# Work Plan for Estimating Copper Emissions from Brake Lining Wear in Alameda County

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# 1 Introduction

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

The size of the particles that are released to air is important because it determines to a large extent what the fate of the air emissions will be. A particle size distribution provides information on the fraction of air releases that fall into each particle size range.

One of the common components of brake lining material is copper. The quantity of copper that is released from brake lining wear is not well understood. This document describes a work plan for estimating the quantity and partitioning of copper emissions from brake lining wear in Alameda County. This work plan will include the particle size distribution of copper releases to air from brake lining wear.

The overall approach for estimating copper from brake lining wear will be to apply emission factors. In this case, the emission factor would be expressed as mass of copper per vehicle mile traveled. This work plan describes how emission factors will be developed for five vehicle categories: 1) passenger cars and light-duty trucks, 2) medium-duty vehicles, 3) heavy-duty vehicles, 4) buses, and 5) motorcycles.

In general, several emission factors will be available or will be calculable for each category of vehicle. In some cases, it will be possible to adjust an existing emission factor so that it more accurately reflect conditions in Alameda County.

As described in this work plan, one emission factor for each vehicle category will be selected for use in conducting the inventory of copper releases from brake lining materials, based on its current applicability in Alameda County. The remaining emission factors will aid in determining the upper and/or lower bounds of emissions for that vehicle category and will provide a gauge of the accuracy of the selected emission factor.

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

Once the emission factors are developed, they will be multiplied by the number of vehicle miles traveled in Alameda County in order to estimate releases from brake lining wear.

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

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

A number of assumptions must be made in order to conduct this inventory of environmental releases. Assumptions as stated in this work plan will be tested using sensitivity analyses of the final values. Similarly, sensitivity analyses will also be used to test the effect of potential errors in referenced values on the final results. When there is more than one source of data for a given value that is needed for calculations, the value contained in the reference that is judged to be superior in terms of factors including peer-review of the reference, geography, sample size, and timeliness will be used. If several values are available in different references that are determined to be of equal quality, an average value will be used in calculations. A sensitivity analysis will be conducted across the range of reasonable possible values by observing the effect on the final results when the highest reported value from all reasonable data sources is used and when the lowest reported value from all reasonable data sources is used. If the final result is fairly steady across the range of reported values, then more confidence can be placed in its accuracy. If the final result varies widely across the range of reported values, then further rationale in determining a defensible value is necessary.

# 2 Development of Air Emission Factors for Copper from Brake Lining Wear

Air emissions from brake lining wear have been studied extensively and measured independently of total brake lining wear by many researchers.

There are essentially four categories of information that can be 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 will be 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 will be referred to as the composition/wear approach)
4) laboratory studies of copper emissions from brake lining wear

It is not possible to assess whether laboratory studies of copper emissions from brake lining wear have included brake lining samples that are representative of brake linings that are in use. Therefore, the latter option will not be used in developing emission factors for copper from brake lining wear. These studies are instead useful for determining particle size distributions and brake lining wear partitioning between the air, roadway, and vehicle.

Studies of emissions in roadway tunnels provide an extremely valuable source of information on real-world emissions from mobile sources. A major advantage of tunnel studies is that they measure emission rates averaged over many vehicles. Because brake lining composition and wear rate information is extremely limited, tunnel studies may provide the best possible information available on copper emissions from brake lining wear.

The results of tunnel studies have been used since the late 1980s to verify the accuracy of mobile source emission estimation models. Tunnels can offer a well-defined sampling environment largely protected from weather and non-mobile pollutant sources. Information on the flow rate of air through a tunnel along with the concentration of pollutants in the entrances and exits can be combined with information on vehicle counts and the length of the tunnel in order to arrive at emission factors for the pollutants. However, not many tunnel studies measuring copper have been completed, and tunnel studies do not provide insight into the factors that may influence emissions. Also, traffic conditions in Alameda County might result in different brake pad wear rates per mile than were encountered in the tunnel studies. Therefore, tunnel studies and both of the composition-based approaches will be used to develop emission factors for air releases of copper from brake linings.

## 2.1 Passenger Cars and Light-Duty Trucks

Three categories of information that can be used to derive air emission factors for copper from brake lining wear will be used in conducting the inventory. Emission factors derived from tunnel studies comprise one category. Another category consists of existing air emission factors for brake lining debris combined with lining composition information. The final category consists of emission factors based on the wear rate of brake linings, their composition, and the fraction of wear debris that partitions to air.

### *2.1a Tunnel Studies*

Copper emission factors for passenger vehicles have been developed from tunnel studies. In completing the inventory of copper releases from brake lining materials, emission factors for copper from passenger vehicles taken from tunnel studies conducted in the United States will be compiled. Factors that determine which of the tunnel studies most closely mimic the traffic conditions in Alameda County will be assessed.

Because it is not known whether the formulation of brake linings used in vehicles in Europe matches the formulation of brake linings in the United States, emission factors from tunnel studies conducted in Europe will not be used to develop the emission factor for this project. However, they will be assessed to see if the relative differences between values provide information helpful in gauging the effect of traffic conditions and other variables on emission factors.

There is evidence that factory-installed brake linings in passenger vehicles contain more copper than replacement brake linings and if the tunnel studies are conducted in a region where the vehicle age profile is markedly different than Alameda County, the emission factors from the tunnel studies might need to be adjusted. A separate factor that must be taken into consideration is the year during which the tunnel studies were conducted, as the copper content of brake lining materials in passenger vehicles tends to fluctuate over time.

### *2.1b Composition-Based Approaches*

In essence, both of the composition-based approaches consist of multiplying an emission factor for total air releases from brake lining wear by the copper fraction in the brake lining material in order to arrive at an emission factor for copper releases to air from brake lining wear. The air emission factor used can be taken from reported measured values or calculated based on brake lining wear rate and partitioning information.

**Estimating the Copper Content of Passenger Vehicle Brakes:** 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. The mass fraction of copper of disc brakes and drum brakes will be found separately.

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. It will be assumed that 90% of drum brake wear is trapped as dust in the drum.

Aftermarket brakes and in some cases even original equipment service brakes tend to contain less copper than factory brakes because copper is a relatively expensive material. Because of this, it will be assumed that 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 will be collected separately from information on mass fractions of copper in passenger vehicles that are not factory equipped. From this point forward, it will be understood that new-disc passenger vehicles still have the brake pads they were equipped with at the factory, and that new-drum passenger vehicles still have the brake shoes they were equipped with at the factory. Old-disc passenger vehicles are those that have replaced their factory disc brakes, and old-drum passenger vehicles are those that have replaced their factory drum brakes. Note that a vehicle can be both old-disc and new-drum, because disc brakes have a shorter life than drum brakes. Drum brake linings are typically replaced half as often as disc brake linings.

For the purposes of the inventory, whether a vehicle is equipped with factory disc brakes and/or factory drum brakes will be determined based on vehicle registration data for Alameda county, the number of miles driven per year for the average passenger vehicle, and the average distance traveled before lining replacement. The fraction of passenger vehicles equipped with factory disc brakes will be assigned the variable $R_{\text{new-disc}}$ and the fraction of passenger vehicles equipped with factory drum brakes will be assigned the variable $R_{\text{new-drum}}$.

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 will be 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 2002. The average drum and disc mass fraction of copper for new-disc/new-drum vehicles from Partnership data will be given the variable $C_{\text{Cu, pass, new-disc+drum}}$.

Information on the portion of passenger vehicle brakes that are disc and drum can be obtained from on-line automobile research tools such as www.autotrader.com. Standard brake equipment on the vehicles making up 90% of the vehicle population (according to Ward's Automotive Yearbook) will be sought for the last ten model years, and these data will be used to determine the average number of axles that are equipped with disc brakes on new-disc passenger vehicles, the average number of axles that are equipped with disc brakes on old-disc passenger vehicles, the average number of axles that are equipped with drum brakes on new-drum passenger vehicles, and the average number of axles that are equipped with drum brakes on old-drum passenger vehicles. These values will be assigned the variables $B_{\text{new-disc}}$, $B_{\text{old-disc}}$, $B_{\text{new-drum}}$, and $B_{\text{old-drum}}$.

It may be helpful to think of these variables describing an imaginary average passenger vehicle: one that is equipped with factory disc brakes, factory drum brakes, non-factory disc brakes and non-factory drum brakes in proportion to the average passenger vehicle in the United States. Note that there are two axles per passenger vehicle so that

$$R_{\text{new-drum}} B_{\text{new-drum}} + \left(1 - R_{\text{new-drum}}\right) B_{\text{old-drum}} + R_{\text{new-disc}} B_{\text{new-disc}} + \left(1 - R_{\text{new-disc}}\right) B_{\text{old-disc}} = 2$$

Because of the way Brake Pad Partnership mass fraction of copper data are collected, a value for the average number of axles that are disc brake-equipped on the subset of passenger vehicles included in the survey is also needed. This value will be assigned the variable $B_{\text{BPP-disc}}$.

**The Composition/Wear Approach:** One way to estimate the rate of overall brake lining wear is to multiply the mass of brake lining material on the vehicle by the fraction of material that is worn off when the lining is replaced, then divide that value by the number of miles driven between lining replacements.

