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FUGITIVE DUST EMISSIONS

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INTRODUCTION

Fugitive dust[1] refers to small particles of geological origin that are suspended into the atmosphere from nonducted emitters. Open fields and parking lots, paved and unpaved roads, agricultural fields, construction sites, unenclosed storage piles, and material transfer systems are the major sources of fugitive dust. Large dust plumes are often noticed over these sources when wind speeds are high or when vehicles are moving. These visible plumes do not necessarily correspond to significant amounts of PM_{10} or $PM_{2.5}$ (particles with aerodynamic diameters less than 10 and 2.5 μm, respectively) measured by nearby air-quality monitors.[2] The PM_{10} and $PM_{2.5}$ size fractions are regulated by National Ambient Air Quality Standards.[3] Total suspended particulate (TSP, mass of particles with aerodynamic diameters less than ~30 μm) is also commonly used as a measure of fugitive dust emissions. Although PM_{10} and $PM_{2.5}$ dust particles scatter and absorb light,[4] they are too small to be seen with the naked eye.

PM_{10} and $PM_{2.5}$ fugitive dust emissions for 1997[5] include wind erosion; agriculture and forestry operations such as tilling and harvesting; roads and construction; and industrial processes such as cement production, quarrying, mining, and other mineral industries. Emissions from these fugitive dust source categories constitute 89% of the 33,574 thousand short tons per year (tpy) of PM_{10} and 66% of the 8,288 thousand tpy of $PM_{2.5}$ emitted into the air.[5] In contrast, on-road and off-road vehicle exhaust accounts for 2.4%, open and residential vegetative burning accounts for 1.8%, and other emitters (mostly industrial and residential coal, oil, and natural gas combustion) account for ~7% of total PM_{10} emissions. For $PM_{2.5}$ emissions, 7.5% derive from on-road and off-road vehicle exhaust, 6.9% come from open and residential vegetative burning, with the rest (~19%) deriving from the other emitters.

Figure 1 shows the categories and amounts of fugitive dust emissions.[5] Industrial emissions are a small fraction of the total. Unpaved roads, paved roads, construction, and wind erosion together constitute more than 80% of PM_{10} and 75% of $PM_{2.5}$ fugitive dust emissions. These emissions are from both urban and nonurban areas. Nearly all the agricultural emissions are from crop and livestock activities in nonurban areas. Most of the paved road dust and construction emissions are from urban areas. Unpaved road dust emissions are from both urban and nonurban sources, with a higher proportion from nonurban surroundings. Wind erosion is primarily nonurban, and the estimates are almost exclusively for agricultural operations.[6] These breakdowns give the impressions that unpaved road dust is the most important fugitive dust contributor on a nationwide basis and that most fugitive dust emissions derive from nonindustrial sources.

PM_{10} and $PM_{2.5}$ source apportionment studies use chemical profiles from different source types and from ambient particle samples to estimate source contributions.[7-11] These studies[12,13] show that, on average, fugitive dust contributes ~40% to ~60% of PM_{10} and ~5% to ~20% of $PM_{2.5}$ measured in the atmosphere. Fugitive dust contributions to ambient measurements are often overestimated by dispersion models that simulate contributions to receptor concentrations (e.g., Chow et al.,[14] Venkatram et al.[15]).

Resolving these discrepancies between emissions estimates and ambient source contributions is an important consideration in designing, applying, and evaluating control strategies intended to reduce fugitive dust emissions. The knowledge base needed to accomplish this resolution is incomplete and needs to be expanded. Fugitive dust emissions estimates contain a high amount of variability owing to the meteorological, physical, and chemical factors on which they are based. These factors can vary widely on a national or smaller regional basis. Systematic errors probably dominate over random errors for spatially and temporally averaged emissions rates, such as those of Figure 1. Random error may equal or exceed systematic biases for smaller areas and shorter time intervals.

This survey of fugitive dust emissions explains the processes that cause dust to be injected into and remain in the atmosphere. These processes depend on surface properties as well as the activities conducted on those surfaces. The survey summarizes fugitive dust emission factors and identifies indicators of the activities to which they are applied. Emissions reduction measures are described and quantitative studies of their effectiveness are reviewed. This survey complements, rather than replaces, detailed procedures for estimating emissions in "AP-42: Compilation of Air Pollutant Emission Factors"[16] that are regularly updated by U.S. EPA. Current procedures should be verified prior to use at *http://www.epa.gov/ttn/chief/*. Representative references are cited that can be consulted for more detailed information for each topic.

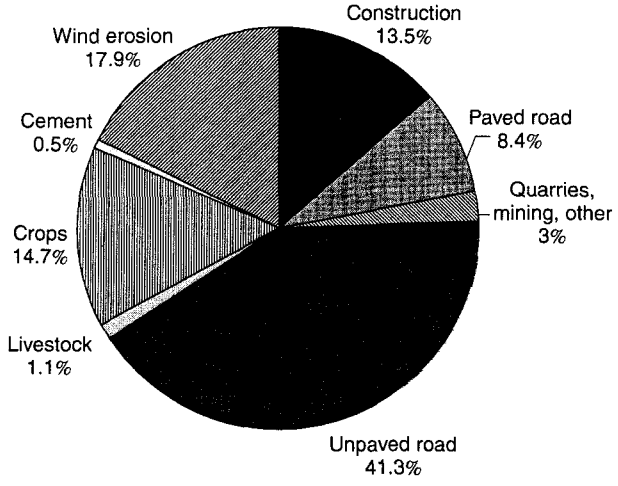
PROCESS DESCRIPTION

Fugitive dust emissions depend on particle sizes, surface loadings, surface conditions, wind speeds, atmospheric and surface moisture, and dust-suspending activities. Emission rates and control measures are also closely related to these properties.

