Upper Alameda	1,772	360	1,051	2,493	3,898	793	2,313	5,484
Santa Clara Valley Central	2,953	601	1,752	4,154	6,496	1,321	3,853	9,138
Castro Valley	282	57	167	397	621	126	368	873
East Bay North	1,969	401	1,168	2,771	4,333	881	2,570	6,095
Upper Colma	801	163	475	1,127	1,762	358	1,045	2,479
Marin South	1,183	241	702	1,664	2,602	529	1,544	3,661
Coyote	4,851	987	2,878	6,824	10,672	2,171	6,331	15,013
East Bay Central	7,052	1,434	4,184	9,921	15,515	3,156	9,204	21,827
East Bay South	1,494	304	886	2,102	3,287	669	1,950	4,624
Solano West	1,359	276	806	1,912	2,991	608	1,774	4,207
Napa	1,618	329	960	2,277	3,560	724	2,112	5,009
North Napa	201	41	119	283	443	90	263	623
North Sonoma	75	15	44	105	164	33	97	231
Marin North	761	155	452	1,071	1,675	341	994	2,357
Contra Costa Central	3,823	778	2,268	5,378	8,410	1,711	4,989	11,831
Petaluma	528	107	313	743	1,162	236	689	1,635
Santa Clara Valley West	6,111	1,243	3,625	8,597	13,444	2,734	7,975	18,913
Upper San Lorenzo	280	57	166	393	615	125	365	865
Contra Costa West	1,369	278	812	1,926	3,012	613	1,787	4,237
Peninsula Central	4,344	884	2,577	6,111	9,557	1,944	5,670	13,445
Sonoma	247	50	147	347	543	111	322	764
Upper San Francisquito	106	21	63	149	233	47	138	327
Upper Corte Madera	240	49	142	338	528	107	313	743
City of San Francisco	3,614	735	2,144	5,084	7,951	1,617	4,717	11,186
Watershed Total (Parts of 8 Counties)	43,420	8,831	25,758	61,082	95,524	19,429	56,667	134,381
9-County Total	53,839	10,950	31,939	75,740	118,447	24,091	70,265	166,628

Table 5.1-4 Estimated copper releases to roadways from brake lining wear in 2003 in San Francisco Bay area sub-watersheds.

Watershed	kg/y				lb/yr			
	Copper released to roadways	Standard uncertainty in copper released to roadways	95% Confidence Interval		Copper released to roadways	Standard uncertainty in copper released to roadways	95% Confidence Interval	
			from	to			from	to
Upper Alameda	1,661	685	291	3,032	3,655	1,507	640	6,670
Santa Clara Valley Central	2,768	1,142	485	5,052	6,090	2,512	1,066	11,113
Castro Valley	264	109	46	483	582	240	102	1,062
East Bay North	1,846	762	323	3,369	4,062	1,675	711	7,413
Upper Colma	751	310	131	1,370	1,652	681	289	3,014
Marin South	1,109	457	194	2,024	2,440	1,006	427	4,452
Coyote	4,548	1,876	796	8,299	10,005	4,126	1,752	18,258
East Bay Central	6,612	2,727	1,158	12,065	14,546	5,999	2,547	26,544
East Bay South	1,401	578	245	2,556	3,082	1,271	540	5,624
Solano West	1,274	526	223	2,326	2,804	1,156	491	5,116
Napa	1,517	626	266	2,769	3,338	1,377	585	6,091
North Napa	189	78	33	344	415	171	73	758
North Sonoma	70	29	12	128	154	64	27	281
Marin North	714	294	125	1,303	1,570	648	275	2,866
Contra Costa Central	3,584	1,478	628	6,540	7,884	3,252	1,381	14,388
Petaluma	495	204	87	904	1,089	449	191	1,988
Santa Clara Valley West	5,729	2,363	1,003	10,455	12,604	5,198	2,207	23,001
Upper San Lorenzo	262	108	46	478	577	238	101	1,052
Contra Costa West	1,283	529	225	2,342	2,823	1,164	494	5,152
Peninsula Central	4,073	1,680	713	7,432	8,960	3,696	1,569	16,351
Sonoma	232	96	41	423	509	210	89	930
Upper San Francisquito	99	41	17	181	218	90	38	398
Upper Corte Madera	225	93	39	411	495	204	87	904
City of San Francisco	3,388	1,397	593	6,183	7,454	3,074	1,305	13,603
Watershed Total (Parts of 8 Counties)	40,706	16,789	7,128	74,284	89,554	36,936	15,682	163,425
9-County Total	50,474	20,818	8,839	92,110	111,044	45,799	19,446	202,642