It is anticipated that sufficient United States-specific data on brake lining material mass and the number of miles driven between replacements will be available and that use of data from European studies will not be necessary.

Information on partitioning of disc brake wear releases to air can be gleaned from dynamometer tests. However, dynamometer tests on air releases from drum brakes have not been conducted. It will be assumed that the 10% of drum brake lining wear that is released to the environment is partitioned proportionally to the partitioning from disc brake wear. This means that if, for example, 50% of disc brake wear material is released to air, then it will be assumed that 5% of drum brake wear material is released to air. Developing values for partitioning is discussed in Section 4 of this work plan.

The equations for calculating the air emission factor for brake lining debris from passenger vehicles using wear rate information are

$$\mathrm{EF}_{\text{air, pass, new-drum}} = \frac{R_{\text{new-drum}} B_{\text{new-drum}} M_{\text{pass, drum}} f_{\text{pass}}}{d_{\text{pass, drum}}} \times 0.1A$$

$$\mathrm{EF}_{\text{air, pass, old-drum}} = \frac{\left(1 - R_{\text{new-drum}}\right) B_{\text{old-drum}} M_{\text{pass, drum}} f_{\text{pass}}}{d_{\text{pass, drum}}} \times 0.1A$$

$$\mathrm{EF}_{\text{air, pass, new-disc}} = \frac{R_{\text{new-disc}} B_{\text{new-disc}} M_{\text{pass, disc}} f_{\text{pass}}}{d_{\text{pass, disc}}} \times A$$

and

$$\mathrm{EF}_{\text{air, pass, old-disc}} = \frac{\left(1 - R_{\text{new-disc}}\right) B_{\text{old-disc}} M_{\text{pass, disc}} f_{\text{pass}}}{d_{\text{pass, disc}}} \times A$$

In these equations, $M_{\text{pass, drum}}$ is the mass of drum brake lining material for a passenger vehicle axle that is drum-equipped, $M_{\text{pass, disc}}$ is the mass of disc brake lining material for a passenger vehicle axle that is disc-equipped, $f_{\text{pass}}$ is the fraction of material that is worn off when the linings are replaced, $d_{\text{pass, drum}}$ is the distance traveled between drum brake lining replacement, $d_{\text{pass, disc}}$ is the distance traveled between disc brake lining replacement, and $A$ is the fraction of disc brake lining debris that is released to air.

Note that a disc-equipped rear axle is likely to have less brake lining material than a disc-equipped front axle on the same vehicle. This difference is assumed to have a negligible effect on the results.

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

$$\begin{aligned}\mathrm{EF}_{\text{air, Cu, pass}} &= \mathrm{EF}_{\text{air, pass, new-drum}} C_{\text{Cu, pass, new-drum}} + \mathrm{EF}_{\text{air, pass, new-disc}} C_{\text{Cu, pass, new-disc}} \\ &\quad + \mathrm{EF}_{\text{air, pass, old-drum}} C_{\text{Cu, pass, old-drum}} + \mathrm{EF}_{\text{air, pass, old-disc}} C_{\text{Cu, pass, old-disc}}\end{aligned}$$

Here, $C_{\text{Cu, pass, new-disc}}$ is the mass fraction of copper in passenger vehicle factory disc brakes, $C_{\text{Cu, pass, new-drum}}$ is the mass fraction of copper in passenger vehicle factory drum brakes, $C_{\text{Cu, pass, old-disc}}$ is the mass fraction of copper in passenger vehicle non-factory disc brakes, and $C_{\text{Cu, pass, old-drum}}$ is the mass fraction of copper in passenger vehicle non-factory drum brakes.

Note that $d_{\text{pass, drum}}$ is roughly equal to $2d_{\text{pass, disc}}$ and that $M_{\text{pass, drum}}$ is roughly equal to $M_{\text{pass, disc}}$. Also, $R_{\text{new-disc}}$ is larger than $R_{\text{new-drum}}$, $B_{\text{new-disc}}$ is larger than $B_{\text{new-drum}}$, $B_{\text{old-disc}}$ is larger than $B_{\text{old-drum}}$, and the mass fraction of copper of drum brake linings is generally lower than the mass fraction of copper of disc brake linings. These considerations make it unlikely that the terms for drum brake linings in the above equation will contribute significantly to the value for $\mathrm{EF}_{\text{air, Cu, pass}}$, so this equation simplifies to

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

Emission factors based on wear rate are sensitive to the values selected to represent the fraction of lining material remaining upon replacement and for the number of miles driven between replacements. It may be useful to conduct a brief survey of automobile mechanics in order to find what percentage of brake lining remains when linings are replaced and also to get an estimate of typical miles driven between lining replacements. Some of the literature values encountered for these values for passenger vehicles do not correlate well with the author's personal experience, and the literature values for passenger vehicles come from the same references as the passenger vehicle values.

An emission factor for air releases from brake lining wear can also be developed by applying information on mass fractions of copper to measured brake wear air emission factors. This is described in the next section.

**The Composition/Existing Emission Factor Approach:** In some cases, researchers and government agencies have developed emission factors for total airborne particulate matter released from brake lining wear of passenger vehicles based on measurements. It is anticipated that sufficient United States-specific data on total air releases from passenger vehicle brake linings will be available and that use of data from European studies will not be necessary. When an emission factor for total airborne particulate matter is available, the equation for calculating a composition/wear rate emission factor for copper releases to air from brake lining wear in passenger vehicles is

$$\mathrm{EF}_{\text{air, Cu, pass}} = \mathrm{EF}_{\text{air, pass}} C_{\text{Cu, pass, ave}} F_{\text{pass}}$$

In this equation, $\mathrm{EF}_{\text{air, pass}}$ is the emission factor for airborne brake wear debris from passenger vehicles, $C_{\text{Cu, pass, ave}}$ is the mass fraction of copper in the brake lining material of passenger vehicles that is a population average of new and old drum and disc brake mass fractions of copper, and $F_{\text{pass}}$ is the fraction of wear debris that is brake lining material (as opposed to rotor or drum material). The equation for calculating the population-averaged mass fraction of copper in passenger vehicle brakes is

$$\begin{aligned}&\left(\left(R_{\text{new-drum}}B_{\text{new-drum}} + \left(1-R_{\text{new-drum}}\right)B_{\text{old-drum}}\right)\frac{0.1M_{\text{pass, drum}}}{d_{\text{pass, drum}}} + \left(R_{\text{new-disc}}B_{\text{new-disc}} + \left(1-R_{\text{new-disc}}\right)B_{\text{old-disc}}\right)\frac{M_{\text{pass, disc}}}{d_{\text{pass, disc}}}\right)C_{\text{Cu, pass, ave}}\\
&= \left(R_{\text{new-drum}}B_{\text{new-drum}}C_{\text{Cu, pass, new-drum}} + \left(1-R_{\text{new-drum}}\right)B_{\text{old-drum}}C_{\text{Cu, pass, old-drum}}\right)\frac{0.1M_{\text{pass, drum}}}{d_{\text{pass, drum}}}\\
&+\left(R_{\text{new-disc}}B_{\text{new-disc}}C_{\text{Cu, pass, new-disc}} + \left(1-R_{\text{new-disc}}\right)B_{\text{old-disc}}C_{\text{Cu, pass, old-disc}}\right)\frac{M_{\text{pass, disc}}}{d_{\text{pass, disc}}}\end{aligned}$$

In all likelihood, the terms for drum brakes in the above equation will be insignificant and can be eliminated. This is not only because 90% of drum brake wear is captured in the drum rather than being released to the environment and because drum brake linings are replaced half as often as disc brake linings, but also because there is typically less copper in drum brakes than in disc brakes and because passenger vehicle axles are more likely to be equipped with disc brakes than drum brakes. In other words, it is unlikely that copper from brake disc lining wear is significantly diluted by less concentrated drum brake lining wear. If the terms for drum brakes are eliminated, the equation becomes

$$C_{\text{Cu, pass, ave}} = \frac{R_{\text{new-disc}}B_{\text{new-disc}}C_{\text{Cu, pass, new-disc}} + \left(1-R_{\text{new-disc}}\right)B_{\text{old-disc}}C_{\text{Cu, pass, old-disc}}}{R_{\text{new-disc}}B_{\text{new-disc}} + \left(1-R_{\text{new-disc}}\right)B_{\text{old-disc}}}$$

The Partnership's mass fraction of copper value includes values from both drum and disc brakes. However, it is impossible to separate the concentration of the drum brake lining material from the concentration of the disc brake lining material because the difference between the mass fraction of copper of drum brakes and disc brakes is not known. The Partnership's mass fraction of copper value will be used uncorrected and corrected assuming that the mass fraction of copper of drum brake linings is zero (the actual value for disc brake linings surveyed by the partnership would fall somewhere between these two values). In other words, the above equation will be used with $C_{\text{Cu, pass, new-disc}}$ equal to $C_{\text{Cu, pass, new-disc+drum}}$ and with $C_{\text{Cu, pass, new-disc}}$ equal to $2C_{\text{Cu, pass, new-disc+drum}}/B_{\text{BPP-disc}}$.

