AIR DEPOSITION MODELING FOR THE ENVIRONMENTAL FATE AND TRANSPORT OF COPPER FROM VECHICLE BRAKE PAD WEAR DEBRIS

WORK PLAN

Submitted to

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1. INTRODUCTION AND OBJECTIVES

The Brake Pad Partnership (BPP) is coordinating a program of environmental monitoring, environmental modeling, and laboratory studies to understand how brake pad wear debris (BPWD) travels in the environment and the potential for impacts on water quality. Copper is a component of BPWD that potentially impacts surface water quality in the San Francisco Bay; hence copper is used as an example for this study. This project pertains to the atmospheric transport and deposition, which represent an important pathway between the emission of BPWD on roadways and the destination of interest, the San Francisco Bay.

A conceptual model of the atmospheric fate and transport of BPWD was presented by K. Moran (2003). Once released from the wheel well during a braking event, BPWD particles can adhere to the vehicle, become airborne, or deposit onto the road surface. The fraction of BPWD that becomes airborne represents "direct" emissions from the view point of air deposition modeling. Airborne BPWD is dispersed by wind. Some portion of material may be carried beyond the watershed of concern. As the BPWD is transported, a fraction of the material will deposit within the watershed on roadways, on buildings, on vegetation, on creeks and rivers, and on the Bay itself. The BPWD that deposits on roadways, together with the portion initially released onto the roadways, becomes a reservoir for "indirect" emissions when road dust are entrained into the air by passing vehicles. Two types of deposition processes are of concern. Dry deposition refers to the removal of particles as they are brought into contact with the ground, vegetation, or structures by atmospheric turbulence or by gravitational settling. Wet deposition of particles typically happens when they are removed from the air by falling rain drops. Air deposition onto the estuary and onto the Bay itself is one of the pathways for BPWD to enter the Bay. BPWD that deposit onto other areas of the watershed can also enter the Bay via storm drains and runoffs into the estuary. The processes included in this model investigation, emissions, air dispersion, and wet and dry deposition, are shown in Figure 1.

This air modeling project serves a dual purpose. First, the air deposition of BPWD directly onto the Bay will be estimated. Second, estimated deposition of BPWD

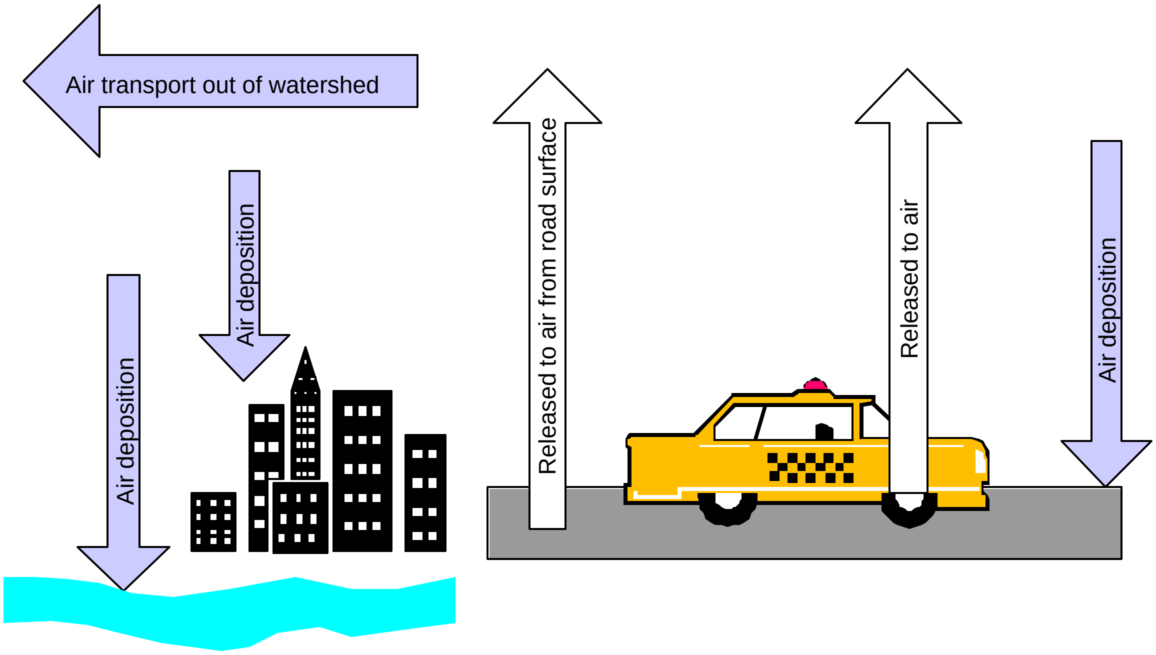

Figure 1. Conceptual model of atmospheric fate and transport of BPWD.

onto other parts of the watershed will be provided to the watershed modelers who will calculate other fluxes of BPWD into the Bay.