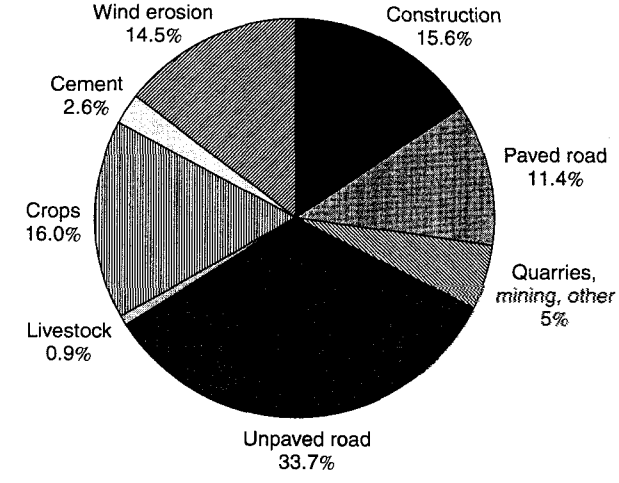
Particle Sizes

Figure 2 shows the size distribution of suspended particles measured from common emission sources, including fugitive dust as determined by resuspension of dust samples and acquisition on filters through size-selective inlets similar to those used for ambient samples.[17-19] Construction dusts, road dusts, and soil dusts result from grinding down of larger particles and are predominantly in the coarse particle size range, larger than 2.5 μm. Combustion particles, on the other hand, dominate the $PM_{2.5}$ size fraction.

Similar size distributions are found in atmospheric particles, where the coarse mode is dominated by elements



PM_{10} Fugitive dust total = 29,778 thousand tpy



$PM_{2.5}$ Fugitive dust total = 5,511 thousand tpy

Figure 1. Fugitive Dust PM_{10} and $PM_{2.5}$ Emissions for Unpaved Roads, Paved Roads, Construction, Wind Erosion, Crops, Livestock, and Industrial Sources.

indicative of geological origin. Pollen and spores also inhabit the coarse particle size range, as do ground-up trash, leaves, and tires. Particles larger than 30 μm deposit to the surface soon after suspension unless they are injected to high altitudes. This deposition effectively limits atmospheric concentrations for very large particles. The peak of the coarse mode in atmospheric size distributions has been measured between ~6 and 25 μm.[20] This peak shifts toward larger particle sizes when fugitive dust emissions are close to the measurement location, and toward smaller particles at nonurban locations far from recent dust emissions.

Laboratory resuspension is not practical for large-scale field surveys. The "silt" fraction of surface dust is most often used as a surrogate for supendable particles. Silt consists of particles with a geometric diameter <75 μm as determined by sieving dried soil samples acquired from surface loading tests. The 75-μm geometric diameter corresponds to an aerodynamic diameter of ~120 μm because the aerodynamic diameter varies inversely with the square root of the density,[21] which is ~2.65 g/cm^3 for minerals. Similarly, a 10-μm aerodynamic diameter dust particle has a ~6-μm geometric diameter, and a 2.5-μm aerodynamic diameter dust particle has a geometric diameter of ~1.5 μm. Little is known about the PM_{10} and $PM_{2.5}$ in surface dust deposits as these fractions are too small to be determined by simple sieving methods.

Particle-size distributions have been determined by sieving samples from different types of soils and recording these in soil surveys. These surveys have been used for agriculture and construction/engineering purposes since the early 1900s in many parts of the United States and are commonly available at county agricultural extension offices. The particle sizing procedure[22,23] most commonly followed for soil surveys creates a soil/water suspension in which soil aggregates are broken into their component parts prior to sieving. While the particle size distribution of the disaggregated sediment is useful for agricultural, construction, and other land uses, it is not entirely applicable for estimating air pollution emissions. This sieving method does not estimate the size of the dust aggregates that are entrained and suspended by surface winds or human activities. The silt fraction is determined by dividing the weight of material passing through the 75-μm sieve by the weight of material presented to a stack of sieves.

Gillette et al.[24] applied two methods to determine the particle and aggregate sizes in soil that might be entrained by winds. The first method ("gentle sieve") consists of drying a soil sample and sieving it gently with about twenty circular gyrations parallel to the plane of the sieve. The second method ("hard sieve") consists of up to one-half hour of vigorous shaking (usually using a shaking machine). Cowherd et al.[25] used a rotary sieving procedure described by Chepil[26] for estimating the modal aggregate size of sediment samples removed from unpaved roads. The gentle sieve method is assumed, without quantitative validation, to be a more suitable approach for determining the potential suspension properties of a soil because it attempts to sample the sediment with its in situ characteristics intact. Silt fractions and amounts determined by the hard sieve method probably provide a reasonable indicator of small particles from roads where vehicle tires abrade the surface. Threshold suspension velocities[24] for windblown dust apply to soil characteristics obtained by the gentle sieve method. Appendix C-2 of AP-42[16] provides detailed procedures for the hard sieve method applicable to other emissions.

