Methodology for Estimating Fugitive Windblown and Mechanically Resuspended Road Dust Emissions Applicable for Regional Air Quality Modeling

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ABSTRACT

Several years ago the Western Governors' Association (WGA), in conjunction with federal, state, tribal and local entities, formed the Western Regional Air Partnership (WRAP) whose goal is to develop and plan regional programs that will reduce emissions and improve visibility in the Western US. One of the major conclusions reached by the Grand Canyon Visibility Transport Commission (the predecessor organization to WRAP) was that fugitive windblown dust and mechanically resuspended paved and unpaved road dust accounted for a large fraction of the visibility degradation occurring at Class I sites in the west. Over the past year, members of WRAP have worked with a panel of air quality experts from both the private and public sectors to identify the best methodology for developing an emission inventory for fugitive windblown dust and mechanically resuspended road dust that contribute to regional haze. This paper will present the expert panel's findings and identify recommendations for future research activities for improving fugitive dust emissions estimation techniques applicable for regional scale air quality modeling.

INTRODUCTION

The Grand Canyon Visibility Transport Commission (GCVTC) was created in response to the Clean Air Act of 1990 with the goal of identifying measures that could be implemented to reduce emissions and improve visibility in the Colorado Plateau. The Commission prepared a report for the EPA in 1995 that included an emission inventory for the study region, outlined several potential control measures and identified areas of investigation to pursue in the future[1]. One of the recommendations was to investigate the near-field and far-field effects of mechanically resuspended fugitive dust from paved and unpaved roads on visibility in Class I areas in the intermountain west. In 1997 a successor organization to the GCVTC was formed known as the Western Regional Air Partnership (WRAP). The Research and Development (R&D) Forum of the WRAP identified windblown fugitive dust as an area needing further study in addition to that of mechanically resuspended road dust. In 2000 a panel of air quality experts was convened by the R&D Forum to identify the best methodology for estimating emissions of fugitive windblown and mechanically resuspended road dust applicable for regional scale air quality modeling, and to make recommendations for future research activities to generate improved fugitive dust emissions estimation techniques applicable for regional scale modeling. Members of the panel included Bill Barnard (Harding ESE, Inc.), Candis Claiborn (Washington State University), Richard Countess (Countess Environmental), Dale Gillette (National Oceanographic and Atmospheric Administration), Doug Latimer (USEPA Region VIII), Tom Pace (USEPA, OAQPS) and John Watson

(Desert Research Institute). This panel derived a list of recommendations based on eleven findings regarding fugitive windblown and mechanically resuspended road dust.

EXPERT PANEL FINDINGS

Finding #1: Not All Suspendable Particles are Transported Long Distances

Fugitive dust sources are ground-level sources, usually line or area sources. The fraction of emissions that are transported long distances from the source of their emissions can be determined from a combination of factors that vary over a wide continuum of values. These factors include:

- **Deposition rates.** The rate at which particulate matter is deposited to the surfaces of vegetation, man-made structures, and the earth depends upon the size and density of the particles. Also, the characteristics of the earth's surface play a major role. For example, the rate of deposition in forests is greater than in open fields, deserts, and urban areas.
- **Vertical mixing.** Depending upon atmospheric conditions and transport time, vertical mixing can range from a few meters to thousands of meters. Deposition is more efficient if the particulate matter plume is shallow and at ground level.
- **Transport time.** Transport time acts to both increase and decrease the rate of loss of PM. Vertical mixing increases with time during which the PM concentration at the ground decreases resulting in less deposition. On the other hand, transport time increases the cumulative time allowing for increasing deposition.

<u>Deposition Rates</u>

The fine and coarse modes of PM_{10} are deposited at different rates. The coarse mode, the coarse fraction of PM_{10}, with mass median aerodynamic diameters of about 5 to 6 μm deposits relatively quickly (0.5 - 5 cm/s). The fine mode, $PM_{2.5}$, with mass median diameters of about 0.3 to 0.5 μm, deposits more slowly (0.05 - 0.2 cm/s). The difference is due to the fact that larger particles have a higher gravitational settling velocity than small particles. Similarly, particles are differentially deposited by inertial impaction depending on the inertia of the individual particle; particles having larger inertia are deposited preferentially to particles having smaller inertia. Deposition by other mechanisms like thermophoresis and electrophoresis may also be important in particle removal. The two order of magnitude range in deposition rates (0.05 - 5 cm/s) varies between two extremes: a maximum for dense forests and a minimum for barren desert areas, with a continuum of values between these two extremes for crop land, prairie land and urban (paved) surfaces.

<u>Vertical Mixing</u>

The initial vertical extent of the freshly generated particulate plume is shallow and for a brief time may be below the height of nearby vegetation, buildings or other obstacles. While the plume is low, enhanced deposition can occur onto these surfaces. After a short time (a few minutes at most which corresponds to a few hundred meters downwind of the source) diffusion has likely taken much of the remaining plume above these surfaces and gravity as well as wet deposition become the predominant removal mechanisms.