5.2 Estimates of Releases in the Castro Valley Watershed

A street map of the Castro Valley watershed, which is shaped somewhat like the silhouette of a hitchhiker's hand, is given in Figure 5.2-1. As this map shows, Interstate 580 passes through the southern portion of the watershed. Table 5.2-1 gives traffic counts and mileage between traffic counting locations for this 1.6-mile long stretch of freeway that lies within the watershed. Note that traffic count data was not available for Interstate 580 at the western border of the watershed. This border lies approximately halfway between the Strobridge Avenue traffic count location and the traffic count location at the intersection of the 580 with the 238. Therefore, the distance and traffic count values for the western boundary are an average of those two locations.

The total vehicle miles traveled per day on the portion of Interstate 580 that lies within the Castro Valley watershed is 500,000. The standard uncertainty for this value is 60,000 mi/d. Multiplying this value by the air emission factor for copper from brake linings results in an estimate of air releases of 170 kg Cu/y with a standard uncertainty of 30 kg Cu/y (370 lb Cu/yr with a standard uncertainty of 60 lb Cu/yr) from brake lining materials. The 95% confidence interval for this estimate is 110 to 230 kg Cu/y (250 to 500 lb/yr). Estimated releases of copper to roadways from brake lining material are 160 kg/y with a standard uncertainty of 60 kg/y (400 lb/yr with a standard uncertainty of 100 lb Cu/yr). The 95% confidence interval for this estimate is 30 to 290 kg/y (70 to 630 lb/yr).

Estimates of vehicle miles traveled on surface streets in the Castro Valley watershed were made using data on road segment-based average daily traffic volume found in the 2000 Alameda County road index report (Alameda County, 2002). As shown in Table 5.2-2, this data provides traffic counts as a range of values from A (0-2000 vehicles per day) to L (more than 40,000 vehicles per day). For the three road segments in the Castro Valley watershed that had a traffic volume of category L, up-to-date traffic count data were used to provide a point value for traffic volume (Alameda County, 2005). If no traffic volume code was given in the road index report, the road segment was assumed to have less than 2000 vehicles per day. The standard uncertainty in each road segment length was assumed to be 0.0005 mi (road segment lengths are given to the nearest thousandth of a mile in the road index report). Standard uncertainties in traffic volume are given in Table 5.2-2.

More than 700 road segments within the Castro Valley watershed were identified in the Alameda County road index. Twenty-seven road segments shown on the street map were not found in either the private or public section of the road index report. These may be roads that were built recently. In any case, they represent a small fraction of the total number of road segments (less than 4%) and were neglected.

There are nearly 90 miles of surface streets in the Castro Valley watershed, two-thirds of which have a traffic volume of less than 2000 vehicles per day (category A). The total estimated surface street vehicle miles traveled per day in the Castro Valley watershed is 283,000, with a standard uncertainty of 7,000. Table 5.2-2 provides total surface street vehicle miles traveled by traffic density for the Castro Valley watershed. This table also gives estimates for vehicle miles traveled and the uncertainty in vehicle miles traveled.

Multiplying the vehicle miles traveled by the air emission factor for copper from brake linings results in an estimate of air releases of 100 kg Cu/y (210 lb Cu/yr) from brake lining materials due to traffic on surface streets. The 95% confidence interval for this estimate is 70 to 120 kg Cu/y (160 to 270 lb/yr). Estimated releases of copper from brake lining materials direct to surface streets in the Castro Valley watershed are 90 kg/y (200 lb/yr). The 95% confidence interval for this estimate is 20 to 130 kg/y (50 to 350 lb/yr).