The size distribution of dust particles affects the suspension process. A flat bed of particles with diameters less than 20 μm is difficult to suspend by wind. Bagnold[27] showed that fine Portland cement could not be entrained by wind velocities in excess of 1 m/sec at the surface. In this situation, there is no large cross section for wind to act on. In addition, adhesive forces such as van der Waals, electrostatic, and surface tension of adsorbed liquid films[21] increase the force required to entrain the particles.

Suspension of PM_{10} and $PM_{2.5}$ is reduced by larger nonerodible particles. Particles that exceed 840 μm in size shelter smaller particles in their lee.[28] Gillette and Stockton[29] sprinkled glass spheres with diameters ranging from 2,400 to 11,200 μm onto a bed of glass spheres with sizes from 107 to 575 μm and found major reductions in the horizontal flux of the smaller particles. However, Logie[30] found that erosion of a sand surface was enhanced when low concentrations of larger nonerodible obstructions were present on the surface. Logie[30] hypothesized that the increased erosion was due to wind acceleration around the isolated obstructions that scoured the

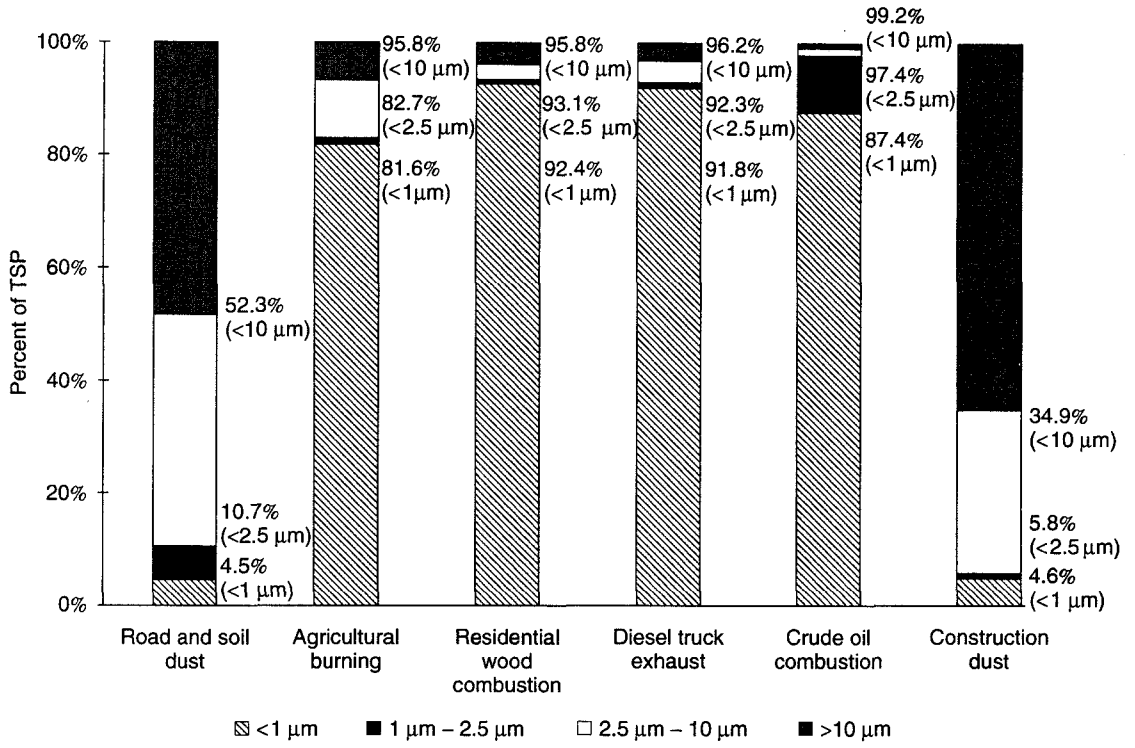


Figure 2. Size Distributions of Several Particulate Source Emissions[17–19].

loose sand. Bagnold[31] estimated that 800-μm particles can be separated from surfaces under high winds, although their large masses cause them to settle to the surface very rapidly.

Rosbury and Zimmer[32] and Flocchini et al.[33] observed higher dust emissions from unpaved road surfaces with lower silt contents and higher gravel content. When acted on by vehicle tires, larger gravel particles replenish the quantity of smaller suspendable particles by enhancing surface abrasion.