In general, the fraction of the mechanically generated fugitive dust from roads and bare surfaces that is removed from the atmosphere by gravitational settling and by impaction on nearby obstacles (such as vegetation) is much larger than that associated with fugitive windblown dust. This is due to the fact that the mechanically generated particles tend to remain closer to the ground for longer periods after suspension than windblown dust such that there is a higher probability that these mechanically generated particles will be removed from the atmosphere close to their source. For mechanically generated road dust, the initial vertical energy associated with the moving vehicles that generated the suspendable particles is short-lived and unsustained. And, in the absence of strong winds with a large vertical component to sustain the vertical motion of these mechanically generated particles, these emissions are dispersed vertically above the ground and any downwind obstacles solely by the daytime turbulent eddies caused by solar heating of the ground. On the other hand, windblown dust emissions may be lofted vertically to great heights above the ground by the sustained energy provided by the vertical component of the wind (especially for strong winds with large vertical components such as those associated with dust devils or thunderstorms) and consequently may be transported much longer distances from the source of emissions than mechanically generated fugitive dust emissions.

The well-mixed wake behind a vehicle often extends 1 to 2 times the vehicle height; thus, initial vertical dispersion can range from 1 to 6 meters (depending on the size of the vehicle). This is consistent with the initial vertical distribution of fugitive dust measured near a road; see Figure 1 that illustrates the PM_{10} flux measured within 2 to 5 meters of the roadway. With further transport time (and distance), atmospheric turbulence further increases the vertical depth of the fugitive dust plume. For a neutral atmospheric stability, the Pasquill-Gifford vertical dispersion coefficient (σ_z) for neutral conditions (D stability class) is 5 m at 100 m downwind, 30 m at 1 km, 120 m at 10 km, and 400 m at 100 km. The extent of vertical mixing is roughly twice the neutral stability numbers. For the stable conditions (categories E and F) characteristic of nighttime dispersion, coefficients are 3 - 5 times lower. For unstable conditions (A, B, and C), characteristic of daytime dispersion with solar heating of the earth's surface, the extent of vertical mixing can be 5 times to orders of magnitude greater than for neutral dispersion. Thus, the range of vertical mixing over a few hours can be three orders of magnitude. This variation combined with different deposition rates, discussed above, adds to the broad range of the continuum of conditions.

Transport Time

Transport time (directly related to transport distance) has a large effect on dry deposition. The amount deposited increases with transport time. Theoretically, for very long transport times, virtually all particulate matter is deposited. Generally, at these long transport times precipitation completes the removal of material. The vertical dispersion of the particulate plume also increases as a function of time. Transport time and distance are related to the wind speed. A typical wind speed of 2.5 m/s (5.6 mph) results in transport to 100 m in 40 seconds, 1000 m in 400 s (6.7 min), 10,000 m in 4000 s (1.1 hr).

Conclusion

The fraction of fugitive dust emissions that is transported beyond the source area can approach one on the high end, and zero on the low end, because of the extremely wide range of deposition rates, vertical mixing heights, and transport times. The rate of particulate matter loss is simply the deposition velocity divided by the mixing height. Thus, the loss rate for particles with a 0.1 cm/s deposition velocity and a mixed layer height of 100 m is 10^{-5} s^{-1} (0.04 h^{-1} or 4%/hr). However, increasing the deposition velocity by a factor of 10 and decreasing the mixing height by a factor of 10 will result in increasing the loss rate to 10^{-3} s^{-1} or 6% per minute. To determine the fraction of fugitive dust transported requires knowledge and integration of the combined effects of the landscape (roughness height), the particle size and density, and the meteorological conditions (stability and wind speed). Because of the wide continuum of each of these parameters, nothing specific and quantitative can be said about the fraction of particulate emissions that remains airborne for transport beyond the initial 100 m or so. In general, PM_{10} is deposited at a rate that is about an order of magnitude greater than $PM_{2.5}$ because of its greater gravitational settling velocity. The rate at which fugitive particulate matter will either be deposited or transported depends on the landscape in which fugitive dust is generated. In forest situations, with large roughness heights and surface areas, deposition will be much faster, greatly reducing (or eliminating) the fraction of PM that is transported. However, in open fields, prairies, deserts, and urban areas, much of the PM emissions will remain airborne. This conclusion demonstrates the importance of characterizing the landscapes of the fugitive dust source, as well as the magnitude and timing of emissions. The fact that $PM_{2.5}$ deposition is roughly an order of magnitude lower than that for the coarse mode suggests that the fine/coarse ratio measured at downwind receptor sites may be a good indicator of the relative contribution of local versus distant sources of fugitive dust emissions.

Finding #2: Regional Scale Vertical Flux is Smaller than the Local-Scale Fugitive Dust Flux

The regional scale vertical dust flux for a large scale transport model applies only to particles that are not deposited in the same grid cell in which they are emitted. Since a portion of the particles are deposited within the same grid cell from which they were emitted, the effective regional scale vertical flux of fugitive dust particles is smaller than the local scale vertical flux. The ratio of the effective regional scale vertical flux to the local scale vertical flux is a function of the friction velocity of the surface and the deposition velocity of the different size particles.

