Methodology to Estimate the Transportable Fraction (TF) of Fugitive Dust Emissions for Regional and Urban Scale Air Quality Analyses

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Background and Introduction

For a number of years air quality analysts have recognized that the ambient impact of fugitive dust sources is substantially lower than emissions inventories would suggest. Analysis of the chemical species collected by ambient air samplers suggests that the modeling process may overestimate PM2.5 from fugitive dust sources by as much as an order of magnitude. This overestimation creates problems for those involved in both PM2.5 and regional haze planning and the determination of conformity budgets and significance determinations. Most experts agree that this overestimation is due to a combination of shortcomings in the inventory-modeling process: 1) faulty emission factor algorithms, 2) imprecise or difficult to obtain activity data to apply these algorithms (including inability to account for the effect of actual meteorological conditions on emissions), 3) the multiplier used to infer PM2.5 from PM10 emissions, and 4) modeling deficiencies (especially in the treatment of particles near their point of emissions). The ambient air sample collection and analysis is believed to be a better estimate of overall fugitive dust impact on the environment because of these issues with the inventory-modeling process.

Fugitive dust categories of interest include unpaved and paved road dust, dust from highway, commercial and residential construction and agricultural tilling. Of these, unpaved roads are the highest single emissions category, accounting for about one third of non-windblown fugitive dust emissions. This is followed in importance by dust from tilling, quarrying and other earthmoving. Note: windblown dust from agricultural and other exposed land is also important, but the transport fraction values suggested in this paper are not recommended for application to windblown dust sources.

In the mid 1990's, the U.S. Environmental Protection Agency's (EPA) Office of Air Quality Planning and Standards (OAQPS) began to use a factor to "adjust" the fugitive dust emission estimates in regional modeling analyses to obtain better agreement between the regional model results and ambient data. This adjustment was an ad hoc "divide-the inventory-by-four" approach to reduce the discrepancy between modeling and ambient data. The adjustment factor was conceived as an interim approach until a thorough investigation could identify which specific problems in the inventory and model were causing the discrepancy. Since the late '90s, the EPA has been actively working to understand the nature of those specific problems. This paper discusses some recent studies and proposes a conceptual model to approximate the dust removal near the source that is not accounted for in either the current emissions inventories or commonly used regional scale air quality models.

DRI / EPA Workshop

The EPA/OAQPS and the Desert Research Institute (DRI) conducted a workshop in 2000 to begin the process of understanding why modeled and monitored crustal material fractions do not agree. OAQPS documented that the field measurements underlying the dust emission estimates were generally taken within 5-10 meters of the source and that on average, about two-thirds of the dust plume is less than 2 meters above ground level at the location where the measurements are made. Based on this information and other workshop discussions, the workshop concluded that since the dust plume is still turbulent and very close to the ground, substantial dust removal processes can occur near the source (probably within several hundred meters), including impaction on land cover (vegetation and structures) and other processes that may enhance deposition on a local scale. It also concluded that regional air quality models (as they are currently applied) do not adequately account for injection height, deposition losses and impaction losses near fugitive dust emission sources. They noted that in practice, the fraction removed by surface cover is variable and that additional testing is needed (Watson and Chow 2000).

WRAP Expert Panel on Fugitive Dust

The DRI / EPA Workshop was followed by the formation of an Expert Panel on Fugitive Dust, sponsored by the Western Regional Air Partnership (WRAP) and chaired by Dr. Richard Countess. The panel concluded that not all suspended particles are transported long distances. Specifically, the report supported the conclusion of the DRI Workshop which was that much of the ground level fugitive dust emissions from soil disturbed by man's activities are likely to be removed close to the source. The low release height and turbulence leaves the particles temporarily close to the ground where they are subject to removal by impaction on nearby horizontal and vertical surfaces, including vegetation and structures. The Countess report recommended field studies to expand upon the current knowledge of the removal effectiveness of trees, desert shrub and buildings (Countess 2001) and several studies were conducted in response to this recommendation.