Carvacho et al.[34] have developed a method that directly measures the reservoir of PM_{10} available for suspension in a bulk soil sample. Pulses of air are run through a fluidized bed containing the sample, and the suspended dust is sampled through a size-selective inlet onto a series of parallel filters. After a few pulses, one of the filters stops sampling. After a few more pulses, another filter stops sampling and so on. Each filter is separately weighed, and the collected mass is plotted as a function of the aggregate agitation (as determined by the number of pulses). A maximum mass loading is reached after many pulses when the suspendable PM_{10} is depleted. This maximum varies between different types of dusts much more than it varies for repeated samples of the same dust. Shimp et al.[35] have related this PM_{10} suspension potential to the silt measurements in California soil surveys to improve their PM_{10} emissions estimates.

Silt fraction or quantity appear as explicit variables in many of the emissions factors cited below. The processes related to particle size indicate that actual emissions of PM_{10} and $PM_{2.5}$ are influenced by more detailed size distributions above and below the 75-μm geometric diameter that specifies silt content.

Surface Loading

Most soil surfaces are limited reservoirs; suspendable dust is depleted after a short time in the absence of direct abrasion. This depletion is represented as a negative exponential[36,37] or inverse[38–40] function of time.

As noted above, depletion of fine particles often results in the exposure of larger nonerodible sediments that shield the suspendable particles from the wind. The larger nonerodible elements also absorb momentum, thereby decreasing the wind's ability to erode the surface.[41,42] When surfaces are continually disturbed by very intense winds, by vehicular movement, or by other human activities, unlimited reservoirs are created that emit dust whenever winds exceed threshold suspension velocities. Suspendable dust loadings may vary substantially, even over periods of a few minutes, when there are no mechanisms to replenish the reservoir.

Surface loadings are determined by sweeping or vacuuming loose particles from several specified areas within a fugitive dust source. These samples are dried and weighed, then divided by the area sampled to determine the mass of dust per unit area. Appendix C-1 of AP-42[16] provides detailed procedures. The same samples are usually sieved to determine the silt fraction and the quantity of larger particle sizes. Surface loadings vary substantially with space and time. Zimmer et al.[43] measured silt loadings that varied by a factor of twenty at different times for the same paved road in Denver, CO. South Coast Air Quality Management District[44] reported paved road silt loadings from 0.112 to 1.83 g/m^2 for different areas with similar road and traffic conditions in the Los Angeles area.

Surface Conditions

Surface conditions refer to the landform shape and cohesion of a potential dust reservoir. The effects of landform shape on dust suspension are embodied in the concept of "surface roughness." Surface roughness is related to the heights of obstructions within and around exposed dust areas. Agriculturists often

orient their furrows perpendicular to prevailing winds, or plant rows of trees upwind of their fields, to minimize soil losses from wind erosion by increasing surface roughness. Larger surface roughness decreases the force exerted by the wind on suspendable surface particles, thereby decreasing emissions. However, larger surface roughness increases vertical turbulence that can mix suspended particles higher into the atmosphere for longer transport distances.

The aerodynamic roughness length is the apparent distance above the surface at which the average wind speed approaches zero. In reality, wind speed does not become zero at this level, but it deviates from the logarithmic increase of wind speed with height that is commonly found in the atmosphere. Aerodynamic surface roughness is one-eighth to one-thirtieth of height of obstructions in and around an exposed area,[45] but it is site-specific and quantified with wind speed measurements taken at different elevations between ~1 and ~10 m above ground level. The ratio of wind speeds at lower levels is plotted against the logarithm of the height of the measurement and extrapolated to a wind velocity of zero. The intersection with the elevation axis at wind speed equals zero is the surface roughness. In practice, estimates from many hours of wind measurements are averaged to determine typical surface roughness. The slope of this relationship is termed the *friction velocity* and indicates the wind shear forces near an erodible surface.[46]

The presence of large particles or obstructions that increase surface roughness attenuates wind erosion by absorbing a significant fraction of the downward momentum flux from the air flow above.[47] While the principles are known, the effects of changes in surface roughness on fugitive dust emissions are not well quantified.

The same surface roughness may be associated with many degrees of surface cohesion. Natural weathered soil in arid environments tends to develop a crust over time that is highly resistant to suspension.[48] This surface is easily broken by footsteps, let alone by vehicular traffic and livestock grazing.[49,50] A large reservoir of suspendable material is often available beneath this crust. Desert pavements require many decades to reform, as evidenced by still-visible wagon tracks along emigrant trails blazed during the 1840s and 1850s.

Gillies et al.[51] estimated the strength and resilience of unpaved road surfaces by measuring the vertical force (kg/cm^2) needed for penetration with a Proctor Penetrometer®. This is similar in concept to the "rupture moduli" applied by Gillette et al.[50] Force measurements were taken across the road width every 0.25 m on different occasions and for different dust suppression treatments. Hard surfaces, similar to but stronger than natural desert crusts, experienced a brittle failure after application of a large force. The surface shattered, creating small aggregates and holes. Loose particles were exposed, as were edges of the surface that could be further ground down by tire wear. A flexible surface created by a polymer emulsion was penetrated at a relatively low force, but the size of the penetration was limited to the diameter of the Penetrometer, and no aggregates were created. While surface strength may be a good indicator of emissions potential for brittle surfaces, the nature of penetration is just as important. Vegetated and moist surfaces exhibit elastic characteristics similar to those of the polymer emulsion.