Note that the uncertainty in distributing vehicle miles traveled by population does not apply to these estimates.

These estimates for vehicle miles traveled can be compared to the estimate that would be obtained by apportioning vehicle miles traveled in Alameda County by population, as was discussed in Section 5.1. Apportioning total vehicle miles traveled by population within the watershed provides an estimate that is meant to include all vehicle miles traveled whether they are on surface streets or major freeways. The Castro Valley watershed has a population of 35,045, while total population in Alameda County is 1,443,741. The estimated vehicle miles traveled in Alameda County are 34,015,800 mi/d. Thus, the estimated vehicle miles traveled in the Castro Valley watershed based on population are 825,691 mi/d. This results in an estimate of airborne copper from vehicle brake linings of 280 kg/y, with a standard uncertainty of 60 kg/y and a 95% confidence interval from 170 to 400 kg/y. The estimated airborne copper releases from estimates of total vehicle miles traveled that were calculated using traffic counts for I580 and traffic density data for surface streets are 270 kg/y with a standard uncertainty of 30 kg/yr. Thus, there is excellent agreement between the two strategies for calculating airborne copper emissions in the Castro Valley watershed. This suggests that apportioning vehicle miles traveled based on population is reasonable.

Table 5.2-3 summarizes copper releases from vehicle brake lining materials in the Castro Valley watershed.