The Role of Surface Cover (Vegetation & Structures) in Removal of Airborne Dust

Early research into the general area of dust removal was done by Slinn for the U. S. Dept. of Energy. Much of Slinn's work focused on particle removal from air flowing above a tree canopy, but he also discussed the concept of a "stilling zone" within and below the canopy. Within the stilling zone, wind velocity is so much reduced that particles have ample time to settle to the ground or impact on the canopy or groundcover (Slinn 1982).

Windbreaks have long been a staple of soil erosion prevention, although most of the research has focused on the use of windbreaks placed upwind of a field to reduce the wind speed (and thus erosion) over the field. More recent work has focused on the effectiveness of vegetation as a removal mechanism. Anecdotally, researchers feel that the forest is a very good filter, both horizontally and vertically. Moreover, field tests suggest that the transmittance of dust through a windbreak is close to the optical transmittance. In other words, if the foliage is dense enough to block light, it also effectively filters particles (Cionco 2002, Raupach 1999, Raupach 2001).

Thus, the combined work of Slinn, Cionco and Raupach, the DRI workshop and the WRAP Expert Panel on Fugitive Dust suggests that fugitive dust particles have ample opportunity to be removed near the source, through impaction or filtration onto vegetation or structures or by other deposition mechanisms. The effect of land cover is expected to be highly variable, depending on the nature and proximity of vegetation to dust sources. They note that surface cover that is taller, denser and closer to the source captures a larger amount of the particles, with the most capture occurring when a narrow source is surrounded on both sides by tall, dense vegetation such as a road within a forest. However, Cowherd and Pace (2002) note that particles transported toward (not generated among) non-porous surfaces such as buildings or very dense vegetation may be diverted above or around those surfaces.

Mechanisms other than impaction and filtration by surface cover may also reduce particles very near the source, while the plume is compact and close to the ground. These mechanisms include electrostatic forces and thermophoresis (which could enhance deposition onto the earth's surface and low ground cover very near the source) and particle agglomeration within the compact plume (which could enhance gravitational settling). These mechanisms aren't as likely to capture particles in thermally buoyant or elevated plumes because those plumes rise above the land cover more quickly. Field testing is needed to quantify these mechanisms. (Cowherd and Gebhart 2003, Flagan 2001, Gieseke 1972).

Fugitive Dust Emissions, Surface Cover Particle Removal and Air Quality Models

As noted above, ground level fugitive dust emissions are measured adjacent to their point of emission; thus, as with emissions from all types of sources, they may be modified or even removed from the atmosphere before they reach receptors. Thus, emission estimates are only meaningful on a very local scale around their release point. In general, this does not present problems if one is concerned with effects on this local scale or when models are available to treat the potential modification or removal. However, these emissions are often used to support analyses on an urban or even larger scale. This could involve inventory tracking budgets (e.g., conformity) but they are also used in grid models whereby they are immediately introduced into model grids much larger than the scale of the removal processes discussed above.

Recently, several researchers and modeling practitioners have identified issues associated with how air quality models treat ground level fugitive dust emissions and how current models and modeling practices can lead to an underestimate of particle removal. Some of these issues were recently documented by staff at the Idaho Department of Environmental Quality (Idaho DEQ 2003). They concluded that Eulerian grid models generally over-predict coarse particle (2.5 ~ 10μm) concentrations, due primarily to the fact that these models artificially re-mix the particles in the lowest modeling layer at each time step (Dong, 2003). DRI, in their work for DOD, also evaluated the removal mechanisms in the Atmospheric Diffusion Equation and in ISC3. They found the ISC better suited to analyze near field dispersion (Etyemezian 2003).

Irwin (2003) noted that both grid and Gaussian models can be configured to estimate particle removal by surface cover, but that many of the parameters are empirical and there is little guidance or supporting research on how to set the input parameters in these models for a range of particle types and surface covers. He also noted that grid models ignore all removal processes in the grid cell into which they are first emitted, so unless the grid size is very small (100 to 1000 times smaller than currently used in regional modeling), they would not be sensitive to removal on the scales (10’s to 100’s of meters) discussed in this paper (Irwin 2003).