### *2.1c Determining the Most Appropriate Air Emission Factor and an Error Estimate*

A table similar to Table 2.1-1 will be used to compile the values from literature that are needed to perform the above calculations. This table will facilitate the selection of the most appropriate air emission factor for passenger vehicles in Alameda County. This table will also aid in the development of an error estimate in the chosen emission factor.

The three main factors that will influence the selection of the emission factor to use in the inventory are shown in the table. The geographic applicability of the data indicates how well the data match conditions in Alameda County and the time applicability reflects how recent the data are. The column labeled “Experimental” will contain an assessment of the techniques used to arrive at the given value. These assessments will show where the data used in the calculations are weakest, and which data will result in the most supportable estimate of emissions.

Table 2.1-1 Data worksheet for developing an air emission factor for the release of copper from brake lining wear in passenger vehicles.

| Data Type | Source | Value | Applicability | | |
|---|---|---|---|---|---|
| | | | Geographic | Time | Experimental |
| Emission factor for airborne brake lining debris from passenger vehicles, lb brake lining/mi ($EF_{air, pass}$) | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Mass of brake lining material on a drum-equipped passenger vehicle axle, lb brake lining/axle ($M_{pass, drum}$)* | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Mass of brake lining material on a disc-equipped passenger vehicle axle, lb brake lining/axle ($M_{pass, disc}$) | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Fraction of passenger vehicle brake lining material worn off at replacement ($f_{pass}$) | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Distance traveled between drum brake lining replacements in passenger vehicles, mi ($d_{pass, drum}$)* | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Distance traveled between disc brake lining replacements in passenger vehicles, mi ($d_{pass, disc}$) | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Copper concentration in passenger vehicle factory brake pads, mass fraction ($C_{Cu, pass, new\text{-}disc}$) | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Copper concentration in passenger vehicle factory brake shoes, mass fraction ($C_{Cu, pass, new\text{-}drum}$)* | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Copper concentration in passenger vehicle non-factory brake shoes, mass fraction ($C_{Cu, pass, old\text{-}drum}$)* | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Copper concentration in passenger vehicle non-factory brake pads, mass fraction ($C_{Cu, pass, old\text{-}disc}$) | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Fraction of wear debris that is brake lining material, ($F_{pass}$) | | | | | |
| | | | | | |
| Tunnel study emission factors for copper from passenger vehicles, lb Cu/mi ($EF_{air, Cu, pass}$) | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

* It is likely that obtaining these values will not be necessary.

## 2.2 Medium-Duty Vehicles

Three categories of information that can be used to derive air emission factors for copper from brake lining wear will be used in conducting the inventory. Emission factors derived from tunnel studies comprise one category. Another category consists of existing air emission factors for brake lining debris combined with lining composition information. The final category consists of emission factors based on the wear rate of brake linings, their composition, and the fraction of wear debris that partitions to air.

### *2.2a Tunnel Studies*

Copper emission factors for heavy-duty vehicles and passenger vehicles have been developed from tunnel studies. Medium-duty vehicles are not generally assigned separate emission factors in tunnel studies. The authors of tunnel study reports must be contacted to determine if medium-duty vehicles are combined with heavy-duty vehicles when calculating emission factors from heavy-duty vehicles in tunnel studies. If medium-duty and heavy-duty vehicles are combined, then the emission factor for heavy-duty vehicles can be applied to medium-duty vehicles (this would be equivalent to applying the heavy-duty vehicle emission factor to the sum of the vehicle-miles-traveled for medium- and heavy-duty vehicles). Emission factors for copper from taken from tunnel studies conducted in the United States will be compiled. Factors that determine which of the tunnel studies most closely mimic the traffic conditions in Alameda County will be assessed.

Because it is not known whether the formulation of brake linings used in vehicles in Europe matches the formulation of brake linings in the United States, emission factors from tunnel studies conducted in Europe will not be used to develop the emission factor for this project. However, they will be assessed to see if the relative differences between values provide information helpful in gauging the effect of traffic conditions and other variables on emission factors.

### *2.2b Composition-Based Approaches*

In essence, both of the composition-based approaches consist of multiplying an emission factor for total air releases from brake lining wear by the copper fraction in the brake lining material in order to arrive at an emission factor for copper releases to air from brake lining wear. The air emission factor used can be taken from reported measured values or calculated based on brake lining wear rate and partitioning information.

**Estimating the Copper Content of Medium-Duty Vehicle Brakes:** It will be assumed that vehicle age does not correlate with the concentration of copper in brake linings for medium-duty vehicles. In other words, it will be assumed that factory-equipped medium-duty vehicles do not have a higher concentration of copper in their brake linings than medium-duty vehicles that are not factory equipped. In general, aftermarket brakes tend to contain less copper than factory brakes because copper is a relatively expensive material. However, the differences in copper content between factory brake linings and replacement brake linings in medium-duty vehicles is not expected to be important to overall inventory results, partly because the copper content of factory-equipped medium-duty vehicle brakes in Europe is already quite low, and is expected to be low in the United States as well.

Information on the copper content in medium-duty vehicle brake linings in the Unites States, if available, will be collected. Researchers in Europe have measured the concentration of copper in heavy-duty vehicle brake linings and brake lining manufacturers have provided information on these concentrations to researchers in Europe but separate information on medium-duty vehicles is not available. It will be assumed that the mass fractions of copper in heavy-duty vehicle brake lining material are the same as the mass fractions of copper in medium-duty vehicles. It will also be assumed that the ratio of copper in heavy-duty vehicle brakes to passenger vehicle brakes in Europe is the same as the ratio of copper in heavy-duty vehicle brakes to passenger vehicle brakes in the United States. For example, if more copper is used in passenger vehicle brake linings in Europe than in passenger vehicle brake linings in the United States, then it will be assumed that more copper is used in heavy-duty vehicle brake linings in Europe than in heavy-duty vehicle brake linings in the United States.

Medium-duty 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. The mass fraction of copper of disc brakes and drum brakes will be found separately. In addition, disc brakes on medium-duty vehicles can be of two types: air-assisted and hydraulic. The formulations of the brake lining material in the two types of disc brakes are different and air assisted brakes are in far more common use in Europe than in the United States. Information on the difference in copper content between the two types of disc brakes is not available and the inventory will consider both types of disc brake linings together.

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.

Information on the portion of medium-duty vehicle brakes that are disc and drum will be taken from the FMSI manual, or from communications from Jim Lawrence of the BMC. The average number of disc brake axles per medium-duty vehicle will be assigned the variable $B_{\mathrm{MDV,\,disc}}$, and the average number of drum brake axles per medium-duty vehicle will be $(2 - B_{\mathrm{MDV,\,disc}})$.

**The Composition/Wear Approach:** One way to estimate the rate of overall brake lining wear is to multiply the mass of brake lining material on the vehicle by the fraction of material that is worn off when the lining is replaced, then divide that value by the number of miles driven between lining replacements.

Medium-duty vehicles in the United States are expected to have approximately the same total mass of brake lining material per axle as heavy-duty vehicles in Europe, so values for heavy-duty vehicles reported in European literature will be included when calculating this average. Also, the number of miles driven between replacements and the fraction of material remaining when heavy-duty linings are replaced will be assumed to be the same for medium-duty vehicles in the United States as for heavy-duty vehicles in Europe.

It will be assumed that brake lining debris partitioning for disc brakes is the same for all vehicle categories. Information on partitioning of disc brake wear releases to air can be gleaned from dynamometer tests. However, dynamometer tests on air releases from drum brakes have not been conducted. It will also be assumed that 90% of drum brake wear is trapped as dust in the drum, and that the 10% that is released to the environment is partitioned proportionally to the partitioning from disc brake wear. This means that if, for example, 50% of disc brake wear material is released to air, then it will be assumed that 5% of drum brake wear material is released to air. Developing values for partitioning is discussed in Section 4 of this work plan.

The equations for calculating the air emission factor for brake lining debris from medium-duty vehicles using wear rate information are

$$\mathrm{EF}_{\text{air, MDV, drum}} = \frac{\left(2 - B_{\text{MDV, disc}}\right) M_{\text{MDV, drum}}\, f_{\text{MDV}}}{d_{\text{MDV, drum}}} \times 0.1A$$

and

$$\mathrm{EF}_{\text{air, MDV, disc}} = \frac{B_{\text{MDV, disc}} M_{\text{MDV, disc}}\, f_{\text{MDV}}}{d_{\text{MDV, disc}}} \times A$$

In these equations, $M_{\text{MDV, drum}}$ is the mass of drum brake lining material for a medium-duty vehicle axle that is drum-equipped, $M_{\text{MDV, disc}}$ is the mass of disc brake lining material for a medium-duty vehicle axle that is disc-equipped, $f_{\text{MDV}}$ is the fraction of material that is worn off when the linings are replaced, $d_{\text{MDV, drum}}$ is the distance traveled between drum brake lining replacement, $d_{\text{MDV, disc}}$ is the distance traveled between disc brake lining replacement, and $A$ is the fraction of disc brake lining debris that is released to air.