2. MODELING APPROACH

BPWD is emitted as fine and coarse particles. While coarse particles (aerodynamic diameter greater than 2.5 µm) may deposit fairly close to the source, fine particles have an atmospheric lifetime of several days in the absence of precipitation and can be transported hundreds of km from the source. For the Castro Valley watershed, BPWD may originate from local roadways (e.g., Highways 580, 880, 238, and 13 and surface streets in Castro Valley, Hayward, San Leandro, and surrounding cities) or from other parts of the San Francisco Bay Area and beyond. This range of spatial scales need to be taken into account in the design of a modeling strategy. A multiscale approach was selected for this work, where a box model will be used to simulate the regional background (excluding emissions from the Castro Valley watershed) and a detailed source model will be used to simulate local impacts. The proposed domains for regional and local modeling are shown in Figure 2. Local impacts will be simulated at finer spatial and temporal resolution compared to the regional background. Results from the regional and local models will be summed for the Castro Valley watershed. For other locations, a scaled regional background (without emissions from that location) can be deduced based on the total emissions to be considered in the regional context. Local impacts are then added. The local results from Castro Valley will be scaled based on local emissions to represent the variability at different land use types based on the proximity to sources.

A modeling period of one year will be analyzed by averaging data from a 5-year simulation so as to provide representative estimates for both wet and dry seasons.

The detailed modeling approach is presented in Figure 3. The modeling procedure is designed to accomplish both the modeling and sensitivity study objectives in the Association of Bay Area Governments (ABAG)/BPP contract (Tasks 2-4 in the BPP contract). The collection of data needed to provide inputs to air deposition modeling is described in Section 2.1. With each input, the associated uncertainties will be compiled

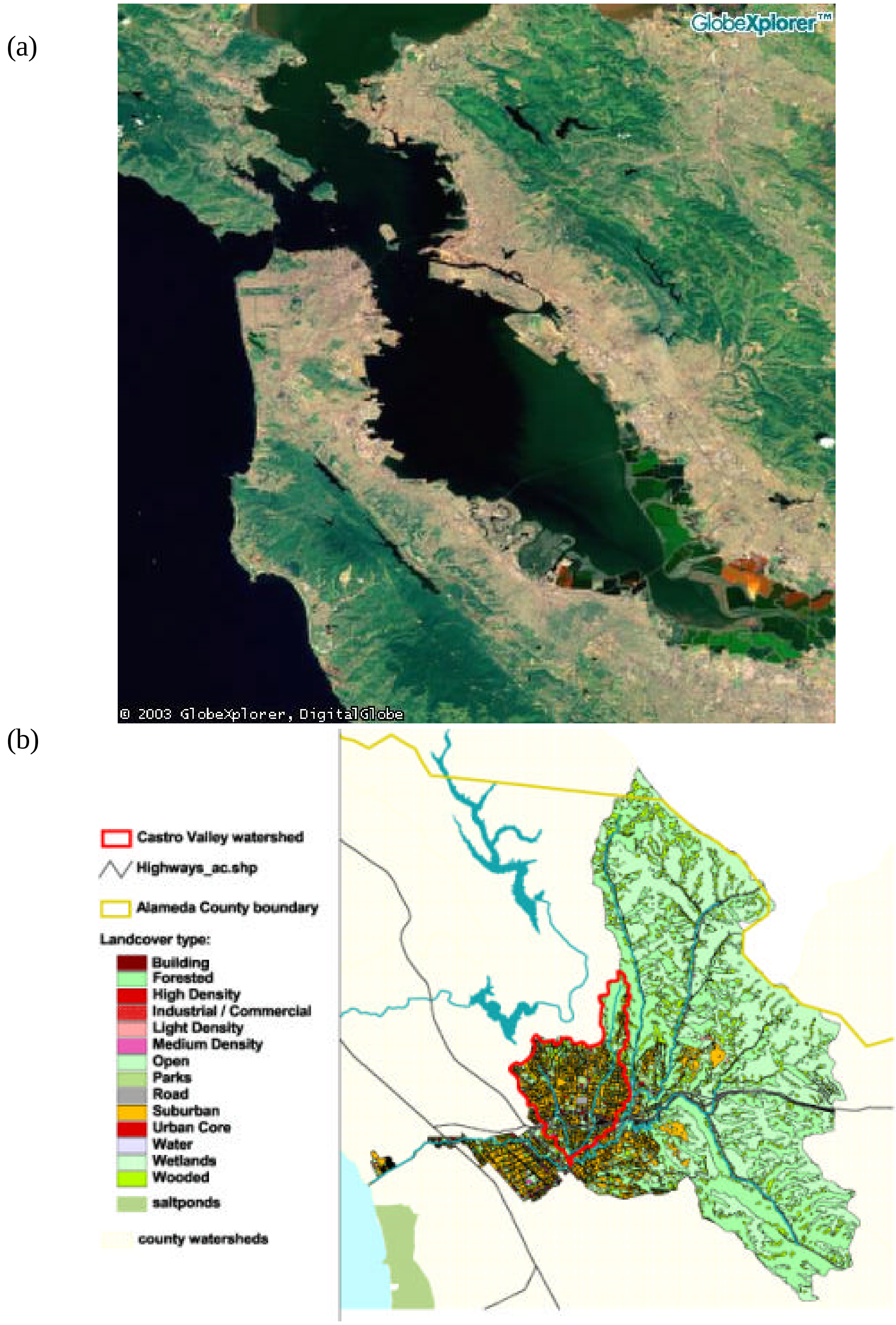

Figure 2. Proposed domains for multiscale modeling: (a) San Francisco Bay Area domain for the box model simulation of regional background (source: http://www.mapquest.com, 2003), (b) the Castro Valley Watershed domain for ISC-ST simulatio of local impacts (source: Pendergast, 2003).