The above discussion suggests that any removal that may occur near the source (on a scale of 10’s to100’s of meters) is beyond the capability of current grid models, which are intended for use in regional scale analyses, as discussed below.   A method is needed to adjust ground level emissions of fugitive dust when they are used to support analyses on a scale larger than 10’s to 100’s of meters. This paper describes a method to adjust the emissions inventory used in such larger scale analyses as a way to compensate for the model’s inability to treat removal by surface cover near the emission source. Note that the adjustment of emissions inventories would be unnecessary if very small grids were used and if the appropriate removal mechanisms were incorporated explicitly into these models. However, use of grid models in this way would be well beyond current computer capabilities.   Thus, the method described in this paper may be useful for the foreseeable future, until models are modified / developed to treat near-source particle removal by surface cover.

Conceptual Model: Near Source Capture (NSC) of Dust Emissions by Surface Cover

As an extension of the work begun by DRI and the WRAP Expert Panel, Cowherd and Pace (2002) suggest the use of a "limiting cases" conceptual model as a way to bound the dust removal potential by surfaces near the source of emissions. An unpaved road in the forest would represent one extreme or limiting case whereby most, if not essentially all of the road dust would be captured within the vegetation canopy. At the other extreme or limit, road emissions in barren areas of the arid southwest would be subject to virtually no capture or removal due to vegetation. Other surface characteristics would fall between these limits. Cowherd and Pace refer to the fraction of a source's mass emissions captured by the vegetation (or other surface obstructions) as the "Capture Fraction (CF)" where 0 <= CF <= 1, where 0 is a barren landscape and 1.0 is within a dense forest. They adapt the term "Transportable Fraction" (TF) from the DRI Workshop and use it to describe those particles remaining airborne and available for transport away from the vicinity of the source, after localized removal has occurred (Watson and Chow 2000, Cowherd and Pace 2002).

(1) Transportable Fraction (TF) $= TE / SE$

$= \{SE - [SE * CF]\} / SE$

Where:

Transportable Emissions (TE) =

Source Emissions (SE) – Locally Captured Emissions, and

Locally Captured Emissions = Source Emissions (SE) * CF

Figure 1 illustrates the conceptual model for near source particle removal by vegetation and structures. In this simple model, capture is assumed to increase as the density, leafiness and height of the vegetation increases. Urban areas are considered to be similar to mixed surroundings, on average. This model does not include any enhanced deposition that might occur due to gravitational, thermal or electrostatic forces. Also note that the exact relationship between capture and the nature of the surroundings cannot be known without further testing.

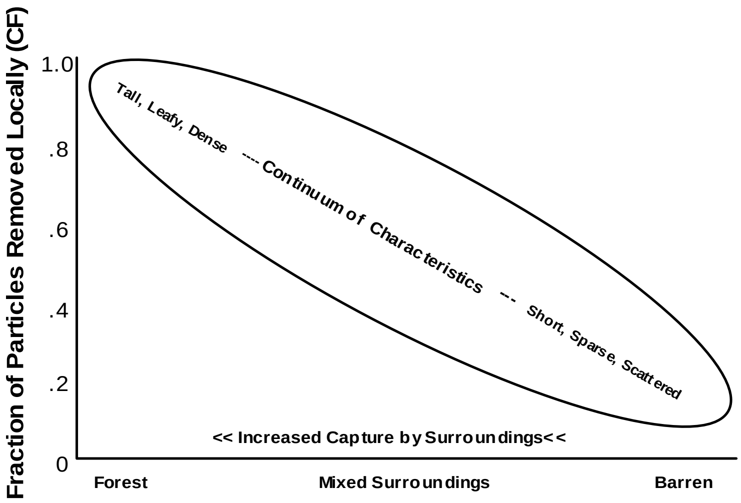

Figure 1. Conceptual Model – Near Source Capture (NSC) of Dust Particles by Surface Cover