Wind Speeds

High wind speeds provide the energy needed to suspend loose particles from a surface; turbulence associated with these winds elevates particles to high altitudes where they can transport over long distances.[52–62] Wind erosion occurs in urban as well as non-urban areas. Figure 3 compares PM_{10} concentrations averaged for different wind speeds near a construction site in Las Vegas, NV, and at a location in the nearby non-urban desert. The urban site shows higher concentrations at wind speeds of 0 to 2 m/sec owing to accumulation of nearby emissions under stagnant conditions. PM_{10} levels begin to increase at wind speeds of 4 to 5 m/sec, attributable to windblown dust emissions from nearby land

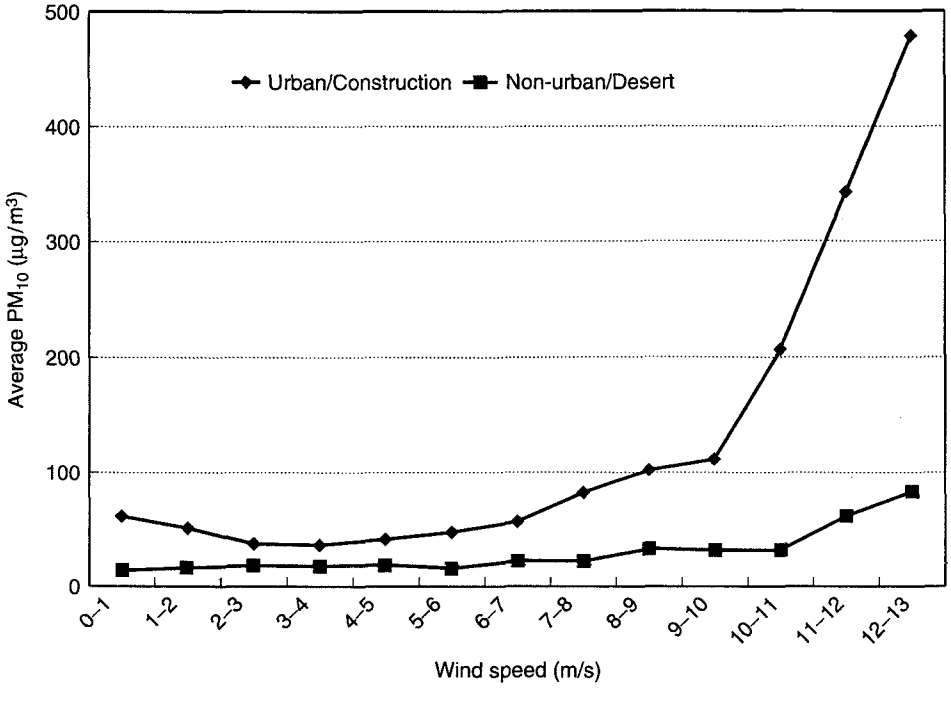


Figure 3. Average PM_{10} Classified by Wind Speed from Hourly Beta Attenuation Monitor Measurements at an Urban/Construction and a Non-Urban/Desert Site Near Las Vegas, NV During 1995.[63] Wind Speeds were Measured at 10 m agl.

parcels denuded for new construction.[14,63] Large increments in PM_{10} are not seen, however, until wind speeds exceed 7 m/sec with concentrations increasing rapidly for wind speeds in excess of 10 m/sec. Fortunately, these high winds are infrequent, occurring for only 83 h during 1995. Several of these hours were consecutive, however, and were associated with 24-h average PM_{10} exceeding 150 $\mu g/m^3$.

The nonurban desert site experienced a similar frequency of high winds, but it does not show significant increases in emissions until these speeds exceed 11 m/sec. A slight increase in PM_{10} is noticeable for wind speeds above 8 m/sec. This example refutes the argument that most urban dust derives from natural surfaces. Only when wind speeds are high and persistent do undisturbed areas provide measurable, though not major, fractions of PM_{10} or $PM_{2.5}$ in the atmosphere. Nonurban surfaces disturbed by off-road traffic, agricultural operations, and construction should not be classified as natural sources because they were created by human intervention.

Chepil and Woodruff[64] and Gillette and Hanson[65] show that the amount of dust suspended by wind depends on particle size distributions, wind speed at the surface, surface roughness, the relative fractions of erodible (<2 mm diameter) and nonerodible (>2 mm diameter) material, and the cohesion of the soil particles with one another. Values for each of these variables affect other variables. For example, a higher moisture content increases cohesion among particles and shifts the size distribution to larger particles. Larger agglomerations of small particles increase surface roughness, thereby decreasing wind speeds at the surface.

The effects of all these variables are embodied in a threshold friction velocity that is experimentally determined by placing a wind tunnel over an example of the affected soil and measuring the surface speed at which soil movement first becomes visible.[24,40,54,66–75] With the more common use of continuous particulate monitors,[76] threshold friction velocities might be inferred from hourly PM_{10}, $PM_{2.5}$, and wind-speed measurements at ambient sampling sites, as demonstrated in Figure 3. Averaging times of 1–5 min would provide more precise estimates than the hourly averages used in Figure 3.