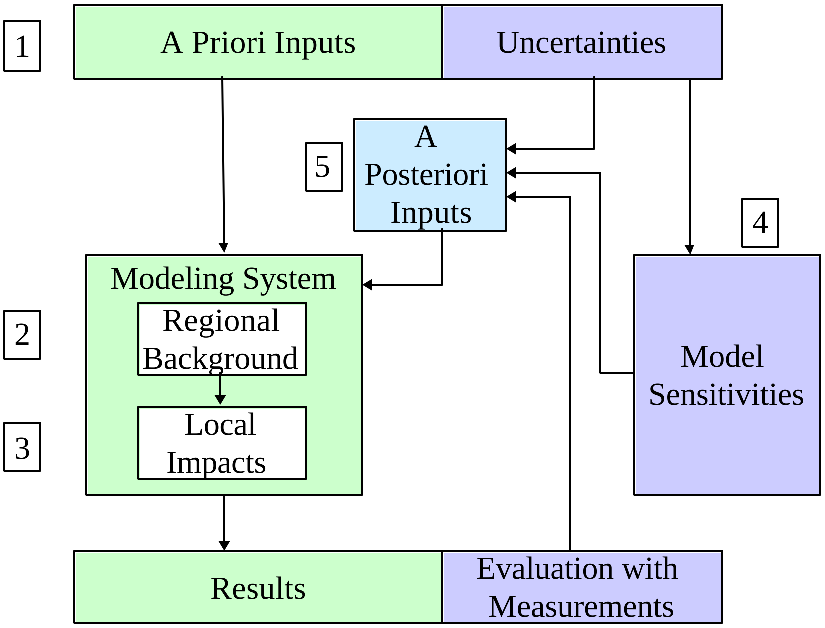

Figure 3. Air Deposition Modeling Tasks

to the extent possible. The modeling system contains a regional model and a local model in this multiscale approach. The set up of the regional model will be discussed in Section 2.2, followed by a discussion of the local model in Section 2.3. After the model is set up, a variety of sensitivity simulations will be pursued to investigate the effects of uncertainties in the inputs on the estimates of the deposition fluxes (Section 2.4). When measurements of dry and wet deposition are available, that information will be combined with the sensitivity analysis to guide the development of a set of a posteriori results, as discussed in Section 2.5, for the final air deposition modeling run that will provide inputs to the watershed models.

2.1 Development of Inputs and Uncertainties

2.1.1 Direct emissions

Direct air emissions copper from BPWD are characterized as follows:

$$\begin{aligned} E_d \text{ (gCu/day)} = &\text{ Air emission factor (gBPWD/mile or gBPWD/stop)} \\ &\times \text{ copper content of BPWD (gCu/gBPWD)} \\ &\times \text{ traffic activity (vehicle miles traveled/day or vehicle stops/day)} \end{aligned} \tag{1}$$

The air emission factor for BPWD used in EPA's MOBILE 6 (EPA, 2003a) and California's EMFAC7g mobile emission models is 13 mg/mi for PM_{10}. This factor originated from an older study (Cha et al., 1983) on asbestos brakes that are no longer commonly used. More recently, several research studies have been conducted to quantify BPWD emissions, e.g., Garg et al. (2000) and Sanders et al. (2002, 2003). In these studies, emission factors for BPWD are estimated in terms of grams per stop or per vehicle mile traveled (VMT), see Table 1. Direct air emissions for BPWD can be decomposed into two processes, the generation of BPWD and a fraction of BPWD becoming airborne. Both the amount of BPWD emitted and the airborne fraction are functions of the brake pad formulation, vehicle type, and driving conditions (i.e., brake temperature). Because traffic data are available as VMT, as a first step, we will determine whether to use data reported per stop (which will need to be converted to a VMT basis) or per VMT. Second, we will determine if sufficient data exist to separate emission factors by brake type (or by vehicle types). Third, we will select the appropriate factor or factors to use for this study based on previous BPWD characterization studies and on other information available in the published literature. The range of measured values will also be documented to provide an estimate for the uncertainties associated with the emission factors.

Table 1. Recent data on BPWD air emission factors and destination distribution from two sources, Garg et al. (2000) and Sanders et al. (2003).