Recent and Ongoing Work to Evaluate Near Source Capture (NSC) by Surface Cover

Field work was conducted for the Western States Air Resources (WESTAR) Council by a team of scientists including Dr. Vic Etyemezian at the Desert Research Institute (DRI). The effect of vegetation and structures on nearby unpaved road emissions was documented in this report. The report supports the Countess findings, noting a wide range of downwind removal rates depending on surface conditions. The DRI results showed little removal in daytime tests in a sparse, barren environment, but a nighttime removal rate of 85 percent was found at a distance of 95 meters downwind when structures were present between the road and the sampling apparatus (Etyemezian 2003a).

A field study conducted by the Midwest Research Institute (MRI) for the U.S. Department of Defense (DOD) measured the effect of groundcover on particle removal near an unpaved road. Initial tests were done over an open field 20 meters wide. In this test, the particles were depleted minimally as they passed over the field, but the depletion was about 57 percent when a bank of cedar trees was added downwind about 8 meters from the unpaved road. The amount of particle depletion was comparable for both PM2.5 and PM10 over these distances and test conditions (Cowherd and Gebhart 2003).

The data from these tests is limited and more testing is needed to improve the confidence in the results. However, substantial near source removal of the particles is apparent, even during the daytime for particles passing over an open field. Cowherd suggested that other factors may enhance the deposition process, even over flat surfaces very near the source. However, Etyemezian saw no apparent effect of deposition over barren land.

Note that the effect of atmospheric stability on CF should also be considered in future work to refine the NSC model. The CF would likely be reduced under unstable atmospheric conditions, which can cause the plume to rise above the earth's surface more quickly. Conversely, the removal due to capture could be even higher under very stable conditions such as were present during the nighttime test around buildings (Etyemezian 2003a). In general, one would expect the role of atmospheric stability in near source particle removal to be less important when vegetation or structures are tall and/or are located near the dust source (Etyemezian 2003b).

Figure 2 compares the results of the MRI and DRI field studies with the conceptual model in Figure 1. Test results from the two field studies were added to the schematic of the conceptual model based on descriptions of land cover between the source and the test instruments. The NSC conceptual model shows reasonable agreement with these field tests and thus, it appears to provide a useful framework for making preliminary estimates of CF based on local land cover characteristics.