A "lumped control volume" approach was developed by Gillette as part of the WGA sponsored project[4] to relate regional scale vertical dust flux to field-scale fugitive dust for situations where the vertical fugitive dust flux is not uniform across the entire surface of the grid cell. For the condition of steady state emissions, solving the equation for conservation of mass within the control volume (CV) results in a value Φ, defined as the ratio of vertical flux of fugitive dust into the atmosphere to the horizontal flux of fugitive dust:

Equation (1) $$\Phi = \frac{\frac{dm_{up}}{dt}}{\frac{dm_{surface}}{dt}} = \frac{0.08u_*}{(V_d + 0.08u_*)}$$

where

dm_{up}/dt	= mass per unit time passing out vertically at the top of the CV
$dm_{surface}/dt$	= mass per unit time emitted from the surface
V_d	= deposition velocity
u_*	= friction velocity

Values of Φ are presented as a function of friction velocity in Figure 2 for different values of deposition velocity.

Finding #3: Fugitive Dust Emission Factors Need to be Appropriate

Many of the past fugitive dust emission inventories were inaccurate since they used inappropriate emission factors. Emission factors should be based on physical models rather than statistically significant variables and should be consistent for different source types with similar suspension mechanisms (e.g., mechanically reentrained dust from paved and unpaved roads; wind erosion from desert, agricultural, and vacant land as well as unpaved roads and construction sites). There have been recent advancements in characterizing the factors that make up the empirically derived emission factor equations as well as the reformulation of the emission factor equations that need to be taken into account. For example, improved algorithms for fugitive dust emissions from construction operations are currently being implemented. Also, the unpaved road dust algorithm is currently under review by the USEPA.

Windblown dust emissions predicted for fugitive dust emission inventories are inaccurate for several reasons. These include using wind erosion models developed for purposes other than air quality emission inventories, temporally- and spatially-averaged meteorological data that averages out wind gusts, inadequately characterized soil and topographic characteristics, and models that do not properly characterize the emission processes. For a detailed discussion of the processes involved in wind erosion and the various models developed to address fugitive windblown dust, the reader is directed to the report by Countess et. al. (2001)[4] and the companion paper for this conference by Claiborn (2001)[5].

The assessment that resulted in the current revision to the AP-42 emission factor for unpaved roads involved iterative modifications of the original factor first published in 1974 that stated that emissions were proportional to vehicle speed. Our review of the original data[6,7] indicates that the emissions increased as some power of the vehicle speed rather than linearly with vehicle speed. It should be pointed out that vehicle speed was omitted in the recent revision of the emission factor since it provided no additional improvement in the overall correlation. This is an example of a potential flaw in the use of statistical evaluations to determine real world parameterizations of physical processes. Intuitively, it is apparent that when the speed of a vehicle increases on an unpaved road, the visual plume also increases (and thus emissions must also be increasing). Thus removing vehicle speed from the emission factor equation simply because it provides no additional information in a statistical correlation analysis makes no sense. For paved roads, recent work[8] has shown that the AP-42 emission factor model yields highly uncertain estimates because it lacks a mechanistic basis; its formulation is highly dependent on the data set used to derive it; and the accuracy of the model is completely determined by the methods used to measure emissions.

Finding #4: Extent of Source Activity Levels Need to be Accurate

Many of the past fugitive dust emission inventories are inaccurate since they used inappropriate estimates of the extent of the source activity levels. There is a large uncertainty in the extent of the reservoir of suspendable particles (which is especially true for wind erosion and paved roads), as well as the impact of meteorological variables and human intervention. This finding is particularly valid for unpaved roads, somewhat valid for paved roads, and varies between somewhat valid to extremely valid for wind erosion. It applies not only to the extent of activity levels, which strictly speaking for paved and unpaved roads is vehicle miles of travel (VMT), but also applies to the data used in the "correction" parameters in the emission factor equations (e.g. silt content, silt loading, average fleet vehicle weight, etc.). The validity of this finding is exacerbated by inventory scale. As the emission inventory scale goes from local to regional to national, locating consistent, readily available databases of activity data or information required for the correction parameters becomes increasingly difficult. The possible exception is VMT on paved roads. Since paved road mileage far exceeds unpaved road mileage, State or local transportation departments are more likely to collect and report VMT on paved roads. Information on individual field parameters for wind erosion or silt loading for specific roads or areas are much more difficult to locate. By necessity, large-scale emission inventories must use values interpolated from or equal to adjacent measured values, or default values presented in AP-42 to determine emissions. This leads to a reduction in the overall accuracy in the emissions estimates.

Finding #5: Fugitive Dust Emissions are not Continuous Processes

Emission inventories (and the emission factors used to develop emission inventories) incorrectly treat fugitive dust emissions as continuous processes. Emission factors developed using the upwind/downwind method are by default treating emissions as a continuous process, since a continuous line source dispersion model is back-calculated to derive the emission factor. For paved roads, this assumption, especially for multi-lane, high average daily traffic volume, is probably reasonable for periods other than the late evening/early morning where non-continuous situations exist. On the other hand, there are many unpaved roads with fewer than 3 cars per hour on average which would not qualify as a continuous line source.