Gillette[53] shows threshold friction velocities that vary from 0.19 to 1.82 m/sec for soils with different degrees of disturbance. Most ambient wind speed measurements such as those in Figure 3 are made at elevations between 5 and 10 m above ground level, and these must be translated to surface friction velocities to determine suspension. This is done using estimates of surface roughness and friction velocities from the actual or similar sites.[16] For this range of surface threshold values, emissions will be initiated at ambient wind speeds (measured at 7 m above the ground level, the height of most National Weather Service wind sensors) between 7 and 10 m/sec (26 to 37 km/h). Even though emissions begin at these velocities, the wind force contains insufficient energy to suspend very much of the erodible soil mass. The amount of dust suspended increases at approximately the cube of the wind speed above the threshold velocity. This is consistent with the measurements in Figure 3.

Particles suspended into the atmosphere are acted upon by gravity in a downward direction and by atmospheric resistance in an upward direction. Every particle attains an equilibrium between these forces at its terminal settling velocity. The settling velocity increases as the square of the particle diameter, and linearly with particle density.[77] For very small particles (<10 μm diameter), turbulent air movements in wind storms can counteract the gravitational settling velocity, and such particles can remain suspended for long times.[78–80] Transport distance depends on the initial elevation of a particle above ground level, the horizontal wind velocity component at the particle elevation, and the gravitational settling velocity.

Pye[81] shows vertical profiles for different-sized particles that might be elevated through a 100 m depth during a wind storm. The particles smaller than 10 μm are nearly uniformly distributed through this depth, while the larger particles exhibit much higher concentrations closer to the surface. Terminal settling velocities dominate most situations for >10 μm particles in the absence of violent winds.

Moisture Content

Water adhering to soil particles increases their mass and surface tension forces, thereby decreasing suspension and transport. Cohesion of wetted particles often persists after the water has evaporated due to the formation of aggregates and surface crusts. Soil moisture content is determined from representative samples swept or vacuumed from the potentially emitting surface and stored in an airtight container. A portion of the sample is weighed before and after 24-h heating at ~110°F in a laboratory drying oven, with the difference being equal to the evaporated water.[82,83] Low temperatures are used to minimize volatilization of materials other than water that might affect the weight change. Appendix C-2 of AP-42[16] provides detailed procedures.

Rosbury and Zimmer[32] found that moisture content affects the ejection of particles by vehicles, as well as the strength of the road bed and hence its ability to deform under vehicle weight. The addition of water to create surface moisture contents exceeding 2% resulted in >80% reductions for PM_{10} emissions compared to a control surface with an average moisture content of 0.56%.[33] Road surface-moisture content enhances the strength characteristics of surface crusts and the stability of aggregates.[84,85]

Kinsey and Cowherd[86] show how watering reduces emissions at a construction site. Significant dust control benefits are derived initially by doubling the area that is watered; however, benefits are reduced as more water is applied to the site. Ultimately, control efficiency is limited because grading operations are continually exposing dry earth and burying the moistened topsoil.

Excessive moisture causes dust to adhere to vehicle surfaces so that it can be carried out of unpaved roads, parking lots, and staging areas. Carryout also occurs when trucks exit heavily watered construction sites.[87] This dust is deposited on paved (or unpaved) roadway surfaces as it dries, where it is available for suspension far from its point of origin. Fugitive dust emissions from paved roads are often higher after rainstorms in areas where unpaved accesses are abundant, even though the rain may have flushed existing dust from the paved streets.

The same amount of moisture affects different dust surfaces in different ways. Moisture capacities of different geological materials are documented in soil surveys. Soil surveys include several indicators of the ability of soils to absorb moisture, with the most common being the "plastic limit." The plastic limit is the moisture content at which a soil changes from a semisolid to a plastic and is determined by adding water to a dry soil sample until it can be rolled into a coherent cylinder. Soil surveys also report liquid limits (the quantity of water required to create a slurry with the consistency of water), the

infiltration rate (the movement of water through soil layers), and field moisture capacity.

The actual moisture content at a given time or place is not recorded and must be estimated. Thornthwaite[88] proposed the ratio of precipitation to evaporation as an indicator of the availability of moisture for soils. Thornthwaite's major concern was the agricultural potential of land in different areas. The precipitation–evaporation effectiveness index (P–E index) is ten times the sum of the monthly precipitation to evaporation ratios. Thornthwaite[88] classified North America as wet (P–E index > 128), humid (64 < P–E index < 128), subhumid (32 < P–E index < 64), semiarid (16 < P–E index < 32), or arid (P–E index < 16). Much of the Western United States is in the arid and semiarid categories. The P–E index has been used to estimate the moisture content of different soils, as an input to calculate emission factors for different surface types.

Precipitation events and the P–E index are crude methods of estimating soil moisture, which is likely to be affected by snow, fogs, and high humidity and to decrease over several days following heavy precipitation. An alternative model uses hourly rainfall, snowfall, relative humidity, and traffic volumes with monthly average Class A Pan evaporation rates to estimate soil moisture content.[89] Cowherd et al.[90] provide a map of average evaporation rates for 1946–1955.