Source	Quantity (units)	Median	Range	Notes
Garg et al. (2000)	Air BPWD emission rate (1) (mg/stop)	0.94	0.11 – 10.8	mean = 18, standard deviation = 2.3; distribution not normal
	BPWD emission rate (mg/mi) (2)		5.1 – 14.1	from small cars to large pickup trucks; based on engineering estimates
Sanders et al. (2003)	Airborne BPWD emission rate (mg/stop) (3)	2.1	1.1 - 11.7	PM_{10} mass emissions rate measured, with a median of 2 and a range of 0.9-10.7

(1) 7 brakes tested, including 3 semi-metallic, 2 potasssium titanate (non-asbestos), aramid and copper fiber, 1 aramid, mineral and copper fiber, and 1 aramid fiber

(2) calculated based on engineering estimates of brake wear rates

(3) urban dynamometer program data compiled for three different types of brakes: low metallic, semi-metallic, and non-asbestos; Sanders et al. also tested 1.8 m/s^2 deceleration braking events, with substantially (factors of 4-6) higher emissions

To determine the emissions of copper, the fraction of copper in BPWD needs to be determined. There is some evidence that there is negligible segregation of the elemental ingredient of brake pads during the wear process (Sanders et al., 2003). Therefore, as a first order assumption, the copper content of BPWD is the same as that in the brake pads. Brake pad compositions are quite variable (see Table 2). Therefore, it is desirable to include a range of copper content in our estimates to the extent supported by available data, particularly if several different brake types are represented in the emission estimates. We will characterize copper emissions using a best estimate and an associated range of uncertainty (lower and upper bounds, or by types of brakes). These estimates will be based on available data on copper content of brake pads.

Table 2. Copper content of BPWD

Source	Copper content (weight %)	Notes
BPP, 2003	2.9 - 4.5	top 20 best selling model vehicles in 1998, 1999, 2000, and 2001
Sanders et al. (2003)	1.2 – 3.4	Low metallic linings road vs. dynamometer tests
Garg et al. (2000)	0 – 14	7 different brake pads
von Uexküll (2002)	0 – 67	samples of pads and dust from disc and drum brakes (European autos)

Traffic activity data are needed to establish the direct emissions of BPWD. In addition, such data are used to distribute BPWD emissions on highways vs. local roads. Details on activity data are provided in Section 3.1.4.

2.1.2 Indirect emissions

A fraction of BPWD is released onto the surface of the roadway. Some fraction of airborne BPWD will also deposit onto roadways. The passage of traffic resuspends BPWD-containing dust from the roadways, and causes indirect emissions of BPWD. Therefore, a comprehensive description of this indirect source requires the incorporation of the resuspension mechanism in the model that calculates atmospheric deposition. Based on EPA's compilation of air pollutant emission factors (AP-42, EPA, 2003b), the emission of dust from vehicle traffic on paved road may be estimated using the following empirical formula:

$$E_{dust} = 1.8\ (sL / 2)^{0.65}\ (W/3)^{1.5} \tag{2}$$

where E_{dust} is the $PM_{2.5}$ emission rate from vehicle traffic on a paved road (g /VMT); sL is the silt content of road surface; and W is the average weight (tons) of vehicles traveling the road (which depends on traffic activity). The emission of resuspended dust is assumed to be negligible during a rain event. The indirect emission rate of copper present in BPWD is obtained by multiplying E_{dust} by the fraction of copper associated with BPWD present in road dust. The BPWD copper content in roadway dust can be estimated as the sum of direct BPWD copper emissions onto roadways and the air deposition fluxes of BPWD copper to roadways.

Since Equation 2 is empirical in nature, its applicability to the emissions of BPWD dust includes uncertainties. In addition, the parameters employed in Equation 2, sL and W, are also subject to uncertainty and variability. For example, sL ranges from 0.02 to 400 g/m^2 and W ranges from 2 to 42 tons. From the view point of a mass balance, the indirect source of copper in BPWD through dust resuspension should be smaller than or equal to the sum of the amount of BPWD copper released onto the road plus the fraction of airborne BPWD copper deposited to the road. Such an estimate will be used as a consistency check.

We will estimate the resuspension of BPWD copper as follows. First, a simulation will be conducted to estimate BPWD copper on road surface due to deposition. (As a sanity check, an upper limit of the BPWD copper on road surface due to air deposition can be obtained by assuming that all BPWD copper that is directly emitted into the air undergoes deposition.) We assume that deposited BPWD copper accumulates between rain events, and that such events wash BPWD off road surfaces as a function of rain duration (Carleton and Cocca, 2004). We will coordinate with the watershed modeler to determine the appropriate wash-off function to use during a rain event. In between rain events, BPWD copper accumulating on roadways due to deposition will be calculated by integrating the dry deposition fluxes since the last rain event. This term will be incorporated in the 5-year average models using a monthly average value for days without precipitation. The sum of initial BPWD remaining on roads after the previous rain event, the deposited BPWD copper and the BPWD copper that is originally released onto the road surface will be used as the BPWD copper present on roadways. This quantity will then be used with Equation (2) to estimate the resuspension source term on days without precipitation.

The amount of BPWD directly released onto the road should be proportional to the air emissions. As shown in Table 3, Garg et al. (2000) and Sanders et al. (2002, 2003) provided information on the destination of the BPWD (i.e., direct emission to the atmosphere, deposition to the road and adhesion to the vehicle). Uncertainties associated with the fate of BPWD are quite obvious from the entries of Table 3. Note that the portion of emissions released onto the road surface is subject to similar uncertainties pertaining to the copper content of BPWD as direct emissions described under the previous section.