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

$$\mathrm{EF}_{\text{air, Cu, MDV}} = \mathrm{EF}_{\text{air, MDV, drum}} C_{\text{Cu, MDV, drum}} + \mathrm{EF}_{\text{air, MDV, disc}} C_{\text{Cu, MDV, disc}}$$

Here, $C_{\text{Cu, MDV, disc}}$ is the mass fraction of copper in medium-duty vehicle disc brakes and $C_{\text{Cu, MDV, drum}}$ is the mass fraction of copper in medium-duty vehicle drum brakes.

It will be assumed that the values use for distance traveled between brake lining replacements and the fraction of material remaining upon replacement for heavy-duty vehicles will serve as acceptable values for medium-duty vehicles.

An emission factor for air releases from brake lining wear can also be developed by applying information on mass fractions of copper to measured brake wear air emission factors. This is described in the next section.

**The Composition/Existing Emission Factor Approach:** In some cases, researchers and government agencies have developed emission factors for total airborne particulate matter released from brake lining wear of medium-duty vehicles based on measurements. In such cases, it will be assumed that total air releases from brake linings are the same in Europe as in the United States. When an emission factor for total airborne particulate matter is available, the equation for calculating a composition/wear rate emission factor for copper releases to air from brake lining wear in medium-duty vehicles is

$$\mathrm{EF}_{\text{air, Cu, MDV}} = \mathrm{EF}_{\text{air, MDV}} C_{\text{Cu, MDV, ave}} F_{\text{MDV}}$$

In this equation, $\mathrm{EF}_{\text{air, MDV}}$ is the emission factor for airborne brake wear debris from medium-duty vehicles, $C_{\text{Cu, MDV, ave}}$ is the mass fraction of copper in the brake lining material of medium-duty vehicles that is a population average of drum and disc brake mass fractions of copper, and $F_{\text{MDV}}$ is the fraction of wear debris that is brake lining material (as opposed to rotor or drum material). The equation for calculating the population-averaged mass fraction of copper in medium-duty vehicle brakes is

$$C_{\text{Cu, MDV, ave}} = \frac{\dfrac{B_{\text{MDV, disc}} M_{\text{MDV, disc}} C_{\text{Cu, MDV, disc}}}{d_{\text{MDV, disc}}} + \dfrac{0.1\left(2 - B_{\text{MDV, disc}}\right) M_{\text{MDV, drum}} C_{\text{Cu, MDV, drum}}}{d_{\text{MDV, drum}}}}{\dfrac{B_{\text{MDV, disc}} M_{\text{MDV, disc}}}{d_{\text{MDV, disc}}} + \dfrac{0.1\left(2 - B_{\text{MDV, disc}}\right) M_{\text{MDV, drum}}}{d_{\text{MDV, drum}}}}$$

The factor of 0.1 in the above equation accounts for the fact that an estimated 90% of drum brake wear is captured in the drum rather than being released to the environment. Note that values for heavy-duty vehicles will be used for the mass of lining material, the mass fraction of copper of lining material, and the distance traveled between lining replacements will be used for medium-duty vehicles.

### *2.2c Determining the Most Appropriate Air Emission Factor and an Error Estimate*

A table similar to Table 2.2-1 will be used to compile the values from literature that are needed to perform the above calculations. This table will facilitate the selection of the most appropriate air emission factor for medium-duty vehicles in Alameda County. This table will also aid in the development of an error estimate in the chosen emission factor.

The three main factors that will influence the selection of data to use in the inventory are shown in the table. The geographic applicability of the data indicates how well the data match conditions in Alameda County and the time applicability reflects how recent the data are. The column labeled “Experimental” will contain an assessment of the techniques used to arrive at the given value. The column labeled “MDV-Specific” will be used to identify whether the data were specific to medium-duty vehicles or were taken from heavy-duty vehicle studies. These assessments will show where the data used in the calculations are weakest, and which data will result in the most supportable estimate of emissions.

Table 2.2-1 Data worksheet for developing an air emission factor for the release of copper from brake lining wear in medium-duty vehicles. *

| Data Type | Source | Value | Applicability | | | |
|---|---|---|---|---|---|---|
| | | | Geographic | Time | Experimental | MDV-Specific |
| Emission factor for airborne brake lining debris from MDVs, lb brake lining/mi ($EF_{air,\ MDV}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Average number of medium-duty vehicle axles that are disc brake-equipped ($B_{MDV,\ disc}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Mass of brake lining material on a drum-equipped MDV axle, lb brake lining/axle ($M_{MDV,\ drum}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Mass of brake lining material on a disc-equipped MDV axle, lb brake lining/axle ($M_{MDV,\ disc}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Fraction of brake lining material worn off at replacement ($f_{MDV}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Distance traveled between drum brake lining replacements, mi ($d_{MDV,\ drum}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Distance traveled between disc brake lining replacements, mi ($d_{MDV,\ disc}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Copper concentration in MDV brake shoes, mass fraction ($C_{Cu,\ MDV,\ drum}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Copper concentration in MDV brake pads, mass fraction ($C_{Cu,\ MDV,\ disc}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Fraction of wear debris that is brake lining material, ($F_{MDV}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Tunnel study emission factors for copper from MDVs, lb Cu/mi ($EF_{air,\ Cu,\ MDV}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

*MDV: medium-duty vehicle

## 2.3 Heavy-Duty Vehicles

Three categories of information that can be used to derive air emission factors for copper from brake lining wear will be used in conducting the inventory. Emission factors derived from tunnel studies comprise one category. Another category consists of existing air emission factors for brake lining debris combined with lining composition information. The final category consists of emission factors based on the wear rate of brake linings, their composition, and the fraction of wear debris that partitions to air.

### *2.3a Tunnel Studies*

Copper emission factors for heavy-duty vehicles have been developed from tunnel studies. In completing the inventory of copper releases from brake lining materials, emission factors for copper from heavy-duty vehicles taken from tunnel studies conducted in the United States will be compiled. Factors that determine which of the tunnel studies most closely mimic the traffic conditions in Alameda County will be assessed.

Because it is not known whether the formulation of brake linings used in vehicles in Europe matches the formulation of brake linings in the United States, emission factors from tunnel studies conducted in Europe will not be used to develop the emission factor for this project. However, they will be assessed to see if the relative differences between values provide information helpful in gauging the effect of traffic conditions and other variables on emission factors.

### *2.3b Composition-Based Approaches*

In essence, both of the composition-based approaches consist of multiplying an emission factor for total air releases from brake lining wear by the copper fraction in the brake lining material in order to arrive at an emission factor for copper releases to air from brake lining wear. The air emission factor used can be taken from reported measured values or calculated based on brake lining wear rate and partitioning information.

**Estimating the Copper Content of Heavy-Duty Vehicle Brakes:** It will be assumed that vehicle age does not correlate with the concentration of copper in brake linings for heavy-duty vehicles. In other words, it will be assumed that factory-equipped heavy-duty vehicles do not have a higher concentration of copper in their brake linings than heavy-duty vehicles that are not factory equipped. In general, aftermarket brakes tend to contain less copper than factory brakes because copper is a relatively expensive material. However, the differences in copper content between factory brake linings and replacement brake linings in heavy-duty vehicles is not expected to be important to overall inventory results, partly because the copper content of factory-equipped heavy-duty vehicle brakes in Europe is already quite low, and is expected to be low in the United States as well.

Information on the copper content in heavy-duty vehicle brake linings in the Unites States, if available, will be collected. Researchers in Europe have measured the concentration of copper in heavy-duty vehicle brake linings. Also, brake lining manufacturers have provided information on these concentrations to researchers in Europe. It will be assumed that the ratio of copper in heavy-duty vehicle brakes to passenger vehicle brakes in Europe is the same as the ratio of copper in heavy-duty vehicle brakes to passenger vehicle brakes in the United States. For example, if more copper is used in passenger vehicle brake linings in Europe than in passenger vehicle brake linings in the United States, then it will be assumed that more copper is used in heavy-duty vehicle brake linings in Europe than in heavy-duty vehicle brake linings in the United States.

Heavy-duty 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. The mass fraction of copper of disc brakes and drum brakes will be found separately. In addition, disc brakes on heavy-duty vehicles can be of two types: air-assisted and hydraulic. The formulations of the brake lining material in the two types of disc brakes are different and air assisted brakes are in far more common use in Europe than in the United States. Information on the difference in copper content between the two types of disc brakes is not available and the inventory will consider both types of disc brake linings together.

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.

Information on the portion of heavy-duty vehicle brakes that are disc and drum will be taken from personal communications from Jim Lawrence of the BMC or from the FMSI manual. The average number of disc brake axles per heavy-duty vehicle will be $B_{\mathrm{HDV,\ disc}}$, and the average number of drum brake axles per heavy-duty vehicle will be ($N_{\mathrm{HDV}}$ - $B_{\mathrm{HDV,\ disc}}$), where $N_{\mathrm{HDV}}$ is the average number of axles per heavy-duty vehicle. A value for the average number of axles on heavy-duty vehicles in Alameda County will be sought.

**The Composition/Wear Approach:** One way to estimate the rate of overall brake lining wear is to multiply the mass of brake lining material on the vehicle by the fraction of material that is worn off when the lining is replaced, then divide that value by the number of miles driven between lining replacements.