The moisture content of soils varies throughout the year depending on the frequency and intensity of precipitation events, irrigation, and relative humidity and temperature of the surrounding air. Large amounts of rain falling during one month of a year will not be as effective in stabilizing dust as the same amount of rain interspersed at intervals throughout the year. Vehicle traffic enhances moisture evaporation by increasing air movement among the surface particles and exposing dry soil below the moist surface. Trees and other natural or manmade formations that evapo-transpire or cast shadows can also enhance or retain soil moisture content.

Vehicular Movement

The most common dust-suspending activity is vehicular movement on paved roads, unpaved roads, parking lots, and construction sites. This movement creates a reservoir of particles as well as providing the energy to inject them into the atmosphere.

Vehicle shape, speed, weight, number of wheels, as well as its previous history (e.g., dust acquisition for trackout) interact with different road surfaces to change the particle size, surface loading, wind effects, and surface moisture. Vehicular traffic in these areas adds to particle suspension because tire contact creates a shearing force with the road that lifts particles into the air.[91] Moving vehicles also create turbulent wakes that act much like natural winds to raise particles.[92] Natural crusts are often disturbed by vehicular movement, increasing the reservoir available for wind erosion.

Dust on paved roads must be continually replenished; minimizing the deposition of fresh dust onto these surfaces is a viable method for reducing their PM emissions. Dust loadings on a paved road surface build up by being tracked out from unpaved areas such as construction sites, unpaved roads, parking lots, and shoulders; by spills from trucks carrying dirt and other particulate materials; by transport of dirt collected on vehicle undercarriages; by wear of vehicle components such as tires, brakes, clutches, and exhaust system components; by wear of the pavement surface; by deposition of suspended particles from many emissions sources; and by water and wind erosion from adjacent areas.[1,93]

The relative contribution from each of these sources is unknown. Axetell and Zell[94] estimated typical deposition rates of 67.8 kg/km over a 24-h period for particles of all sizes from the following sources: (1) 42% from mud and dirt carryout; (2) 17% from litter; (3) 8% from biological debris; (4) 8% from ice control compounds (in areas with cold winters); (5) 8% from erosion of shoulders and adjacent areas; (6) 7% from motor vehicles; (7) 4% from atmospheric dustfall; (8) 4% from pavement wear; and (9) less than 1% from spills. Axetell and Zell[94] cite these fractions without describing the methodology used to estimate them.

Unpaved roads and other unpaved areas with vehicular activity are unlimited reservoirs when vehicles are moving. When regularly traveled, these surfaces are always being disturbed, and wind erosion seldom has an opportunity to decrease surface loadings or increase the surface roughness sufficiently to attenuate particle suspension. The grinding of particles by tires against the road surface shifts the size distribution toward smaller particles, especially those in the PM_{10} fraction. Pinnick et al.[95] found the distribution of particle sizes within a vehicle-created dust plume to be bimodal, with one mode peaking at ~50 μm and another mode peaking at ~2.5 μm. Patterson and Gillette[96] reported a similar distribution for naturally generated windblown dust plumes, with fewer large particles in the natural plume than in the vehicle-generated plume. The bimodal distribution was attributed to grinding processes caused by tires for the vehicle dust[95] and to a sandblasting process for wind-generated dust.[96] Nicholson et al.[91] show particle size and emissions rate increasing with vehicle velocity, consistent with higher energy transfer through surface contact and turbulent wakes at higher speeds.

Dyck and Stukel[97] hypothesized that vehicle weight and road type influence dust emissions. Mollinger et al.[98] found the shape of vehicles to have a large impact on the amount of dust suspension; a cylinder, an elliptical solid, and a rectangular solid were mounted on a pendulum that swung back and forth over dust-covered test areas. After twenty passes by the cylinder and elliptical solid, 65% and 45% of the dust remained in the test area, respectively. After twenty passes by the rectangular solid traveling at the same velocity, less than 20% of the dust remained. Moosmuller et al.[92] found that only high-profile vehicles, such as semi tractor trailers, produced sufficient turbulence to suspend dust along an unpaved shoulder next to a paved road. Normal passenger vehicles and pickup trucks produced negligible shoulder emmissions when traveling at speeds of 80 to 96 km/h.

Figure 4 shows the effect of several variables, especially surface loading, on emissions from a paved roadway.[99] PM_{10} (light scattering equivalent) measured behind a vehicle tire on a clean-looking roadway was 10 to 100 times the PM_{10} in the surrounding air. PM_{10} measured behind the tire increased by another order of magnitude when the vehicle passed over a visible deposit from construction site trackout. Figure 4 demonstrates the variability of road emissions over short distances. It also suggests a method to evaluate roadway emissions potential that would couple high time-response PM_{10} measurements with geographic positioning system (GPS) tracking. These continuous measurements may be more closely related to actual emissions than sporadic silt content and surface loading samples.