Table 3. Fate of BPWD

Source	Quantity (units)	Median	Range	Notes
Garg et al. (2000)	Fraction of airborne BPWD	0.21	0.07-0.48	Temperature dependent, lowest fraction (0.16) at higher temperatures (300-400 C), fractions at 100 C and 200 C are 0.35 and 0.24, respectively
Sanders et al. (2002)	Fraction of airborne BPWD		0.2–0.53	Data for asbestos brakes not included
	Fraction on roadways	0.05	0.03– 0.3	Based on 3 different brake types
	Fraction on hardware	0.1	0.08-0.25	As above
	Fraction on wheels	0.19	0.16-0.22	As above
Sanders et al. (2003)	Fraction of airborne BPWD		0.5 – 0.7	Sanders et al. (2003) corrected the Garg et al. average of 0.35 to 0.64 assuming sampling loss in that study.
Trainer (2001)	Fraction of airborne BPWD	0.47		One reported value

2.1.3 Particle size distribution of BPWD

Information on the particle size distribution of BPWD is needed for the calculation of both wet deposition and dry deposition. Data available from Garg et al. (2000) and Sanders et al. (2003) indicate that the size distribution of BPWD may be a function of temperature and brake pad materials, as shown in Table 4. It is conceivable that the fraction of BPWD that is released to roadways has a characteristic size distribution that is different from that of airborne particles. Hence, the size distribution characteristic of indirect emissions (resuspension) may be different from that of direct emissions. With guidance from the BPP Steering Committee, we will develop appropriate characterizations of the size distribution for direct and indirect emissions from available data for the first round of modeling. Measurements conducted by BPP on particle size distribution of representative airborne and fall-out BPWD will be incorporated as they become available.

Aerodynamic diameters are typically measured while Stokes diameters are used in models. These two quantities are related via the density of particles. Trainer (2001) reported a value of 2.98 g/cm^3 for BPWD, and Sanders et al. (2002) measured a range of 2.32 to 2.94 g/cm^3 for different brake materials.

Table 4. Measurements of mass mean diameters (mmd) (μm)

Source	mmd	Notes
Garg et al. (2000)	2.49 ± 3.47	100 C
	0.62 ± 0.53	200 C
	1.4 ± 1.22	300 C
	1.43 ± 1.03	400 C
Sanders et al. (2003)	3.9 to 5.9	PM_{10} from low metallic brakes with MOUDI vs. ELPI (1)
	6.2 to 7.2	total mass mean diameter by MOUDI for low metallic brakes
	~5 to 6.2	extrapolated from ELPI PM_{10} measurements to all particles for three types of brakes
von Uexküll (2002)	1 to 5	Mode of lognormal mass distribution

(1) MOUDI stands for micro-orifice uniform deposit impactor; ELPI stands for electrical low-pressure impactor

2.1.4 Traffic activity data

While the emissions of BPWD is naturally associated with braking events, traffic data on the number of stops on particular stretches of roadways are not available. Therefore, VMT data will be used to establish the source of direct BPWD emissions (Equation 1). Data on vehicle miles traveled (VMT) are available from the Metropolitan Transportation Commission (MTC) by counties. The total VMT data for the Bay Area Counties will be used to determine the direct air emissions for the regional background model, as well as the amount of BPWD deposited onto roadways that may be re-emitted as an indirect source.

For the local simulation, VMT data on highway vs. city streets (available from the California Department of Transportation and Metropolitan Transportation Commission) will be used to distribute the emissions of BPWD as a function of space. Supplemental data may also be available from Alameda County and the Bay Area Air Quality Management District (BAAQMD). Temporal resolution (e.g., for different days of the week, hours of each day, if available) will be used to distribute the emissions of BPWD as a function time.

Because different types of brakes may be used in different vehicle types, traffic activity data by vehicle type (up to 13 vehicle types including passenger vehicles, trucks, buses and motorcycles), will be used, if available (e.g., from the BAAQMD), to refine the VMT estimate that is pertinent for the emission of copper. In that event, we will discuss/confirm with the BPP Steering Committee the degree to which traffic data by vehicle type or class can correlate to BPWD and if it is effective to distribute BPWD emissions by vehicle types in the air deposition modeling effort.

We will conduct "sanity checks" to assure the quality of the emissions data. For example, are the relative emission factors (per mile) for BPWD and vehicle exhaust consistent with the relative urban concentrations of these two types of vehicle-related emissions (using data available from chemical mass balance analyses (e.g., Kenski, 2002))? If traffic activity data are available on the number of stops as well as VMT, do the two approaches to calculate emissions, using emission factors per miles and per stop, give consistent results?

2.1.5 Meteorological data

For the background and local conditions, we propose to work with an "averaged year" by averaging the results of five years (e.g., 1998 to 2003) with different meteorology. 2004 data will be used in the event a complete data set becomes available within the time frame of the project. We plan to use this approach because it is difficult to defend any choice of a specific year to be representative of the conditions in the Bay Area even if the selected year is free of extreme climate conditions (e.g., drought, El Niño). With this modeling strategy, deposition results will be representative of typical meteorological conditions, but will not be directly comparable to measurements taken during any given year.

Meteorological data are available for a fee from the National Climatic Data Center. Surface data have been pre-compiled for 1995 to 2002. More recent data can be purchased via special order. Upper air data (mixing layer height) need to be special ordered for the modeling period. Surface and upper air meteorological data are available at Oakland Airport; supplemental data may be available at the Hayward Airport, although the quality of the Hayward data is unknown.