Heavy-duty vehicles in the United States are expected to have approximately the same total mass of brake lining material per axle as heavy-duty vehicles in Europe, so values reported in European literature will be included when calculating this average. Also, the number of miles driven between replacements and the fraction of material remaining when heavy-duty linings are replaced will be assumed to be the same in the United States as in Europe.

It will be assumed that brake lining debris partitioning for disc brakes is the same for all vehicle categories. Information on partitioning of disc brake wear releases to air can be gleaned from dynamometer tests. However, dynamometer tests on air releases from drum brakes have not been conducted. It will also be assumed that 90% of drum brake wear is trapped as dust in the drum, and that the 10% that is released to the environment is partitioned proportionally to the partitioning from disc brake wear. This means that if, for example, 50% of disc brake wear material is released to air, then it will be assumed that 5% of drum brake wear material is released to air. Developing values for partitioning is discussed in Section 4 of this work plan.

The equations for calculating the air emission factor for brake lining debris from heavy-duty vehicles using wear rate information are

$$\mathrm{EF}_{\text{air, HDV, drum}} = \frac{\left(N_{\text{HDV}} - B_{\text{HDV, disc}}\right) M_{\text{HDV, drum}}\, f_{\text{HDV}}}{d_{\text{HDV, drum}}} \times 0.1A$$

and

$$\mathrm{EF}_{\text{air, HDV, disc}} = \frac{B_{\text{HDV, disc}} M_{\text{HDV, disc}}\, f_{\text{HDV}}}{d_{\text{HDV, disc}}} \times A$$

In these equations, $M_{\text{HDV, drum}}$ is the mass of drum brake lining material for a heavy-duty vehicle axle that is drum-equipped, $M_{\text{HDV, disc}}$ is the mass of disc brake lining material for a heavy-duty vehicle axle that is disc-equipped, $N_{\text{HDV}}$ is the average number of axles per heavy-duty vehicle in Alameda County, $f_{\text{HDV}}$ is the fraction of material that is worn off when the linings are replaced, $d_{\text{HDV, drum}}$ is the distance traveled between drum brake lining replacement, $d_{\text{HDV, disc}}$ is the distance traveled between disc brake lining replacement, and $A$ is the fraction of disc brake lining debris that is released to air.

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

$$\mathrm{EF}_{\text{air, Cu, HDV}} = \mathrm{EF}_{\text{air, HDV, drum}} C_{\text{Cu, HDV, drum}} + \mathrm{EF}_{\text{air, HDV, disc}} C_{\text{Cu, HDV, disc}}$$

Here, $C_{\text{Cu, HDV, disc}}$ is the mass fraction of copper in heavy-duty vehicle disc brakes and $C_{\text{Cu, HDV, drum}}$ is the mass fraction of copper in heavy-duty vehicle drum brakes.

Emission factors based on wear rate are sensitive to the values selected to represent the fraction of lining material remaining upon replacement and for the number of miles driven between replacements. It may be useful to conduct a brief survey of heavy-duty vehicle mechanics in order to find what percentage of brake lining remains when linings are replaced and also to get an estimate of typical miles driven between lining replacements. Some of the literature values encountered for these values for passenger vehicles do not correlate well with the author's personal experience, and the literature values for heavy-duty vehicles come from the same references as the passenger vehicle values.

An emission factor for air releases from brake lining wear can also be developed by applying information on mass fractions of copper to measured brake wear air emission factors. This is described in the next section.

**The Composition/Existing Emission Factor Approach:** In some cases, researchers and government agencies have developed emission factors for total airborne particulate matter released from brake lining wear of heavy-duty vehicles based on measurements. In such cases, it will be assumed that total air releases from brake linings are the same in Europe as in the United States. When an emission factor for total airborne particulate matter is available, the equation for calculating a composition/wear rate emission factor for copper releases to air from brake lining wear in heavy-duty vehicles is

$$\mathrm{EF}_{\text{air, Cu, HDV}} = \mathrm{EF}_{\text{air, HDV}} C_{\text{Cu, HDV, ave}} F_{\text{HDV}}$$

In this equation, $\mathrm{EF}_{\text{air, HDV}}$ is the emission factor for airborne brake wear debris from heavy-duty vehicles, $C_{\text{Cu, HDV, ave}}$ is the mass fraction of copper in the brake lining material of heavy-duty vehicles that is a population average of drum and disc brake mass fractions of copper, and $F_{\text{HDV}}$ is the fraction of wear debris that is brake lining material (as opposed to rotor or drum material). The equation for calculating the population-averaged mass fraction of copper in heavy-duty vehicle brakes is

$$C_{\text{Cu, HDV, ave}} = \frac{\dfrac{B_{\text{HDV, disc}} M_{\text{HDV, disc}} C_{\text{Cu, HDV, disc}}}{d_{\text{HDV, disc}}} + \dfrac{0.1\left(N_{\text{HDV}} - B_{\text{HDV, disc}}\right) M_{\text{HDV, drum}} C_{\text{Cu, HDV, drum}}}{d_{\text{HDV, drum}}}}{\dfrac{B_{\text{HDV, disc}} M_{\text{HDV, disc}}}{d_{\text{HDV, disc}}} + \dfrac{0.1\left(N_{\text{HDV}} - B_{\text{HDV, disc}}\right) M_{\text{HDV, drum}}}{d_{\text{HDV, drum}}}}$$

The factor of 0.1 in the above equation accounts for the fact that an estimated 90% of drum brake wear is captured in the drum rather than being released to the environment.

### *2.3c Determining the Most Appropriate Air Emission Factor and an Error Estimate*

A table similar to Table 2.3-1 will be used to compile the values from literature that are needed to perform the above calculations. This table will facilitate the selection of the most appropriate air emission factor for heavy-duty vehicles in Alameda County. This table will also aid in the development of an error estimate in the chosen emission factor.

The three main factors that will influence the selection of data to use in the inventory are shown in the table. The geographic applicability of the data indicates how well the data match conditions in Alameda County and the time applicability reflects how recent the data are. The column labeled "Experimental" will contain an assessment of the techniques used to arrive at the given value. These assessments will show where the data used in the calculations are weakest, and which data will result in the most supportable estimate of emissions.

Table 2.3-1 Data worksheet for developing an air emission factor for the release of copper from brake lining wear in heavy-duty vehicles.*

| Data Type | Source | Value | Applicability | | |
|---|---|---|---|---|---|
| | | | Geographic | Time | Experimental |
| Emission factor for airborne brake lining debris from HDVs, lb brake lining/mi ($EF_{air, HDV}$) | | | | | |
| Average number of medium-duty vehicle axles that are disc brake-equipped ($B_{HDV, disc}$) | | | | | |
| Mass of brake lining material on a drum-equipped HDV axle, lb brake lining/axle ($M_{HDV, drum}$) | | | | | |
| Mass of brake lining material on a disc-equipped HDV axle, lb brake lining/axle ($M_{HDV, disc}$) | | | | | |
| Fraction of brake lining material worn off at replacement ($f_{HDV}$) | | | | | |
| Distance traveled between drum brake lining replacements, mi ($d_{HDV, drum}$) | | | | | |
| Distance traveled between disc brake lining replacements, mi ($d_{HDV, disc}$) | | | | | |
| Copper concentration in HDV brake shoes, mass fraction ($C_{Cu, HDV, drum}$) | | | | | |
| Copper concentration in HDV brake pads, mass fraction ($C_{Cu, HDV, disc}$) | | | | | |
| Fraction of wear debris that is brake lining material, ($F_{HDV}$) | | | | | |
| Average number of axles per HDV in Alameda county ($N_{HDV}$) | | | | | |
| Tunnel study emission factors for copper from HDVs, lb Cu/mi ($EF_{air, Cu, HDV}$) | | | | | |

*HDV: heavy-duty vehicle

## 2.4 Buses

It is unlikely that copper emissions from bus brake lining materials are going to be significant in Alameda County. This is because buses account for less than one-half of one percent of vehicle miles traveled in the county and the mass fraction of copper in bus brake lining materials is expected to be lower than the mass fraction of copper in passenger vehicles. However, buses are much heavier than passenger vehicles (total air releases due to brake lining wear are proportional to curb weight). Before conducting an inventory of copper emissions from bus brake linings, it should be determined if it is possible that bus brake linings contribute significantly to the total brake lining copper emissions in Alameda County. This could be done by choosing a high value for the mass fraction of copper in bus brake lining materials, along with a high rate of wear. If this screening calculation provides a result that indicates that buses make a significant contribution to total copper from brake lining releases, then the following instructions can be used for estimating brake lining copper releases from buses.

Three categories of information that can be used to derive air emission factors for copper from brake lining wear will be used in conducting the inventory. Emission factors derived from tunnel studies comprise one category. Another category consists of existing air emission factors for brake lining debris combined with lining composition information. The final category consists of emission factors based on the wear rate of brake linings, their composition, and the fraction of wear debris that partitions to air.