Finding #6: Annual Fugitive Dust Emission Inventories are not Sufficient

Annual emission inventories are not sufficient to develop emission control strategies for haze events. Improved seasonal and diurnal profiles are needed for use in emission inventories. Wind erosion is highly variable and poorly characterized. Many of these variations are affected by certain meteorological conditions that are not currently considered in emissions models. Fugitive dust emissions have been observed to vary over annual, seasonal, daily, and even diurnal periods owing to differences in the material available for suspension and the activities that cause that suspension[9-11]. Yearly and seasonal variations can be practically addressed in emissions inventories. Day-to-day and diurnal emissions might be addressed for specific episodes for a few sources, but this requires prior planning to track emissions events that is impractical under most circumstances.

Finding #7: Spatial Allocation of Fugitive Dust Emissions is Important

Better spatial surrogates than are currently in use are available for estimating available fugitive dust reservoirs, locations, dust-generating activities, and temporal changes in surface properties and surroundings. Use of these spatial surrogates would provide better information to support the models used for emissions estimates.

Most inventories use national activity surrogates that are remotely related to dust reservoirs and activities that create dust. Meteorological surrogates that affect emissions (moisture, wind speed) are averaged temporally and spatially. Reservoirs are assumed to be unlimited, rather than depletable. Improvements can be made in all of these areas by using spatial surrogates that are related to the availability of dust for suspension (currently done by estimating the “silt” fraction or loading in surface dust) such as maps of roads, vegetative land cover, land use, soil types, and spatially and temporally resolved meteorological data.

Finding #8: The Fine Fraction of Fugitive Dust Emissions is not Adequately Characterized

Few empirical measurements exist for characterizing the fine aerosol fraction of fugitive dust emissions (i.e., that fraction that has the longest residence time in the atmosphere and that has the largest impact on visibility degradation). The majority of the measurements made as part of emission factor development studies focused on total suspended particulates (TSP) since that was the regulatory standard at the time the measurements were made. These measurements were augmented with a modest amount of PM_{10} data when PM_{10} became the regulatory standard coupled with some measurements of $PM_{2.5}$. Few direct measurements of fine particles exist for wind erosion. When these field studies measured fine particles, many used older particulate measurement devices that did not correctly characterize the particle size cut points and/or did not adequately account for particle bounce (Note: any particle bounce would have caused the $PM_{2.5}/PM_{10}$ ratio to be too high.). EPA has recently reviewed the collected information on $PM_{2.5}/PM_{10}$ ratios developed during these measurement programs to determine the effects particle bounce may have had. That review resulted in modifications to the $PM_{2.5}/PM_{10}$ ratio used to estimate emissions for the National Emissions Trend (NET) inventory. In addition, in most of the exposure profile studies, particle size distribution information was only collected at one height in the profiler array. As a consequence, the change in the vertical distribution of particle sizes (or particle size ratios) cannot be adequately determined. Thus, information on the particle size distribution of the vertical flux of material would be difficult to evaluate with the current data.

Finding #9: Air Quality Models Need to Integrate Meteorology and the Emissions Processes

Regional scale air quality models need to integrate all the appropriate meteorological processes with the fugitive dust emissions generation processes. Meteorological parameters used for estimating transport and dispersion should be combined with the fugitive dust emission estimates for both mechanically-generated and wind erosion-generated conditions. For example, to model windblown dust, if time-averaged wind speeds are used, it is important to account for smaller time-scale wind gusts. The use of air quality dispersion models that account for injection heights and deposition losses should allow one to distinguish the relative impact from near field (i.e., local) emissions versus far field (i.e., regional) emissions on ambient air quality.

One of the problems with a grid model is that it instantaneously mixes emissions throughout a grid cell. For area sources of fugitive dust, such instantaneous diffusion may completely miss the significance of an air quality effect. For example, for a 36 km by 36 km grid cell, emissions would be mixed uniformly throughout this cell, even though in reality a plume would be limited to a few hundred meters on a side and may not touch the ground. Existing air quality models generally do not simulate violent wind events such as dust devils and thunderstorms which can provide sufficient energy to disturb natural surfaces and to entrain dust from already disturbed surfaces. However, by changing the temporal and spatial scale of such model applications, it may be possible to model such events on a crude basis. A serious limitation of traditional Gaussian models is their assumption of steady state emissions. Since fugitive dust emissions are highly variable in nature, traditional Gaussian models need to be revised to handle intermittent emissions. If all of the relevant inputs to the diffusion equation are quantified within a specified accuracy, the diffusion equation can provide realistic estimates of the aerosol concentrations throughout an area or a region. However, in most cases there are large uncertainties associated with the inputs to the diffusion equation; namely the advection, diffusion, emissions and deposition terms. These include uncertainties associated with wind strengths that are highly variable with height and location in the region, atmospheric turbulence that varies depending on the time of day and the amount of insolation, emissions that are diluted to varying degrees based on the meteorological conditions, and deposition that is highly dependent on particle size and the release height of the emissions.