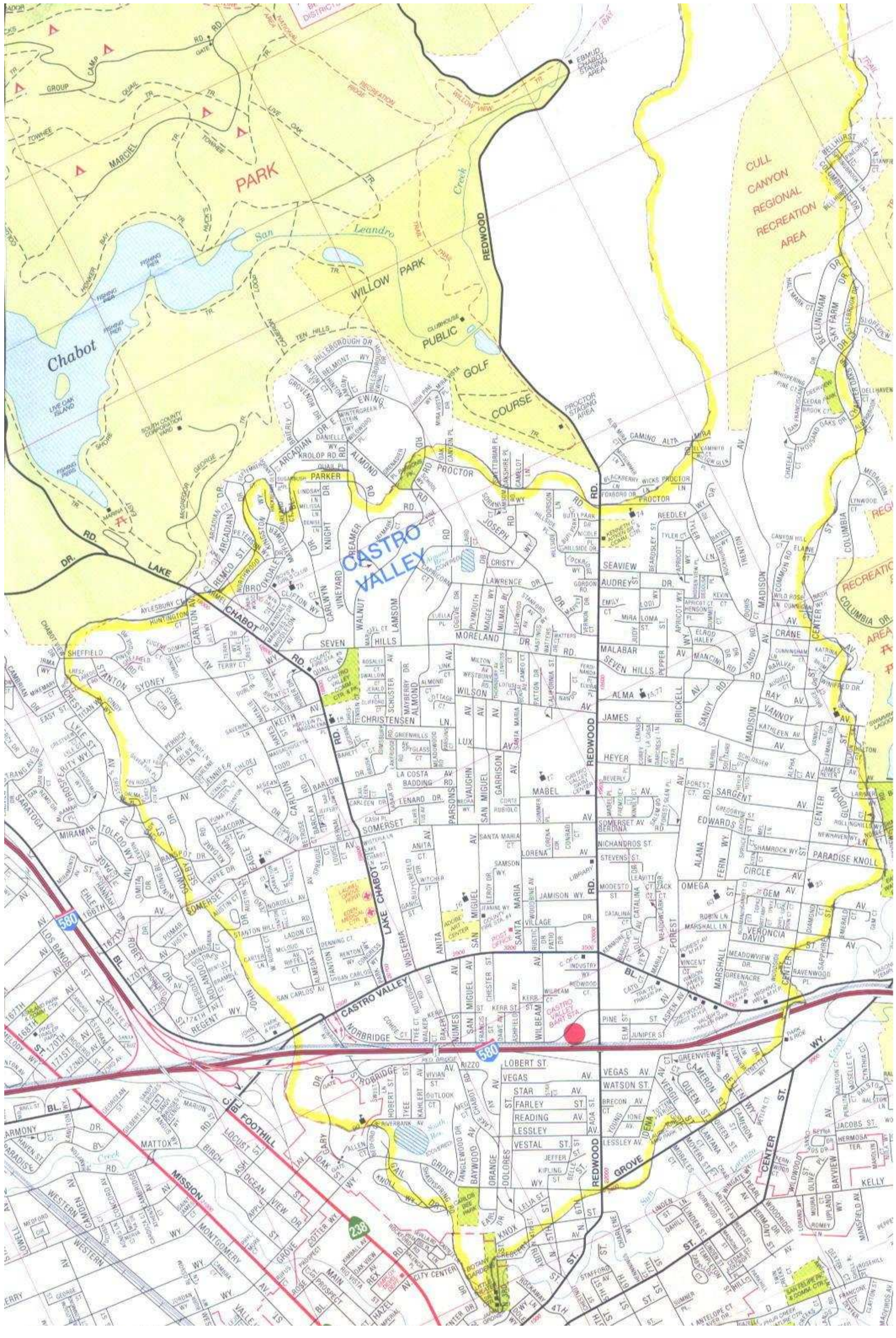

Figure 5.2-1 A street map of the Castro Valley watershed. The watershed boundary is outlined in yellow. (California Automobile Association, 2002; Feng, 2005).

Table 5.2-1 Traffic count and mileage information for the portion of Interstate 580 that lies within the Castro Valley watershed (CA DOT, 2005).

Segment of Interstate 580	Miles	Annual Average Daily Traffic Headed West (# of Vehicles)	Annual Average Daily Traffic Headed East (# of Vehicles)	Vehicle Miles Traveled per Day Headed West	Vehicle Miles Traveled per Day Headed East	**Total Vehicle Miles Traveled per Day**
from eastern edge of watershed (Center St.) to Redwood Rd.	0.4	148,500	155,500	59,400	62,200	121,600
from Redwood Rd. to Strobridge Ave.	0.98	155,500	155,500	152,390	152,390	304,780
from Strobridge Ave. to western edge of watershed	0.23	159,250	147,500	36,627	33,925	70,552
from eastern edge of watershed to western edge of watershed	1.6			248,418	248,515	**496,933**

Table 5.2-2 Traffic density data and vehicle miles traveled on surface streets in the Castro Valley watershed.

Traffic Density Category	Total Mileage for Traffic Category	Range of Traffic Density for this Category	Traffic Density Point Value	Standard Uncertainty in Traffic Density	Number of Road Segments	Vehicle Miles Traveled per Day	Standard Uncertainty in Vehicle Miles Traveled per Day
A	60.202	<2,000	1,000	577	629	60,202	1,904
B	10.395	2,000-4,000	3,000	1,155	44	31,184	2,474
C	1.296	4,000-6,000	5,000	1,155	7	6,480	697
D	3.706	6,000-8,000	7,000	1,155	10	25,939	1,584
E	0.544	8,000-10,000	9,000	1,155	1	4,896	628
F	1.984	10,000-15,000	12,500	2,887	6	24,794	3,018
G	2.204	15,000-20,000	17,500	2,887	6	38,577	3,117
H	0.587	20,000-25,000	22,500	2,887	1	13,208	1,695
I	0.452	25,000-30,000	27,500	2,887	2	12,428	1,181
J	0.972	30,000-35,000	32,500	2,887	2	31,590	2,193
K	0.426	35,000-40,000	37,500	2,887	2	15,975	1,210
L	0.182	>40,000	54,246	5,774	1	9,878	1,576
L	0.083	>40,000	41,898	5,774	1	3,457	635
L	0.115	>40,000	36,646	5,774	1	4,229	999
TOTAL	83.147				713	282,835	6,811

Table 5.2-3 Estimated copper releases from brake lining materials in the Castro Valley watershed. Amounts are in kg Cu/y.

Release to	Value		Interstate 580	Surface Streets	Total Based on Traffic Density VMT*	Total Based on Population-Weighted VMT*
Air						
	Estimated releases		170	100	270	280
	Uncertainty		30	10	30	60
	95% Confidence interval	Low	110	70	200	170
		High	230	120	330	400
Roadway						
	Estimated releases		160	90	250	300
	Uncertainty		60	30	70	100
	95% Confidence interval	Low	30	20	60	50
		High	290	130	420	500

*Vehicle miles traveled.