Meteorological inputs needed for the regional model include rainfall amount and duration, stability class, temperature, pressure, wind speed, and mixing layer height. Precipitation is needed for the calculation of wet deposition. Stability class, temperature, pressure, wind speed and mixing layer height are needed for the calculation of dry deposition. Wind speed and mixing layer height will be used in the simulation of horizontal transport and vertical mixing. In addition, specific inputs required by the local impacts model (ISC-ST) include friction velocity, Monin-Obukhov length, roughness height, radiation, leaf area index, precipitation type, and precipitation rate. Both surface and upper air data are required for temperature and wind for the local model.

2.1.6 Summary of data needs

The data needed to conduct air deposition modeling, together with the anticipated data sources, are listed in Table 5. In many instances, the available information is incomplete or conflicting. AER will relay on guidance and expertise in the BPP Steering Committee to make the most defensible use of available information.

Table 5. List of data needs, information, and guidance

Data	Source	Guidance Needed
Emission modeling strategy (1)		1. A more detailed approach by types of brakes and by class of vehicles vs. a simpler approach using an average vehicle. The BPWD and traffic data need to be in the same resolution.
Total BPWD (1,2)	Literature (initial phase) and BPP measurements	1. Deriving meaning numbers out of conflicting information (see Table 1) 2. Conversion mg/stop number to mg/VMT, if needed
Copper content (1,2)	BPP	1. Combining data from different years that may be representative of different fractions of vehicles? 2. Extrapolation to on-road fleet that may use original equipment and after-market brakes? 3. Combining data from different brake types or different individual brake pads (Table 2)
Fraction of BPWD emitted to air, road, or vehicle (1,2)	Literature (initial phase) and BPP measurements	1. Best estimate based on literature values (Table 3) 2. Adjustment from experimental conditions to road conditions
Representation of particle size distribution (1)		1. Strategy of representation (mean, mean and width of particle size distribution, or detailed shape of particle size distribution) 2. Need for distinct distribution for airborne vs. road-bound BPWD
Mass mean aerodynamic diameter(1,2)	Literature (initial phase) and BPP measurements	1. Best estimate based on literature values (Table 4)
Traffic activity(1)	MTC, BAAQMD, Alameda county	1. Use VMT vs VMT by vehicle class 2. Existence of other traffic data (stops, average speed)
Meteorology(3)	NCDC	1. Possibility of using data from local rainfall gauges
Rain wash-off function(1)	BPP/watershed modeler	1. Coordination to use a wash-off function and parameters consistent with the watershed model.
Road silt content	AP-42	
Vehicle weight	BAAQMD	

(1) Direct and indirect source term guidance needed before modeling activity starts; preferably by March 15. On this date, the modeling strategy will be finalized, although parameters (e.g., mass mean aerodynamic diameter) can be updated before final model evaluation run.

(2) Measurements or any updated information on source term to be received by October 15, to be incorporated into model evaluation run

(3) We will use existing meteorological data to set up the model. Meteorology data will be fixed after they are purchased for this project (tentative purchase date June 2004).

2.2 Regional Scale Modeling

A box model will be used to provide the background estimates of BPWD deposition. The modeling domain will cover most of the San Francisco Bay Area and will include the counties of San Francisco, San Mateo, most of Alameda, and parts of Santa Clara, Contra Costa, and Marin (see Figure 1 for the proposed domain).

In the regional background simulation, emissions from the local modeling domain (see Section 2.3) will be removed to avoid double counting of the emissions. Therefore, local impacts can be superimposed on the regional background for the Castro Valley watershed to determine air deposition of BPWD in that area.

The box model (Pun and Seigneur, 2001) will include all significant physical transport processes that govern the atmospheric concentration and deposition fluxes of BPWD and its copper content. Such processes include dry deposition, wet deposition, emissions, horizontal transport, and vertical mixing. We are not aware of any chemical reactions and/or phase transition of BPWD and particulate copper; hence, these particulate matter (PM) components will be treated as inert species in the simulations. Coagulation between BPWD and other particles will be ignored.

The dry deposition flux, F_d, is typically expressed as the product of the concentration of the species of interest, C, and a deposition velocity, V_d.

$$F_d = C\ V_d \tag{3}$$

The Venkatram and Pleim (1999) formulation is used for the dry deposition velocity.

$$V_d = \frac{V_g}{\left(1 - e^{-rV_g}\right)} \tag{4}$$

where r is the sum of aerodynamic resistance, quasi laminar layer resistance, and surface resistance (typically assumed to be zero for particles). V_g is the particle settling velocity due to gravity.

Wet deposition of particles is the result of two different processes: in-cloud scavenging (rainout) and below-cloud scavenging (precipitation scavenging or washout). In-cloud scavenging comprises nucleation scavenging (particles that act as cloud condensation nuclei growing into cloud droplets) and interstitial aerosol collection, which is a slow process (Seinfeld and Pandis, 1998). Because BPWD are emitted at the surface and we are studying their fate and transport in a limited domain (the Bay Area), BPWD are unlikely to be present in significant concentrations at cloud heights. Therefore, in-cloud scavenging is not considered important for BPWD in this study and we will only consider washout as the wet deposition route.