Finding #10: Disturbed Surfaces Produce Significantly More Fugitive Dust than Undisturbed Surfaces

In general, undisturbed surfaces produce much less dust than disturbed surfaces. This is because the undisturbed surface usually requires considerably higher (threshold) wind speeds to become a significant emission source. A surface having a lower threshold velocity produces much more dust than a surface having a higher threshold velocity. The primary influence of disturbing a surface is to lower the threshold velocity and increase dust emissions. Gillette, et. al. (1980) found that the disturbance of vehicular traffic on natural surfaces decreased the threshold velocity[12]. At the same time, the disturbances usually acted to smooth the surfaces which decreased the drag coefficients. For almost all of these surfaces the large decrease in the threshold velocity was sufficient to greatly increase dust emissions even though the drag coefficient was decreased.

Finding #11: Receptor Models May Be Used to Distinguish Contributions from Different Sources of Fugitive Dust

Uncertainties in fugitive dust emission estimates for crustal materials can be estimated and reduced to acceptable ranges by reconciliation with ambient measurements. Variations in particle size and chemical composition of the fugitive dust at a receptor site as well as the temporal and spatial variations in composition and concentration for multiple receptor sites can be used to indicate the spatial scale of the sources, the portion of the day when fugitive dust contributions are large, and whether or not the fugitive dust is wind generated. Additional chemical and physical measurements of the ambient aerosol at receptor sites may shed some light on specific dust sources. Receptor measurements should be used with model estimates to evaluate modeled source contributions and to focus inventory improvement efforts.

The most commonly used receptor models include the Chemical Mass Balance (CMB) receptor model and the Enrichment Factors (EF) receptor model. The EF model utilizes ratios of atmospheric concentrations of chemical components normalized to a reference component compared to the same ratios in geological material that represent an average crustal composition for a region or sampling site to identify different sources. Heavy metal enrichments are usually attributed to industrial emitters; potassium enrichment is attributed to wood combustion. Soil and road dust compositions may differ from regional crustal compositions, and enrichments or depletions for certain species may indicate the presence or absence of more or less of these regional dust contributions.

EXPERT PANEL RECOMMENDATIONS

The expert panel developed a series of recommendations based on the 11 findings presented above. These recommendations are numbered to coincide with the finding to which they pertain, and are listed below.

1.1) Conduct PM_{10} and $PM_{2..5}$ upwind/downwind experiments at different elevations around roadways and exposed surfaces similar to those used to develop TSP and PM_{10} horizontal flux measurements in order to determine the flux of particles at different heights.

1.2) Determine values for parameters such as barrier height, length, permeability, surface roughness and friction velocity for different ground covers for different seasons. These parameters should then be used in emissions models to estimate how wind speeds are attenuated and to derive accurate estimates of deposition velocities that remove particles from long-range transport.

1.3) Make preliminary estimates of deposition velocity for these parameters and link to a gridded database of land cover across the US.

2.1) Test the validity of Gillette's semiempirical "box" model described in Countess et. al., (2001)[4] in a relatively clean environment where fugitive dust from vehicular traffic is a dominant source of PM_{10}.

2.2) Upgrade this semiempirical model with more sophisticated submodels to account for deposition and diffusion near the surface.

3.1) Field test the performance of the Wind Erosion Prediction System (WEPS) model[13] for predicting PM_{10} emissions during windblown dust episodes.

3.2) Adopt the modeling approach developed by Draxler et al. (2001)[14] for predicting PM_{10} emissions during windblown dust episodes. This method requires a limited amount of *a priori* information on the surface to estimate the threshold friction velocity and calculate the horizontal flux. The proportionality constant for estimating windblown dust emissions from the horizontal flux will be needed for specific soils.

3.3) Evaluate alternative forms for EPA's empirical emission factor equations listed in AP-42 and revise these equations in keeping with a mechanistically based physical model in order to improve the accuracy of emissions predictions. This evaluation should include reviewing recent emission factor development (exposure profiling) studies. In addition, the vertical concentration distribution measured during exposure profiling studies should be evaluated to determine if the data are sufficient to make an assessment of the vertical flux.

3.4) Acquire information on silt loadings, silt content and moisture content (i.e., the "correction" factors utilized by the emission factor equations) at the county or sub-county level for areas upwind of Class I areas for different periods throughout the year. Update this information regularly.

4.1) Acquire information on source activity levels at the county or sub-county level for areas upwind of Class I areas for fugitive dust emissions for both windblown dust and mechanically suspended road dust for different periods throughout the year. Update this information regularly.

4.2) Identify the mechanisms leading to particle reservoir replacement, and quantify the time period required for replenishment, and the effects of this replenishment process on emission estimates.

5.1) Investigate the use of "puff" type dispersion models, which assume that emissions are fairly instantaneous rather than continuous, with upwind/downwind exposure profiling measurements to back-calculate source strengths and develop emission factors.