### *2.4a Tunnel Studies*

To the author's knowledge, copper emission factors for buses have not been developed from tunnel studies. In completing the inventory of copper releases from brake lining materials, the emission factor for buses will be taken as the average of the emission factors for heavy-duty vehicles and passenger vehicles, taken from tunnel studies conducted in the United States. Factors that determine which of the tunnel studies most closely mimic the traffic conditions in Alameda County will be assessed.

Because it is not known whether the formulation of brake linings used in vehicles in Europe matches the formulation of brake linings in the United States, emission factors from tunnel studies conducted in Europe will not be used to develop the emission factor for this project. However, they will be assessed to see if the relative differences between values provide information helpful in gauging the effect of traffic conditions and other variables on emission factors.

### *2.4b Composition-Based Approaches*

In essence, both of the composition-based approaches consist of multiplying an emission factor for total air releases from brake lining wear by the copper fraction in the brake lining material in order to arrive at an emission factor for copper releases to air from brake lining wear. The air emission factor used can be taken from reported measured values or calculated based on brake lining wear rate and partitioning information.

**Estimating the Copper Content of Bus Brakes:** It will be assumed that vehicle age does not correlate with the concentration of copper in brake linings for buses. In other words, it will be assumed that factory-equipped buses do not have a higher concentration of copper in their brake linings than buses that are not factory equipped. In general, aftermarket brakes tend to contain less copper than factory brakes because copper is a relatively expensive material. However, the differences in copper content between factory brake linings and replacement brake linings in buses is not expected to be important to overall inventory results, partly because the copper content of factory-equipped bus brakes in Europe is already quite low, and is expected to be low in the United States as well.

Information on the copper content in bus brake linings in the Unites States, if available, will be collected. Researchers in Europe have measured the concentration of copper in bus brake linings. Also, brake lining manufacturers have provided information on these concentrations to researchers in Europe. It will be assumed that the ratio of copper in bus brakes to passenger vehicle brakes in Europe is the same as the ratio of copper in bus brakes to passenger vehicle brakes in the United States. For example, if more copper is used in passenger vehicle brake linings in Europe than in passenger vehicle brake linings in the United States, then it will be assumed that more copper is used in bus brake linings in Europe than in bus brake linings in the United States.

Buses are equipped with drum brakes (per Jim Lawrence, BMC). 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.

**The Composition/Wear Approach:** One way to estimate the rate of overall brake lining wear is to multiply the mass of brake lining material on the vehicle by the fraction of material that is worn off when the lining is replaced, then divide that value by the number of miles driven between lining replacements.

Buses in the United States are expected to have approximately the same total mass of brake lining material per axle as buses in Europe, so values reported in European literature will be included when calculating this average. Also, the number of miles driven between replacements and the fraction of material remaining when heavy-duty linings are replaced will be assumed to be the same in the United States as in Europe.

It will be assumed that brake lining debris partitioning for disc brakes is the same for all vehicle categories. Information on partitioning of disc brake wear releases to air can be gleaned from dynamometer tests. However, dynamometer tests on air releases from drum brakes have not been conducted. It will also be assumed that 90% of drum brake wear is trapped as dust in the drum, and that the 10% that is released to the environment is partitioned proportionally to the partitioning from disc brake wear. This means that if, for example, 50% of disc brake wear material is released to air, then it will be assumed that 5% of drum brake wear material is released to air. Developing values for partitioning is discussed in Section 4 of this work plan.

The equations for calculating the air emission factor for brake lining debris from buses using wear rate information are

$$\mathrm{EF}_{\text{air, bus, drum}} = \frac{2M_{\text{bus, drum}} f_{\text{bus}}}{d_{\text{bus, drum}}} \times 0.1A$$

In these equations, $M_{\text{bus, drum}}$ is the mass of drum brake lining material for a bus axle that is drum-equipped, $f_{\text{bus}}$ is the fraction of material that is worn off when the linings are replaced, $d_{\text{bus, drum}}$ is the distance traveled between drum brake lining replacement, and $A$ is the fraction of disc brake lining debris that is released to air.

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

$$\mathrm{EF}_{\text{air, Cu, bus}} = \mathrm{EF}_{\text{air, bus, drum}} C_{\text{Cu, bus, drum}}$$

Here, $C_{\text{Cu, bus, drum}}$ is the mass fraction of copper in bus drum brakes.

An emission factor for air releases from brake lining wear can also be developed by applying information on mass fractions of copper to measured brake wear air emission factors. This is described in the next section.

**The Composition/Existing Emission Factor Approach:** In some cases, researchers and government agencies have developed emission factors for total airborne particulate matter released from brake lining wear of buses based on measurements. In such cases, it will be assumed that total air releases from brake linings are the same in Europe as in the United States. When an emission factor for total airborne particulate matter is available, the equation for calculating a composition/wear rate emission factor for copper releases to air from brake lining wear in buses is

$$\mathrm{EF}_{\text{air, Cu, bus}} = \mathrm{EF}_{\text{air, bus}} C_{\text{Cu, bus, drum}} F_{\text{bus}}$$

In this equation, $\mathrm{EF}_{\text{air, bus}}$ is the emission factor for airborne brake wear debris from buses, $C_{\text{Cu, bus, drum}}$ is the mass fraction of copper in the brake lining material of buses, and $F_{\text{bus}}$ is the fraction of wear debris that is brake lining material (as opposed to drum material). The factor of 0.1 in the above equation accounts for the fact that an estimated 90% of drum brake wear is captured in the drum rather than being released to the environment.

### *2.4c Determining the Most Appropriate Air Emission Factor and an Error Estimate*

A table similar to Table 2.4-1 will be used to compile the values from literature that are needed to perform the above calculations. This table will facilitate the selection of the most appropriate air emission factor for buses in Alameda County. This table will also aid in the development of an error estimate in the chosen emission factor.

The three main factors that will influence the selection of data to use in the inventory are shown in the table. The geographic applicability of the data indicates how well the data match conditions in Alameda County and the time applicability reflects how recent the data are. The column labeled “Experimental” will contain an assessment of the techniques used to arrive at the given value. The column labeled “Bus-Specific” will be used to identify whether the data were specific to buses or were taken from heavy-duty vehicle and/or passenger vehicle studies. These assessments will show where the data used in the calculations are weakest, and which data will result in the most supportable estimate of emissions.

Note that it is anticipated that a sufficient quantity of data on the mass of bus brake linings, the distance traveled between lining replacements in buses, the fraction of lining remaining on the bus at replacement, and the concentration of copper in the linings will be available. If not, values for heavy-duty vehicles may be used when calculating copper releases from buses. Any such substitution will be taken into account in sensitivity analyses and when determining the error in the estimated copper releases.

Table 2.4-1 Data worksheet for developing an air emission factor for the release of copper from brake lining wear in buses.

| Data Type | Source | Value | Applicability | | | |
|---|---|---|---|---|---|---|
| | | | Geographic | Time | Experimental | Bus-Specific |
| Emission factor for airborne brake lining debris from buses, lb brake lining/mi ($EF_{air, bus}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Mass of brake lining material on a drum-equipped bus axle, lb brake lining/axle ($M_{bus, drum}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Fraction of brake lining material worn off at replacement ($f_{bus}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Distance traveled between drum brake lining replacements, mi ($d_{bus, drum}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Copper concentration in bus brake shoes, mass fraction ($C_{Cu, bus, drum}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Fraction of wear debris that is brake lining material, ($F_{bus}$) | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Tunnel study emission factors for copper from buses, lb Cu/mi ($EF_{air, Cu, bus}$) | | | | | | |
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## 2.5 Motorcycles

Motorcycles represent 1/300$^{th}$ of the vehicle miles traveled represented by passenger cars and light trucks in Alameda County. They are expected to have approximately 1/4$^{th}$ of the total airborne brake wear debris per mile releases of passenger vehicles because they weigh substantially less than passenger vehicles (total airborne brake wear debris releases correlate with curb weight). Even if motorcycle brake lining materials have copper concentrations that are 20 times that of passenger car brake lining materials, they will be responsible for on the order of 1/100$^{th}$ of the copper releases that passenger vehicles have. This is well outside the uncertainty range of any inventoried amounts. Because it is unlikely that copper emissions from motorcycle brake lining materials are going to be significant in Alameda County, , copper emissions from motorcycles will not be estimated.

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

The size of the particles that are released to air as brake linings wear is important because it determines to a large extent what the fate of the air emissions will be. A particle size distribution provides information on the fraction of air releases that fall into each particle size range.

A number of researchers have measured the particle size distribution of brake wear material emitted to air. These particle size distributions will be tabulated. The calculated distribution will most likely be based on the latest dynamometer studies commissioned by the Brake Pad Partnership, but the other studies will provide information valuable for conducting sensitivity analyses and developing an estimate of error.

# 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.

A number of researchers have measured the portion of brake wear material that is emitted to air. These measurements will be tabulated. The calculated distribution will most likely be based on the latest dynamometer studies commissioned by the Brake Pad Partnership, but the other studies will provide information valuable for conducting sensitivity analyses and developing an estimate of error. The value for the fraction of total brake lining wear that is emitted to air is assigned the variable *A*.