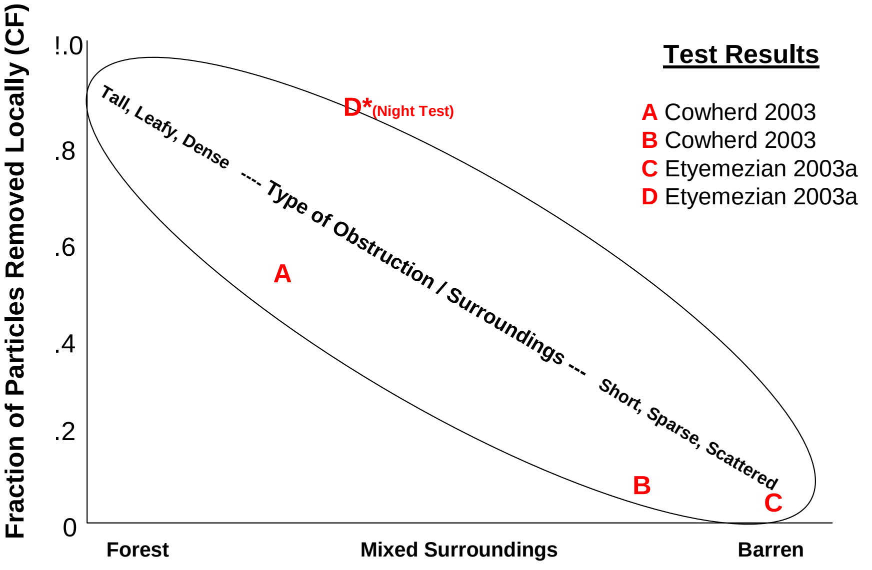

Figure 2. Comparison of Test data with NSC Conceptual Model

Default Recommendations for CF

Estimation of values of CF for specific geographic areas requires use of a land cover dataset such as the Biogenic Emission Land cover Database (BELD). BELD is a compendium of surface cover (mainly vegetation) characteristics used by the Biogenic Emission Inventory System (BEIS) biogenic emission model (Birth & Geron 1995). It contains data on several hundred species of vegetation at a 1 km cell size.

In the analysis presented in this paper, the land cover described in BELD was grouped into five cover type groups, e.g., barren & water; agricultural; grasses, scrub and sparsely wooded; urban; and forested. The estimated ranges and recommended values for CF are given in Table 1 along with the average vegetation heights assumed in BELD. (Urban structures were assumed to range from 5 to over 50 meters). Ranges for the CF for each cover type are based on field work and observations available from Watson and Chow, Raupach, Etyemezian and Cowherd, the height of the ground cover relative to the plume and seasonal changes in the cover characteristics. The ranges conform to the linear conceptual model in Figure 1 in that the CF is assumed to increase linearly with the seasonal presence, height and density of the surface cover. The recommended CF values assigned to Barren and Water (0) and Forest (1) are chosen to be consistent with the limits (extreme values) in the conceptual model, although as noted, the values could in fact be less than 1 for forest and greater than 0 for water & barren. The mid-points of the estimated ranges are used as the recommended CF for the other land cover types. The ranges and recommended CF values should be considered a first approximation and further refinement is welcomed.

Note that the CF's in Table 1 are only generalized defaults and should be modified by local data or as further research becomes available. Also, the estimated CF's herein are believed to be too high for windblown dust events because the wind's turbulence will usually lift particles higher more quickly, and the opportunity for vegetative removal is likely reduced.

Land Cover Type	Average Height (m)	Recommended CF (%)	Estimated CF Range (%)	COMMENT
Forest	18-20	100%	80 to 100%	Forested areas will capture dust effectively
Urban	5 – 50+	50%	25 to 75%	Structures are interspersed with open areas
Scrub, Sparsely Wooded & Grasses	1 – 2	25%	10 to 40%	Portion of plume is below sparse vegetation
Agricultural	1 - 2	25%	10 to 40%	Portion of plume is below crop (seasonally)
Barren / Water	0	0%	0 to 10%	Impediment-free surfaces are ineffective to capture dust

Table 1. Recommended CF (%) for Five Land Cover Types

Method to Estimate the Transportable Fraction in Specific Geographic Areas

The fraction of land area assigned to each land cover type in each US County was obtained from the BELD dataset. The county average transportable fraction was estimated by combining the CF's in Table 1 with the corresponding fractional surface cover in each county and computing a weighted average CF for each county. The TF for each county is then estimated using equation 1 above. The results are shown in Figure 3. Note that these same surface cover data are available in the BELD dataset at a 1 km resolution detail, and the accuracy of the method could be improved by using grid- instead of county-weighted CF's.

Figure 3 shows how the TF varies by county across the US, depending on the variation in surface cover. The differences are apparent across the heavily forested areas in the southeast and the Pacific NW, the arid areas of the Southwest, the agricultural breadbaskets of the Central US and the San Joaquin Valley in CA. Note that nationally, the county average TF ranges from 0 to 0.92. The TF averages approximately 0.49 across all counties in the US, which is less of a reduction in dust emissions than was realized in the old "divide-by-four: approach. Recent analysis by Pace (2005) suggests that additional reduction in PM2.5 fugitive dust emissions may occur when the EPA completes their investigation of apparent errors in the multiplier used to derive PM2.5 emission factors from old PM10 emission factor field measurements.