5.2) Characterize emission rates for short time frames.

6.1) Account for emissions on a seasonal basis, for example following the California methodology[10] that includes identifying and evaluating agricultural, meteorological, and land use data bases for selected Class I areas.

6.2) Adapt nephelometer sampling schedules and wind measurements at selected IMPROVE sites to 5-minute averages to better detect pulses that might arise from fugitive dust and other sources.

6.3) Operate continuous particle monitors at 30-minute or shorter time resolution at selected IMPROVE sites, and examine these data to determine the fraction of a 24-hour sample that is contributed by short duration events, and evaluate the magnitude of these events relative to longer-term emissions estimates.

7.1) Catalog, describe, and evaluate spatial data bases such as soil surveys, digital road maps, satellite and other land use data, meteorological measurements and models to interpolate and extrapolate measurements, and traffic demand estimates; determine the availability and costs of these data; and identify technical and cost impediments for using them to improve fugitive dust inventories.

7.2) Develop and apply a systematic program to sample representative soils; determine their PM_{10} and $PM_{2.5}$ indices based on the methodology of Carvacho et. al (1996)[15], which uses the ASTM wet sieve method rather than the dry sieve method used by EPA in AP-42; relate these to soil texture properties in soil surveys; and use these to estimate suspendable particle reservoirs on open lands.

7.3) Develop and apply a practical method to obtain continuous roadway dust loadings such as that being developed by Kuhns et. al., (2000)[16] that uses a pair of forward-scattering nephelometers; evaluate the potential to apply this method during normal driving cycles of park personnel and others in Class I areas; evaluate these data to determine statistical distributions of surface loadings; and determine how they change with different variables.

7.4) Develop and apply a flexible GIS emissions modeling structure that continuously acquires and updates spatial surrogates from existing and planned data bases and propagates this new information into better estimates of reservoirs, dust-suspending activities, and attenuation from obstacles near the point of emission.

8.1) Conduct field tests to quantify the vertical $PM_{2.5}$ flux for fugitive windblown dust and mechanically suspended road dust.

9.1) Reconcile model predictions with measurements by incorporating an interim method for accounting for near source removal of particles into regional models. This will involve running air quality dispersion models utilizing estimates of the vertical fugitive dust emissions flux rather than the local-scale horizontal flux as inputs for the model for those cases where the model(s) predicted ambient concentrations that were considerably larger than the observed downwind concentrations.

9.2) Incorporate more refined particle removal estimation methods into regional models as they become available.

10.1) Catalog existing studies and conduct studies to determine if different surfaces are supply limited or supply unlimited in terms of their particle reservoir.

10.2) Conduct studies to determine the effect that different kinds of disturbance have on the aerodynamic roughness height of different surfaces.

11.1) Examine the IMPROVE data base for enrichments of geological elements relative to median ratios or to soil compositions typical of the areas in which samplers are located; and determine the extent to which different elemental ratios are observed, outside of natural variability, and the extent to which these are correlated with elevated $PM_{2.5}$ soil or coarse particle mass concentrations.

11.2) Examine the impactor measurements for soil related species from IMPROVE special studies; identify typical size distributions and deviations from those distributions; and relate outliers to $PM_{2.5}$ and coarse mass concentrations.

11.3) Examine nephelometer light scattering data from the IMPROVE network; and determine the extent to which spikes are observed and whether or not these can be related to fugitive dust or other sources.

11.4) Critically review previous studies of microscopic, isotopic, organic, and other measurement methods with respect to their ability to distinguish among different land forms and fugitive dust emitters; and determine which methods can be practically applied to source characterization and ambient sampling.

11.5) Design and implement a systematic source profile measurement program for geological samples obtained from open surfaces upwind of Class I areas in the West; examine existing soil and geological maps to identify areas that have suspension potential; obtain sufficient dust quantities from these areas for a variety of analysis methods; suspend and sample these quantities through PM_{10} and $PM_{2.5}$ size selective inlets; analyze samples using selected chemical and physical methods; and apply appropriate mathematical tests to determine the degree to which profiles are collinear or are dissimilar enough to distinguish between fugitive dust source types and areas.

11.6) Implement high time resolution methods, preferably ones that are specific to coarse particles, at several IMPROVE sites and between these sites and suspected source areas; examine these to determine when dust events occur, their durations, and their contributions to 24-hour averages; and use this information to focus emissions inventory efforts.

11.7) Characterize the chemical composition of the coarse aerosol fraction collected at selected IMPROVE sites and use different receptor models to differentiate between different fugitive dust source categories.

11.8) Identify/develop methodology for resolving local sources of fugitive dust from distant sources.

11.9) Identify/develop methodology for resolving road dust from windblown dust.