The change of mass of particles, M_p, due to below-cloud scavenging during a rain event is modeled as follows:

$$d M_p / dt = - \Lambda M_p \tag{5}$$

where Λ is the scavenging coefficient, which can be characterized as a function of rainfall intensity, rain drop size, and the size distribution of particles (Seinfeld and Pandis, 1998, Figure 20.12). Given that Λ is very variable depending on the particle size distribution parameters and data on the size of raindrops may not be readily available, wet deposition estimates may be quite uncertain due to uncertainties in the size distribution characteristics of BPWD particles. Such uncertainties will be investigated in sensitivity model runs and the effects on deposition estimates will be documented and communicated to BPP and its contractors.

Regional emission inventories of BPWD and copper will be used in this simulation with relatively coarse spatial and temporal resolution. Total air and road surface emissions of BPWD will be estimated based on the methodology outlined in Section 2.2. First, we will run a preliminary simulation with air emissions to estimate the deposition onto roadways of BPWD directly released to the air. The results of this simulation combined with the direct release of BPWD to roadways will then be used to estimate the source term for the resuspension of BPWD from roadways. Then, the base case simulation will be conducted with both direct air emissions and resuspension.

The regional model will be run for 5 years with daily varying meteorology. Results of the background air concentration of BPWD and wet and dry deposition fluxes due to emissions of BPWD outside the Castro Valley watershed will be aggregated to a temporal resolution of one month. The monthly average background air concentrations will be added to the local simulation. The deposition flux due to regional emissions will be included in the estimation of indirect sources (i.e., resuspension) for the local simulation for that given month.

2.3 Local Scale Modeling

Local impacts will be estimated using the dispersion model ISC-ST (EPA, 1995). ISC-ST stands for the Industrial Source Complex (Short Term) model and is an EPA-approved model for local air dispersion modeling. While it was originally developed to model industrial sources, EPA has applied ISC for the modeling of urban areas (EPA, 1999). We propose to use ISC on a domain centering on the Castro Valley watershed (Figure 2), with a Cartesian grid of receptors that extends about 100 km in each direction. We will design the grid based on the resolution desired for the receptor points, in coordination with the watershed modeler. Model results will be generated for an average year. We will use the same temporal span (average of five years) as selected for the modeling of the background concentrations.

ISC-ST is a computationally efficient model that treats transport, dispersion, dry deposition and wet deposition. The treatment of dry deposition in ISC-ST is very similar to that presented in Equation 3, using a deposition velocity to calculate the dry deposition flux. In ISC-ST, the deposition velocity is a function of the aerodynamic resistance (r_a), the quasi laminar layer resistance (r_b), and the gravitational settling velocity (V_g) as follows:

$$\mathrm{V_d} = \frac{1}{r_a + r_b + r_a r_b \mathrm{V_g}} + \mathrm{V_g} \tag{6}$$

While the mathematical formulation is different from Equation 4, there should be little practical difference (Venkatran and Pleim, 1999).

Wet deposition by below-cloud scavenging (washout) is treated in ISC-ST. The wet deposition flux (F_w) is defined as follows.

$$F_w = \int_z \lambda C dz \tag{7}$$

where C is the concentration of BPWD in the mixing layer, λ (s^{-1}) is the scavenging coefficient. The scavenging coefficient is the product of the precipitation rate (mm/hr) and r_c, a scavenging parameter (hr/mm/s). r_c depends upon the particle size distribution and the nature of precipitation.

Direct and indirect emissions of BPWD and copper will be represented in detail in the local simulation. Total emissions will be calculated using traffic activity within the domain of the local simulation. We will then distribute the emissions spatially and temporally. For spatial allocation, these emissions will be distributed onto highways and surface streets using a Geographic Information System (GIS), if needed. Line sources (represented by elongated area sources in ISC) will be used for highways and area sources will be used for traffic distributed on surface streets. Traffic data (e.g., VMT) by different vehicle types and by road types will be used to refine the spatial distribution of BPWD. We will also use available information regarding the distribution of traffic as a function of time and day-of-the-week to add temporal resolution to the emissions.

ISC-ST outputs atmospheric concentrations and wet and dry deposition fluxes at all receptor locations. ISC-ST provides a choice for the temporal resolution for the output, annual average, seasonal average, or with finer time resolution. We will coordinate with the watershed modeler in our selection of the appropriate output format, so as to provide data required for the watershed model in a mutually agreeable format. We plan to provide the output to BPP and the watershed modeler in October 2004. Furthermore, the deposition results can be presented as contour plots, which can be used to aid the selection of appropriate monitoring sites. We will coordinate with the air deposition monitoring contractor regarding the selection of representative monitoring locations and appropriate measurement frequency and duration based on the modeling results.

We plan to set up the models and complete the nominal base case for regional and local modeling within 6 months after the work plan is approved.