The county average TF's in Figure 3 represent the first attempt to apply the conceptual model to estimate how dust removal by ground level airflow obstructions might vary across the US; they will be revised as more information becomes available. The transportable fraction concept can be extended to finer spatial resolution using an emissions processor such as SMOKE (Pace and Cowherd 2003). In fact, the WRAP has estimated the TF at a 2 km resolution in support of some of their analyses (Mansell 2005). In Figure 3, the county-level TF is displayed in five ranges, each containing an equal number of counties.

A preliminary estimate of the county-level TF was provided to the WRAP by OAQPS for use with their unpaved road dust emissions inventory. Countess recently applied the NSC concept to modeling in the San Joaquin Valley. He used the method posed by Pace and Cowherd to develop county specific TF's based on weighted average land use and ground cover information for the SJV counties. He found that use of those TF's resulted in adjusted emission estimates that agree well with ambient measurements in these SJV counties (Countess 2003).

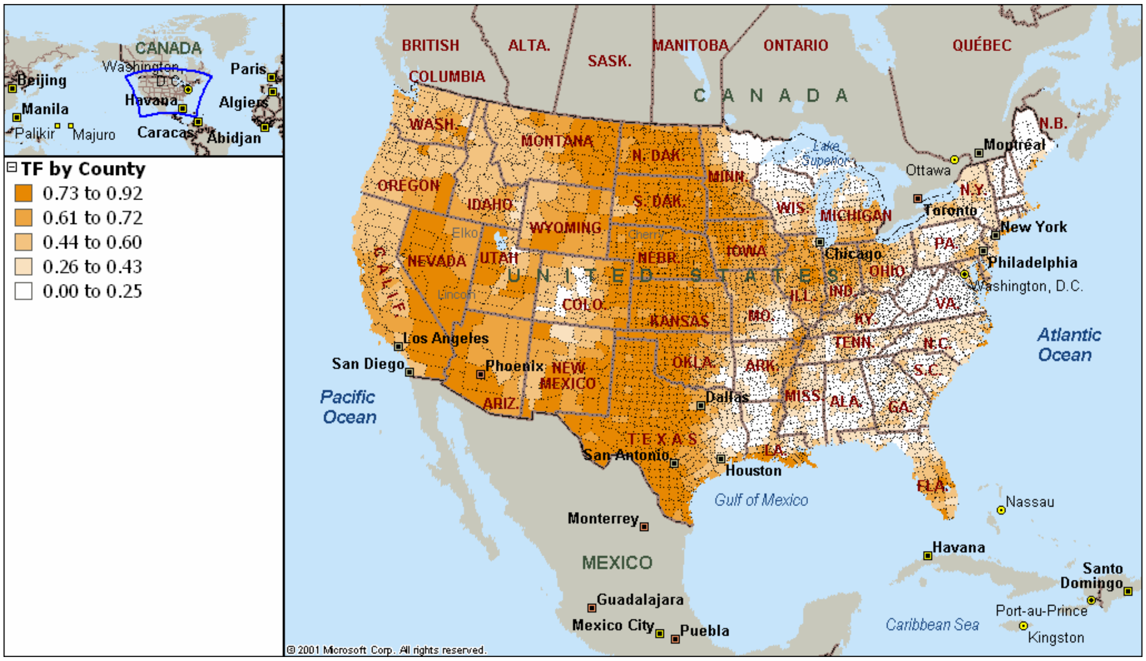

Figure 3. Geographic Variability of the Transportable Fraction

Recommendations and Limitations for Use of the Near Source Capture Adjustment
Based on the discussion above, it is recommended that the NSC adjustment be applied to emission estimates for paved roads, unpaved roads, construction, tilling and quarrying in grid model analyses, until near-source particle removal mechanisms are incorporated into the models (U. S. EPA 2004). EPA has applied the NSC adjustment in regional modeling applications and county-level TF adjustment capability has been incorporated into the SMOKE emissions processor. An important consideration in the application of the NSC concept is the scale represented by the land cover data. Land cover interacts with the source plumes over a scale of several hundred meters from the emission point. Thus, land cover data will be much more representative if it is obtained on a 1 km grid for example instead of the county-level as discussed herein. This is quite practical to do when one is using emission processors to prepare emissions for grid-based modeling since the BELD dataset is available at a 1 km resolution. However, county-level land cover data may be useful to adjust regional and county-level emission inventories for summary reporting and may be useful for use with grid models if finer resolution isn't available.