TIME FRAME FOR IMPLEMENTING RECOMMENDATIONS

The recently enacted Regional Haze Rule requires that many of states complete their SIPs by December 2003. In order for these states to meet the SIP deadline, they will need to implement many of the expert panel's recommendations over the next two years. These recommendations have been grouped into three categories: (1) short term recommendations that can realistically be implemented in the next six to 12 months, (2) intermediate term recommendations that should be implemented in the next 12 to 18 months, and (3) long-term recommendations that should be implemented in the next 18 to 30 months. Recommendations 4.1, 11.1, and 11.7 fall into the short term category; recommendations 2.2, 4.2, 5.1, 6.3, 7.4, 9.2, and 11.6 fall into the long term category; and the balance of the recommendations fall into the intermediate category.

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REFERENCES

1. Grand Canyon Visibility Transport Commission. "Recommendations for Improving Western Vistas"; report prepared for U.S. Environmental Protection Agency by Grand Canyon Visibility Transport Commission, Denver, CO. 1966.

2. Watson, J.G.; Chow, J.C. "Reconciling Urban Fugitive Dust Emissions Inventory and Ambient Source Contribution Estimates: Summary of Current Knowledge and Needed Research"; report No. 6110.4D2 prepared for U.S. Environmental Protection Agency by Desert Research Institute, Reno, NV. 2000.

3. Watson, J.G.; Chow, J.C.; Gillies, J.A.; Moosmüller, H.; Rogers, C.F.; DuBois, D.W.; Derby, J.C. "Effectiveness Demonstration of Fugitive Dust Control Methods for Public Unpaved Roads and Unpaved Shoulders on Paved Roads"; report No. 685-5200.1F prepared for San Joaquin Valley Unified Air Pollution Control District by Desert Research Institute, Reno, NV. 1996.

4. Countess, R.J.; Barnard, W.; Claiborn, C.; Gillette, D.; Latimer, D; Pace, T; Watson, J. "Methodology for Estimating Fugitive Windblown and Mechanically Resuspended Road Dust Emissions Applicable for Regional Air Quality Modeling"; final report prepared for the Western Governors' Association by Countess Environmental, Westlake Village, CA. 2001.

5. Claiborn, C.S. "Emission Models for Estimating the Contribution of Windblown Dust in Emission Inventories," Presented at the 10th Annual USEPA Emission Inventory Conference, Denver, CO. 2001.

6. Roberts, J.W.; Watters, H.A.; Mangold, C.A.; Rossano, A.T. "Cost and Benefits of Road Dust Control in Seattle's Industrial Valley", *JAPCA*. 1975, 25**,** 948-952.

7. Sehmel, G.A. "Particle Resuspension from an Asphalt Road Caused by Car and Truck Traffic", *Atmos. Environ.* 1973, 7**,** 291-309.

8. Venkatram, A. "A Critique of Empirical Emission Factor Models: a Case Study of the AP-42 Model for Estimating PM_{10} Emissions from Paved Roads", *Atmos. Environ.* 1999, 34**,** 1-11.

9. Barnard, W.R.; Stewart, M.A. "Improved Fugitive Dust PM_{10} Emissions Estimates for Trends". In *Proceedings, Emission Inventory Issues in the 1990s*; Air & Waste Management Association, Pittsburgh, PA, 1992; pp. 673-684.

10. Campbell, S.; Shimp, D.R. "Spatial and Seasonal Distribution of PM_{10} and $PM_{2.5}$ Emissions in Central Kern County, California", In *Proceedings, $PM_{2.5}$: A Fine Particle Standard*, Chow, J.C. and Koutrakis, P., Eds.; Air & Waste Management Association, Pittsburgh, PA, 1998. pp. 475-486.

11. Chow, J.C.; Watson, J.G. "Fugitive Dust and Other Source Contributions to PM_{10} in Nevada's Las Vegas Valley"; Report No. DRI 4039.1F prepared for Clark County, Nevada Department of Comprehensive Planning by Desert Research Institute, Reno, NV. 1997.

12. Gillette, D.A.; Adams, J.B.; Endo, A.; Smith, D.; Kihl, R. "Threshold Velocities for Input of Soil Particles into the Air by Desert Soils", *J. Geophys. Res.* 1980, 85, 5621-5630.

13. Hagen, L. "USDA Wind Erosion Prediction System: Technical Description". In *Proceedings, WEPP/WEPS Symposium,* Des Moines, IA, 1995.

14. Draxler, R.; Gillette, D.; Kirkpatrick, J.; Heller, J. "Estimating PM_{10} Concentrations in Dust Storms in Iraq, Kuwait, and Saudi Arabia", submitted to *J. Geophys. Res.* 2001.

15. Carvacho, O.F.; Ashbaugh, L.L.; Matsumura, R.T.; Southard, R.J.; Flocchini, R.G. "Measurement of PM_{10} Potential from Agricultural Soils Using a Dust Resupension Test Chamber". In *Proceedings, International Conference on Air Pollution from Agricultural Operations,* Kansas City, MO. 1996.

16. Kuhns, H.D.; Etyemezian, V.; Landwehr, D.; Macdougall, C.S.; Pitchford, M.L.; Green, M.C. "Testing Re-entrained Aerosol Kinetic Emissions from Roads (TRAKER): A New Approach to Infer Silt Loading on Roadways", accepted for publication in *Atmos. Environ.* 2001.