The portion of material that falls to the floor during dynamometer testing will represent the portion of brake wear material that falls to the road during vehicle use. The value for the fraction of total brake lining wear that is released directly to the road during use is assigned the variable *S*. The roadway emission factors are

$$\mathrm{EF}_{\text{road-dir, Cu, pass}} = \frac{\mathrm{EF}_{\text{air, Cu, pass}} S}{A}$$

$$\mathrm{EF}_{\text{road-dir, Cu, MDV}} = \frac{\mathrm{EF}_{\text{air, Cu, MDV}} S}{A}$$

$$\mathrm{EF}_{\text{road-dir, Cu, HDV}} = \frac{\mathrm{EF}_{\text{air, Cu, HDV}} S}{A}$$

In the study commissioned by the Brake Pad Partnership, the ductwork and braking apparatus is going to serve as a stand-in for brake wear material that sticks to the vehicle. The fraction of total brake lining wear material that adheres to the vehicle after being released will be assigned the variable *V*. The emission factors for material that adheres to the vehicle are

$$\mathrm{EF}_{\text{veh, Cu, pass}} = \frac{\mathrm{EF}_{\text{air, Cu, pass}} V}{A}$$

$$\mathrm{EF}_{\text{veh, Cu, MDV}} = \frac{\mathrm{EF}_{\text{air, Cu, MDV}} V}{A}$$

$$\mathrm{EF}_{\text{veh, Cu, HDV}} = \frac{\mathrm{EF}_{\text{air, Cu, HDV}} V}{A}$$

It will be assumed that the total amount of material adhered to vehicles is at a steady-state level (i.e., it does not continuously accumulate). Of the material that sticks to the vehicle, some is removed during precipitation events, when the vehicle is driven through standing water that has collected on the road, or when the vehicle is parked where water is being sprayed for irrigation.

Some is removed when the vehicle is washed at a non-commercial carwash. Some might fall to the road when the vehicle is jarred, as well.

An inventory of brake wear material that adheres to a vehicle but that does not get washed off in a commercial carwash must be prepared. It is assumed that all commercial carwashes discharge to publicly owned treatment works. This inventory will be prepared using two separate methodologies.

In the first means of calculating the fraction of material that adheres to the vehicle and is later removed at a commercial carwash, it will be assumed that other than commercial carwashes, precipitation events are the only significant means of removal of brake wear material from vehicles. If consumer data on the average frequency of commercial carwash use are available, the ratio of these data to the number of significant precipitation events in which the vehicle is operated can be used to determine the fraction of vehicle-adhered brake wear material is washed off in a commercial carwash and the fraction that is released to the road after adhering to the vehicle. The definition of a significant rain event will be one in which at least one quarter of an inch of rain falls and that has a duration of at least 15 minutes. Table 4-1 gives formulas for calculating the fraction of vehicles that are exposed to rain events of varying durations. The values in this table are based on passenger vehicles and light-duty trucks being in use two hours per day, medium-duty vehicles being in use eight hours per day, and heavy-duty trucks and buses being in use 12 hours per day. The equations for calculating the portion of vehicle-adhered copper that is washed off at commercial carwashes are

$$\mathrm{EF}_{\text{POTW, Cu, pass}} = \left( \frac{W_{\text{pass}}}{W_{\text{pass}} + P} \right) \mathrm{EF}_{\text{veh, Cu, pass}}$$

$$\mathrm{EF}_{\text{POTW, Cu, MDV}} = \left( \frac{W_{\text{MDV}}}{W_{\text{MDV}} + P} \right) \mathrm{EF}_{\text{veh, Cu, MDV}}$$

$$\mathrm{EF}_{\text{POTW, Cu, HDV}} = \left( \frac{W_{\text{HDV}}}{W_{\text{HDV}} + P} \right) \mathrm{EF}_{\text{veh, Cu, HDV}}$$

In these equations, $W_{\text{pass}}$ is the number of times per year that the average passenger vehicle is washed at a commercial carwash, while $W_{\text{MDV}}$ and $W_{\text{HDV}}$ correspond to the number of times per year that the average medium-duty and heavy-duty vehicle, respectively, are washed at a commercial carwash. $P$ is the average number of significant rainfall events per year in Alameda County.

A separate means of determining how much brake lining material is removed from a vehicle at commercial carwashes requires consumer data on the average frequency of commercial carwash use along with data on the copper concentration of used wash water and the volume of water needed to wash a car. Information on copper discharges from commercial carwashes is probably more likely to be available for facilities that cater to passenger vehicles. This will provide a value for the quantity of brake lining copper removed from the average vehicle during a carwash. This combined with data on the average frequency of commercial carwash use can be used to calculate the amount of vehicle-adhered copper that is washed off at commercial carwashes. The equations are

$$\mathrm{EF}_{\text{POTW, Cu, pass}} = \frac{C_{\text{Cu, pass, CW}} V_{\text{pass}} W_{\text{pass}}}{D_{\text{pass}}}$$

$$\mathrm{EF}_{\text{POTW, Cu, MDV}} = \frac{C_{\text{Cu, MDV, CW}} V_{\text{MDV}} W_{\text{MDV}}}{D_{\text{MDV}}}$$

$$\mathrm{EF}_{\text{POTW, Cu, HDV}} = \frac{C_{\text{Cu, HDV, CW}} V_{\text{HDV}} W_{\text{HDV}}}{D_{\text{HDV}}}$$

In these equations, $C_{\text{Cu, pass, CW}}$ is the copper concentration in untreated effluent from a commercial passenger vehicle carwash, $V_{\text{pass}}$ is the average volume of water used to wash a passenger vehicle in a commercial carwash, and $D_{\text{pass}}$ is the average annual mileage on a passenger vehicle.

The emission factors for copper that is released to the road after adhering to the vehicle are

$$\mathrm{EF}_{\text{road-ind, Cu, pass}} = \mathrm{EF}_{\text{veh, Cu, pass}} - \mathrm{EF}_{\text{POTW, Cu, pass}}$$

$$\mathrm{EF}_{\text{road-ind, Cu, MDV}} = \mathrm{EF}_{\text{veh, Cu, MDV}} - \mathrm{EF}_{\text{POTW, Cu, MDV}}$$

$$\mathrm{EF}_{\text{road-ind, Cu, HDV}} = \mathrm{EF}_{\text{veh, Cu, HDV}} - \mathrm{EF}_{\text{POTW, Cu, HDV}}$$

Thus, the total copper released to the road from brake lining wear is

$$\mathrm{EF}_{\text{road-tot, Cu, pass}} = \mathrm{EF}_{\text{road-dir, Cu, pass}} + \mathrm{EF}_{\text{road-ind, Cu, pass}}$$

$$\mathrm{EF}_{\text{road-tot, Cu, MDV}} = \mathrm{EF}_{\text{road-dir, Cu, MDV}} + \mathrm{EF}_{\text{road-ind, Cu, MDV}}$$

$$\mathrm{EF}_{\text{road-tot, Cu, HDV}} = \mathrm{EF}_{\text{road-dir, Cu, HDV}} + \mathrm{EF}_{\text{road-ind, Cu, HDV}}$$

Table 4-1   Fraction of vehicles exposed to rain events of varying durations.

| Vehicle Category | Fraction of Vehicles Exposed to Rain Event of Duration *t* (where *t* is in hours) | |
|---|---|---|
| Passenger vehicles and light-duty trucks | $0.08t$ ($t < 12$ hours) | 1 ($t > 12$ hours) |
| Medium-duty vehicles | $0.3t$ ($t < 3$ hours) | 1 ($t > 3$ hours) |
| Heavy-duty vehicles and buses | $0.5t$ ($t < 2$ hours) | 1 ($t > 2$ hours) |

# 5 Summary

This document describes a work plan for inventorying the releases of copper due to brake lining wear in Alameda County. The approach requires development of an air emission factor specific to each category of vehicle using three largely independent sets of data. Emission factors for quantities that are released to the road and to the vehicle are based on the air emission factor, along with partitioning information gleaned from dynamometer tests of actual brake lining material. Data on rainfall events, the frequency with which vehicles are washed in a commercial carwash, and commercial carwash copper discharges will be used to determine the fraction of vehicle-adhered brake lining material that is discharged to publicly owned treatment works. Any vehicle-adhered brake lining material that is not discharged to a publicly owned treatment work will be assumed to be released to the road. Release estimates are made by multiplying the emission factors by vehicle miles traveled. The particle size distribution of air releases will also be taken from dynamometer tests.