Note that the NSC adjustment should NOT be used to adjust emission estimates (e.g., permit applications) where local scale impacts are important. Also, the adjustment should not be applied to emissions input to Gaussian models. For Gaussian model applications, one should adjust the appropriate input parameters contained in these models to account for near source dust removal. The NSC adjustment is not applicable to elevated emissions of fugitive dust such as material transfer points, dust generated by wind erosion or low level emissions of buoyant plumes such as open fires or vehicle exhaust since in such cases, the particles are assumed to be above or rapidly rise above the height of the surface cover. Also, the adjustment doesn't currently attempt to account for enhanced deposition on the ground due to thermal, electrostatic or inertial forces.

Future Work

Many refinements have been made to the dust emissions estimation and air quality modeling methodologies over the years. However, significant issues remain and much work is still needed:

1) Improve the emission estimation algorithms, such as correcting (reducing) the emissions for lower vehicle speeds and re-estimating the relationship of PM2.5 to PM10;
2) Improve activity data, such as vehicle miles traveled (VMT), silt content and soil moisture on unpaved roads, surface loading on paved roads and soil conditions during agricultural tilling operations and windblown dust events;
3) Investigate ways to reduce reliance on such difficult to obtain activity data as silt content, surface loading and soil conditions;
4) Improve both the physical and empirical understanding of the near-source enhanced deposition processes (e.g., thermal and electrostatic forces, agglomeration);
5) Compare and critically review the various models for the transmission and removal of suspended particles by different obstructions and surface cover and refine the NSC methodology accordingly;
6) Incorporate the effect of atmospheric stability into the concept of the capture fraction (CF) concept;
7) Extend the NSC methodology to windblown dust models to incorporate removal by NSC;
8) More guidance is needed on the specification of specialized input parameters required by plume models;
9) Continue to improve the removal mechanisms in both grid and Gaussian models.

Conclusions

Our understanding of factors affecting particle removal near ground level fugitive dust sources has improved because of work begun at the EPA-sponsored Fugitive Dust Workshop held at DRI. Models are limited in their ability to fully account for near source removal of particles for a variety of physical and practical reasons, and this limitation is a major reason for the disparity between modeled and monitored estimates of fugitive dust. The recognition that vegetation captures some of this dust has led to a useful, albeit emerging methodology to account for the near source removal of particles in regional and urban scale analyses. This method is an improvement upon the national divide-by-four adjustment that has been used for about ten years. It may be applied in regional scale analyses where fugitive dust is emitted from paved and unpaved roads, construction, agricultural tilling, quarrying and earthmoving. Note that as research in this area evolves, other approaches or assumptions may be deemed more appropriate so it will be prudent to review the NSC adjustment methodology as new studies are published. Also, local knowledge about surface cover should be incorporated when available.

Acknowledgements

The author is grateful to Drs. John Watson, Judith Chow, Richard Countess, John Irwin, Frank Binkowski, Dale Gillette, Chatten Cowherd, Vican Etyemezian, Mr. Philip Lorang and Mr. William Barnard for their research, insight and thoughtful consideration of the issues as this conceptual model evolved.

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Note: The 080305 revision made minor changes in the values assigned for the capture fractions for several land cover types. Overall effect was to reduce the county-level transport fraction (national grand average) from 0.49 to 0.46. However, some individual county TF's changed by as much as +/- 20%.

The original document, published August 3, 2003, was titled "Conceptual Model to Adjust Fugitive Dust Emissions to Account for Near Source Particle Removal in Grid Model Applications."