6 Nomenclature

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

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

Table A-1 Summary of values and standard uncertainties in values used to calculate air emission factors 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 et al, 2003.	airborne emissions 8.2-8.3 mg/stop/brake for low-met brakes used on mid-sized car, 2 mg/stop/brake for semimet brakes on full-sized truck (2 runs), 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 et al, 1983; Trainor, 2001; Abu-Allaban, 2003)
Mass of brake lining material on a disc-equipped passenger vehicle axle ($M_{pass, disc}$)	Brake Pad Partnership, 2004; 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 et al, 2000; Armstrong, 1994).
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 source for US values (Miller, 2004)

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
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).
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 multiplying 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 – the "black box" pads they measured had copper concentrations of 2.3 and 2.45%.	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

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 wear debris that is brake lining material, (F_{pass})	Link, 2004b.	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	these are the 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 brake pads designed to be representative; agrees with other researchers (Link, 2004a; Sanders et al, 2003), disagrees slightly with Trainor, 2001
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; 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 Cu/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 emission 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 between HDV, MDV, and passenger vehicles. No correction for resuspended road dust. PM10 only. Deposition not discussed. Average fleet mix was 97.4% LD and 2.6% HD. Over 30,000 vehicles pass through the tunnel during the study runs.	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 A-2 Summary of values and standard uncertainties in values used to calculate air emission factors 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 and Boulter, 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, 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, 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, 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, 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, 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.
Tunnel study emission factors for copper from HDVs, lb Cu/mi ($EF_{air,\ Cu,\ HDV}$)	Gillies et al, 2001.	.53+-.06 mg/km; no breakdown of resuspended vs. direct; this is for PM10	530	ug Cu/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 emission 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. Average fleet mix was 97.4% LD and 2.6% HD. Over 30,000 vehicles pass through the tunnel during the study runs.	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

Table A-3 Summary of values and standard uncertainties in values used to calculate air emission factors 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 and Boulter, 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, 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
Mass of brake lining material on a drum-equipped HDV axle ($M_{HDV, drum}$)	Westerlund, 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

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 disc-equipped HDV axle ($M_{HDV, disc}$)	Westerlund, 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
Fraction of brake lining material worn off at replacement (f_{HDV})	Westerlund, 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, 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, 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, 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, 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., 2004b.	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 brake pads designed to be representative; agrees with other researchers (Link, 2004a; Sanders et al, 2003), disagrees slightly with Trainor, 2001
Tunnel study emission factors for copper from HDVs, lb Cu/mi ($EF_{air, Cu, HDV}$)	Gillies et al, 2001.	.53+-.06 mg/km; no breakdown of resuspended vs. direct; this is for PM10	530	ug Cu/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 emission 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 between HDV, MDV, and passenger vehicles. No correction for resuspended road dust. PM10 only. Average fleet mix was 97.4% LD and 2.6% HD. Over 30,000 vehicles pass through the tunnel during the study runs.	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

Appendix B Abstract from Gillies et al, 2001

Abstract from: Gillies, JA, AW Gertler, JC Sagebiel, WA Dippel. On-road particulate matter ($PM_{2.5}$ and PM_{10}) emissions in the Sepulveda Tunnel, Los Angeles, CA. *Environ. Sci. Technol.* 35, 1054-1063. 2001.