2.4 Analysis of Model Sensitivities to Input Uncertainties

Since our modeling approach zooms in onto the Castro Valley watershed, we do not anticipate the need to calibrate the model to local conditions. After a nominal estimate is obtained, we plan to use the models in a series of sensitivity studies to investigate key areas of uncertainties identified in the input data and other parameters. Potential sources of uncertainties include:

- air emission factors of BPWD
- copper content of BPWD
- fraction of BPWD on road surfaces that is subjected to indirect emissions
- parameters in the dust emission equation (e.g., silt content, weight of vehicles)
- characteristics of BPWD (e.g., particle size distribution and density)
- traffic activity data
- the distribution of VMT onto highways vs. local roads
- meteorological data used in the calculation of wet and dry deposition, including the spatial variability of rainfall
- wet deposition parameters

The goals of this task are to (1) provide uncertainty bounds on the air deposition estimates, (2) identify the relative importance of the various air transport mechanisms, and (3) identify key parameters whose uncertainties contribute to uncertainties in the deposition estimates, and recommend additional measurements to BPP, if warranted. For example, existing data for the size characteristics of brake dust appear quite variable, ranging from a mass-median diameter of 0.6 to 2.5 μm in Garg et al. (2000) to a mass mean diameter of 6 μm in Sanders et al. (2003). Additional data on the size distribution will probably be useful for reducing uncertainties in this parameter if our sensitivity study confirms its importance for BPWD deposition. We will conduct the sensitivity analysis and communicate our results to BPP within 2 months after the base run is completed.

2.5 Developing Best Estimates of Deposition

We propose to conduct air deposition modeling in a phased approach. We will evaluate the air deposition predictions against available data, including measurements taken by BPP contractors. Such a comparison cannot and will not be used to "calibrate" the model. Wet and dry deposition measurements of copper in the atmosphere will contain copper originating from brake pads among other sources, which are not represented in the models. Therefore, the measurements should represent an upper bound for the modeled values. The comparison will also be semi-quantitative in the sense that the meteorological conditions modeled will be an average of several years, while the measurement conditions will be specific to 2004. The measurements will include both wet and dry deposition and will be taken during winter 2004 and spring/summer 2004. Therefore, a full year of measurements will not be available. For consistency, we will compare the modeling results for total deposition of copper to the measurements for the seasons when measurements took place. In addition, we will compare the modeled relative amounts of wet and dry deposition, relative amounts of winter versus spring/summer deposition, relative amounts of week day versus week-end deposition and relative amounts of deposition at different sites to the corresponding measured values. Such comparisons will allow us to evaluate the ability of the model to reproduce the process, temporal and spatial variability observed in the measurements.

Armed with the knowledge of uncertainties associated with many input parameters and results from the sensitivity analyses, we will identify opportunities to improve model performance by using alternative input values that are consistent with available data. The final round of modeling will also take advantage of new measurements of key parameters to improve the model. We will provide our best estimate deposition fluxes to the watershed modelers and document our choices of inputs as well as key areas of remaining uncertainties

We anticipate completing the modeling no later than November 2004, so that a draft final report can be prepared to meet the November 2004 deadline.

3. REPORT, COORDINATION AND MEETINGS

We will participate in meetings with the BPP project team, steering committee and scientific advisory team on a regular basis, either in person or by teleconference. We understand that meetings will be held quarterly or at higher frequencies. We will prepare presentations and provide information to support the BPP Stakeholder Communication Plan.

We will coordinate with the BPP project team to ensure the most effective use of the study results. Several critical areas were identified in the technical approach section. First, we will identify key areas of uncertainties that affect the air deposition results. The uncertainty analysis can be used to guide experimental data collection aimed to reduce uncertainties in the modeling of BPWD. In particular, we will provide inputs to the brake wear debris characterization subcontractor regarding modeling data needs (e.g., further characterization of the BPWD particle size distribution). Second, because the air deposition modeling results will be used in the watershed model, it is important that we understand the need of the watershed model and provide the data required in an easy-to-use format. Finally, we have already interacted with the air deposition monitoring team to provide guidance on the selection of sampling site location, sampling period and frequency. We will coordinate with the San Francisco Estuary Institute to provide inputs regarding data and format needed for model evaluation.

We will provide brief written monthly progress reports to BPP and stakeholders via e-mail and brief quarterly verbal updates to the steering committee.

We will submit a draft final report no later than December 15, 2004. The final version of the report will be submitted within two weeks of receiving comments from BPP. The report deliverable will be provided in Acrobat and Microsoft Word formats.

4. SCHEDULE

Table 6. Project time line.

Task	**Date**
Start date	1 December 2003
Task 1 - Work plan	19 December 2003
Task 1 - Revised work plan	30 January 2004
Task 2 - First round modeling	15 September 2004 (*, 1)
Task 3 - Sensitivity study	15 November 2004 (*, 2)
Task 4 - Last iteration of modeling	30 November 2004 (3)
Task 5 - Draft final report	15 December 2004
Task 5 - Final report	30 January 2005 (*, 4)

* tentative date
1. 6 months after receipt of guidance from BPP Steering Committee regarding source term
2. 2 months after first round modeling is completed
3. 1 month after monitoring data become available for evaluation
4. 2 weeks after the receipt of comments from BPP (BPP to provide comments 1 month after the receipt of the draft report)

5. BUDGET

Our budget by task is listed below:

Table 7. Project budget.

Task	**Budget**
Task 1 - Work plan	$5,460
Task 2 – First round modeling	$43,256
Task 3 – Sensitivity study	$8,772
Task 4 – Last iteration of modeling	$3,568
Task 5 – Report	$8,272
Task 6 – Coordination, meetings	$5,608

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