# 6 Nomenclature (with a Potential Set of Units)

| | |
|---|---|
| $A$ | Mass fraction of disc brake lining debris that is released to air |
| $B_{\text{HDV, disc}}$ | Average number of heavy-duty vehicle axles that are disc brake-equipped |
| $B_{\text{MDV, disc}}$ | Average number of medium-duty vehicle axles that are disc brake-equipped |
| $B_{\text{BPP-disc}}$ | Average number of axles that are disc brake-equipped on the subset of passenger vehicles included in the Partnership survey |
| $B_{\text{new-disc}}$ | Average number of axles that are equipped with disc brakes on new-disc passenger vehicles |
| $B_{\text{new-drum}}$ | Average number of axles that are equipped with drum brakes on new-drum passenger vehicles |
| $B_{\text{old-disc}}$ | Average number of axles that are equipped with disc brakes on old-disc passenger vehicles |
| $B_{\text{old-drum}}$ | Average number of axles that are equipped with drum brakes on old-drum passenger vehicles |
| $C_{\text{Cu, bus, ave}}$ | Population-averaged copper concentration in bus brakes, mass fraction |
| $C_{\text{Cu, bus, drum}}$ | Copper concentration in bus brake shoes, mass fraction |
| $C_{\text{Cu, HDV, ave}}$ | Population-averaged copper concentration in heavy-duty vehicle brakes, mass fraction |
| $C_{\text{Cu, HDV, CW}}$ | Concentration of copper in untreated heavy-duty vehicle carwash effluent, lb/gal |
| $C_{\text{Cu, HDV, disc}}$ | 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 |
| $C_{\text{Cu, MDV, CW}}$ | Concentration of copper in untreated medium-duty vehicle carwash effluent, lb/gal |
| $C_{\text{Cu, MDV, disc}}$ | 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 |
| $C_{\text{Cu, pass, CW}}$ | Concentration of copper in untreated passenger vehicle carwash effluent, lb/gal |
| $C_{\text{Cu, pass, new-disc}}$ | 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 |
| $d_{\text{bus, drum}}$ | Distance traveled between drum brake lining replacements in buses, mi |
| $D_{\text{HDV}}$ | Average distance driven per year for a heavy-duty vehicle, mi/yr |
| $d_{\text{HDV, disc}}$ | Distance traveled between disc brake lining replacements in heavy-duty vehicles, mi |

| | |
|---|---|
| $d_{\text{HDV, drum}}$ | Distance traveled between drum brake lining replacements in heavy-duty vehicles, mi |
| $D_{\text{MDV}}$ | Average distance driven per year for a medium-duty vehicle, mi/yr |
| $d_{\text{MDV, disc}}$ | Distance traveled between disc brake lining replacements in medium-duty vehicles, mi |
| $d_{\text{MDV, drum}}$ | Distance traveled between drum brake lining replacements in medium-duty vehicles, mi |
| $D_{\text{pass}}$ | Average distance driven per year for a passenger vehicle, mi/yr |
| $d_{\text{pass, disc}}$ | Distance traveled between disc brake lining replacements in passenger vehicles, mi |
| $d_{\text{pass, drum}}$ | Distance traveled between drum brake lining replacements in passenger vehicles, mi |
| $\text{EF}_{\text{air, bus}}$ | Emission factor for airborne brake lining debris from buses, lb brake lining/mi |
| $\text{EF}_{\text{air, bus, drum}}$ | Air emission factor for brake lining debris from drum brakes in buses, lb brake lining/mi |
| $\text{EF}_{\text{air, Cu, bus}}$ | Emission factor for air releases of copper from buses, lb Cu/mi |
| $\text{EF}_{\text{air, Cu, HDV}}$ | Emission factor for air releases of copper from heavy-duty vehicles, lb Cu/mi |
| $\text{EF}_{\text{air, Cu, MDV}}$ | Emission factor for air releases of copper from medium-duty vehicles, lb Cu/mi |
| $\text{EF}_{\text{air, Cu, pass}}$ | Emission factor for air releases of copper from passenger vehicles, lb Cu/mi |
| $\text{EF}_{\text{air, HDV}}$ | Emission factor for airborne brake lining debris from heavy-duty vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, HDV, disc}}$ | Air emission factor for brake lining debris from disc brakes in heavy-duty vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, HDV, drum}}$ | Air emission factor for brake lining debris from drum brakes in heavy-duty vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, MDV}}$ | Emission factor for airborne brake lining debris from medium-duty vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, MDV, disc}}$ | Air emission factor for brake lining debris from disc brakes in medium-duty vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, MDV, drum}}$ | Air emission factor for brake lining debris from drum brakes in medium-duty vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, pass}}$ | Emission factor for airborne brake lining debris from passenger vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, pass, new-disc}}$ | Air emission factor for brake lining debris from factory disc brakes in passenger vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, pass, new-drum}}$ | Air emission factor for brake lining debris from factory drum brakes in passenger vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, pass, old-disc}}$ | Air emission factor for brake lining debris from non-factory disc brakes in passenger vehicles, lb brake lining/mi |
| $\text{EF}_{\text{air, pass, old-drum}}$ | Air emission factor for brake lining debris from non-factory drum brakes in passenger vehicles, lb brake lining/mi |

| | |
|---|---|
| $EF_{POTW, Cu, HDV}$ | Emission factor for POTW discharges of copper from commercial carwashes servicing heavy-duty vehicles, lb Cu/mi |
| $EF_{POTW, Cu, MDV}$ | Emission factor for POTW discharges of copper from commercial carwashes servicing medium-duty vehicles, lb Cu/mi |
| $EF_{POTW, Cu, pass}$ | Emission factor for POTW discharges of copper from commercial carwashes servicing passenger vehicles, lb Cu/mi |
| $EF_{road\text{-}dir, Cu, HDV}$ | Emission factor for direct releases of copper to the road from heavy-duty vehicles, lb Cu/mi |
| $EF_{road\text{-}dir, Cu, MDV}$ | Emission factor for direct releases of copper to the road from medium-duty vehicles, lb Cu/mi |
| $EF_{road\text{-}dir, Cu, pass}$ | Emission factor for direct releases of copper to the road from passenger vehicles, lb Cu/mi |
| $EF_{road\text{-}ind, Cu, HDV}$ | Emission factor for copper that is released to the road after adhering to heavy-duty vehicles, lb Cu/mi |
| $EF_{road\text{-}ind, Cu, MDV}$ | Emission factor for copper that is released to the road after adhering to medium-duty vehicles, lb Cu/mi |
| $EF_{road\text{-}ind, Cu, pass}$ | Emission factor for copper that is released to the road after adhering to passenger vehicles, lb Cu/mi |
| $EF_{road\text{-}tot, Cu, HDV}$ | Emission factor for all copper released to the road from heavy-duty vehicles, lb Cu/mi |
| $EF_{road\text{-}tot, Cu, MDV}$ | Emission factor for all copper released to the road from medium-duty vehicles, lb Cu/mi |
| $EF_{road\text{-}tot, Cu, pass}$ | Emission factor for all copper released to the road from passenger vehicles, lb Cu/mi |
| $EF_{veh, Cu, HDV}$ | Emission factor for copper that adheres to the vehicle after being released from heavy-duty vehicles, lb Cu/mi |
| $EF_{veh, Cu, MDV}$ | Emission factor for copper that adheres to the vehicle after being released from medium-duty vehicles, lb Cu/mi |
| $EF_{veh, Cu, pass}$ | Emission factor for copper that adheres to the vehicle after being released from passenger vehicles, lb Cu/mi |
| $f_{bus}$ | Mass fraction of bus brake lining material worn off at replacement |
| $F_{bus}$ | Mass fraction of wear debris that is brake lining material in buses |
| $f_{HDV}$ | 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 |
| $M_{bus, drum}$ | Mass of brake lining material on a drum-equipped bus axle, lb brake lining/axle |

| | |
|---|---|
| $M_{\text{HDV, disc}}$ | Mass of brake lining material on a disc-equipped heavy-duty vehicle axle, lb brake lining/axle |
| $M_{\text{HDV, drum}}$ | Mass of brake lining material on a drum-equipped heavy-duty vehicle axle, lb brake lining/axle |
| $M_{\text{MDV, disc}}$ | Mass of brake lining material on a disc-equipped medium-duty vehicle axle, lb brake lining/axle |
| $M_{\text{MDV, drum}}$ | Mass of brake lining material on a drum-equipped medium-duty vehicle axle, lb brake lining/axle |
| $M_{\text{pass, disc}}$ | Mass of brake lining material on a disc-equipped passenger vehicle axle, lb brake lining/axle |
| $M_{\text{pass, drum}}$ | Mass of brake lining material on a drum-equipped passenger vehicle axle, lb brake lining/axle |
| $N_{\text{HDV}}$ | Average number of axles per heavy-duty vehicle in Alameda County |
| $P$ | Average number of significant rainfall events per year in Alameda County |
| $R_{\text{new-disc}}$ | Fraction of passenger vehicles equipped with factory disc brakes |
| $R_{\text{new-drum}}$ | 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 |
| $t$ | Duration of rain event, hours |
| $V$ | Mass fraction of total brake lining wear debris that adheres to the vehicle after being released |
| $V_{\text{HDV}}$ | Average volume of water required to wash one heavy-duty vehicle, gal |
| $V_{\text{MDV}}$ | Average volume of water required to wash one medium-duty vehicle, gal |
| $V_{\text{pass}}$ | Average volume of water required to wash one passenger vehicle, gal |
| $W_{\text{HDV}}$ | Number of times per year that the average heavy-duty vehicle is washed at a commercial car wash |
| $W_{\text{MDV}}$ | Number of times per year that the average medium-duty vehicle is washed at a commercial car wash |
| $W_{\text{pass}}$ | Number of times per year that the average passenger vehicle is washed at a commercial car wash |