Total and speciated particulate matter ($PM_{2.5}$ and PM_{10}) emission factors from in-use vehicles were measured for a mixed light- (97.4% LD) and heavy-duty fleet (2.6% HD) in the Sepulveda Tunnel, Los Angeles, CA. Seventeen 1-h test runs were performed between July 23, 1996, and July 27, 1996. Emission factors were calculated from mass concentration measurements taken at the tunnel entrance and exit, the volume of airflow through the tunnel, and the number of vehicles passing through the 582 m long tunnel. For the mixed LD and HD fleet, $PM_{2.5}$ emission factors in the Sepulveda Tunnel ranged from 0.016 (±0.007) to 0.115 (±0.019) g/vehicle·km traveled with an average of 0.052 (±0.027) g/vehicle·km. PM_{10} emission factors ranged from 0.030 (±0.009) to 0.131 (±0.024) g/vehicle·km with an average of 0.069 (±0.030) g/vehicle·km. The $PM_{2.5}$ emission factor was ~74% of the PM_{10} factor. Speciated emission rates and chemical profiles for use in receptor modeling were also developed. $PM_{2.5}$ was dominated by organic carbon (OC) (31.0 ± 19.5%) and elemental carbon (EC) (48.5 ± 20.5%) that together account for 79% (±24%) of the total emissions. Crustal elements (Fe, Mg, Al, Si, Ca, and Mn) contribute ~7.8%, and the ions Cl^-, NO_3^-, NH_3^+, SO_4^{2-}, and K^+ together constitute another 9.8%. In the PM_{10} size fraction the particulate emissions were also dominated by OC (31 ± 12%) and EC (35 ± 13%). The third most prominent species was Fe (18.5 ± 9.0%), which is greater than would be expected from purely geological sources. Other geological components (Mg, Al, Si, K, Ca, and Mn) accounted for an additional 12.6%. PM_{10} emission factors showed some dependence on vehicle speed, whereas $PM_{2.5}$ did not. For test runs in which the average vehicle speed was 42.6 km/h a 1.7 times increase in PM_{10} emission factor was observed compared to those runs with an average vehicle speed of 72.6 km/h. Speciated emissions were similar. However, there is significantly greater mass attributable to geological material in the PM_{10}, indicative of an increased contribution from resuspended road dust. The $PM_{2.5}$ shows relatively good correlation with NO_x emissions, which indicates that even at the low percent of HD vehicles, which emit significantly more NO_x than LD vehicles, they may also have a significant impact on the $PM_{2.5}$ levels.

Appendix C Vehicle Miles Traveled by Vehicle Category

The Sepulveda Tunnel study was of a mixed fleet consisting of 2.6% heavy-duty and 97.4% light-duty vehicles. The definition of light-duty vehicles applied here includes only passenger vehicles; the heavy-duty vehicles category includes every other category of vehicle including medium-duty vehicles (Gertler, 2005b).

Table C-1 shows the vehicle category distribution of vehicle miles traveled in the Bay watershed. The fraction of vehicle miles traveled by vehicles that are heavy-duty according to Gillies' definition in the Bay watershed is 14%. Thus, the vehicle fleet distributions in the Sepulveda Tunnel and in the Bay watershed are substantially different.

Table C-1 Vehicle miles traveled by vehicle category in the San Francisco Bay watershed.

County	Vehicle Miles Traveled (in thousands) (Fanai, 2005)						Fraction of County's Population in Watershed	Vehicle Miles Traveled in Watershed, Adjusted by Population and to Include Buses and Motorcycles	
	Light-Duty Vehicles	Medium-Duty Vehicles	Heavy-Duty Vehicles	Buses	Motorcycles	Total		Light-Duty Vehicles	Heavy-Duty Vehicles*
Alameda	28,084	2,324	2,696	237	111	33,452	0.999	28,822,035	5,151,923
Contra Costa	22,043	1,979	1,325	163	87	25,597	0.833	16,309,041	2,444,543
Marin	5,960	836	334	71	29	7,230	0.947	5,409,713	1,061,974
Napa	2,708	274	297	22	15	3,316	0.977	2,360,417	497,710
San Francisco	10,146	1,000	1,183	230	66	12,625	1.000	8,700,571	1,872,004
San Mateo	19,411	1,882	1,228	123	78	22,722	0.804	13,612,496	2,180,973
Santa Clara	38,959	3,294	2,643	171	162	45,229	0.945	34,294,127	5,226,115
Solano	6,151	426	420	61	24	7,082	0.709	5,662,455	778,806
Sonoma	8,037	742	724	35	36	9,574	0.238	2,033,821	370,982
Total	141,503	12,754	10,852	1,113	607	166,829		117,204,676	19,585,030

*This includes all non-passenger vehicles, for comparison to the vehicle fleet description given in Gillies et al, 2001.