Figure 1. Cumulative horizontal PM_{10} flux at different downwind elevations above different unpaved roads (Watson et. al., 2000)[2].

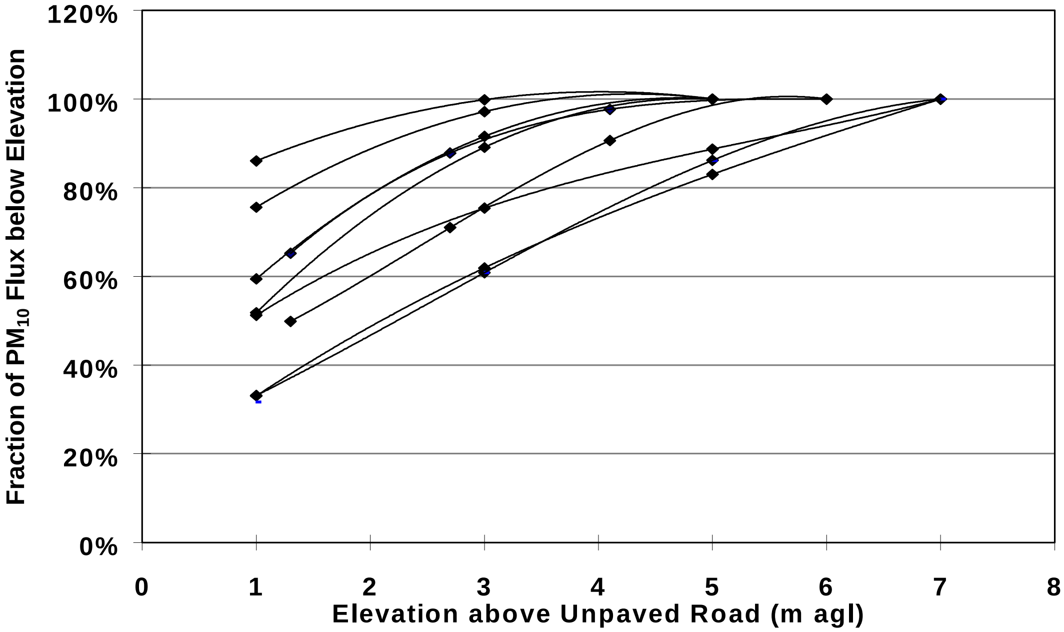
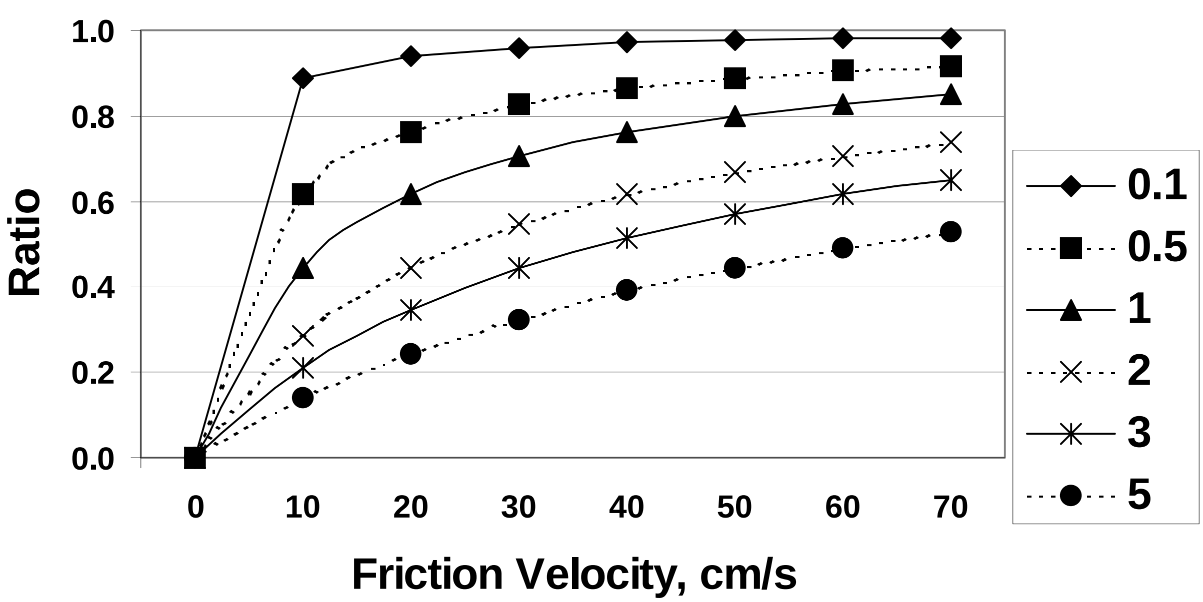


FIGURE 2. Ratio of regional scale vertical fugitive dust flux to local scale horizontal fugitive dust flux as a function of friction velocity for different values of deposition velocity (0.1 to 5 cm/s).



KEYWORDS

Fugitive Dust
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PM_{10}
$PM_{2.5}$
Paved Roads
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