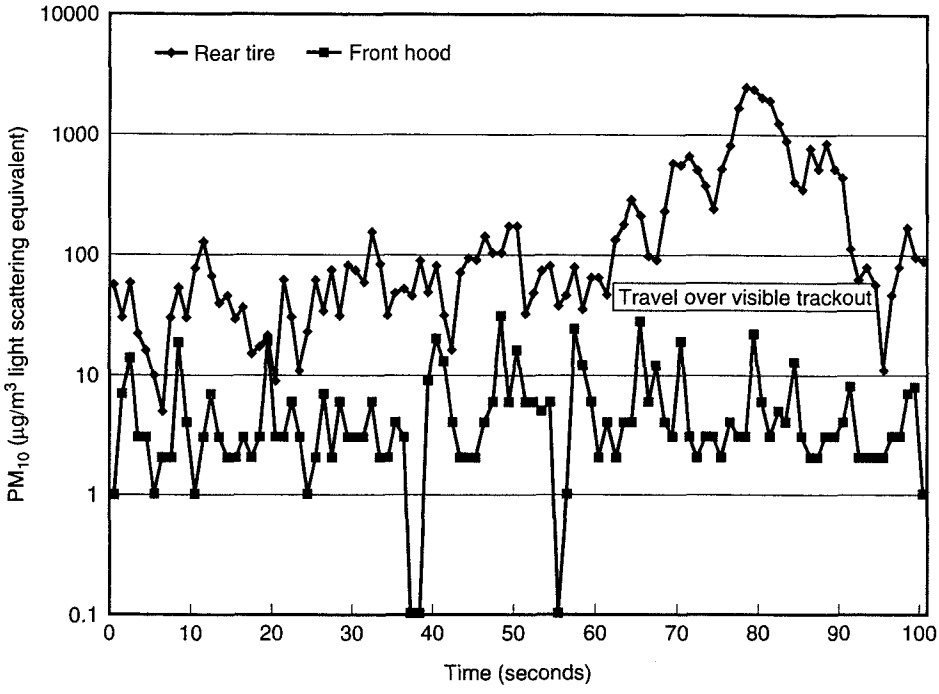


Figure 4. PM_{10} Equivalent Concentrations on a Paved Road on the Front Hood (~ 1 m Above Ground Level and Behind the Right Front Tire (~ 0.25 m agl) of a Vehicle Moving at 10 mph. Concentrations Behind the Tire Increased Considerably with Travel Over a Surface with Visible Trackout from a Construction Site. One-Second PM_{10} Concentrations are Estimated Using a DUSTRAK® Photometer Calibrated with Arizona Road Dust.

Industrial Processes and Construction

In addition to paved and unpaved roads and disturbed areas, many industrial and construction sites that use mineral products have storage pile, material conveyance, and loading, digging, dozing, grading, scraping, and blasting activities. These activities create dust reservoirs, mechanically inject dust into the atmosphere, and present targets for wind erosion. Most of these operations are affected by the same variables described above, but the frequency, spatial extent, and magnitudes differ from those of urban and nonurban dust sources. Since most industrial operations are confined to private property, the combined PM_{10} and $PM_{2.5}$ emissions that travel beyond the property limits are of greatest concern to attainment of National Ambient Air Quality Standards. Visible clouds and deposition of large particles (>30 µm) on neighboring communities are often nuisances that need to be addressed.

Most modern industrial sites have designed the placement of their operations to minimize both emissions and transport of dust outside of property boundaries. Large blending domes, for example, are becoming more widely used in the cement industry to obtain a more homogeneous composition of the feed material to the kiln, thereby making better use of raw materials and minimizing upsets. Underground transport systems and covered conveyers are commonly used to minimize product loss. A fortunate by-product of these technological advances is to reduce fugitive dust from materials handling and plant upsets while increasing product volume and quality.

Other Dust-Emitting Activities

Botsford et al.[100] examined emissions from landfills, leafblowers, and equestrian facilities, and found them minor compared to those from paved roads, unpaved roads, construction, and wind erosion. These sources may be important within certain neighborhoods, however.

Botsford et al.[100] estimated landfill emissions to range from less than one ton per year for a small landfill about 650,000 m^2 and handling 1,150 m^3 of waste material to nearly 38 tons per year for a larger landfill about 5,120,000 m^2 in size and handling about 6,100 m^3 per day. For California and Nevada, it was concluded that landfills accounted for less than one percent of the local urban area fugitive dust emissions inventories.

Botsford et al.[100] estimate made an aerodynamic calculation of potential dust suspension from leafblowers used in the Los Angeles area. With ~420,000 units used one day per week to clean an area of ~1,000 m^2, fugitive dust emissions could be almost 9 tons per day. This represented about 2% percent of the 1993 PM_{10} inventory for the South Coast Air Quality Management District.

Botsford et al.[100] used a box model to estimate emissions from horse-riding activities in the Los Angeles area. Based on surveys of equestrian centers in the Los Angeles area, it was concluded that about 13,000 horses were associated with equestrian centers, and that PM_{10} emissions from horse-riding activities were less than 0.2 tons per day, or less than 0.1% of the local fugitive dust inventory.

FUGITIVE DUST EMISSIONS CHARACTERIZATION

Fugitive dust emissions rates are determined by the following relationship:

$$E_{jkl} = R_{jkl} K_{jkl} A_{jkl} (1 - P_{jkl}) \quad (1)$$

where E_{jkl} is the emissions rate from source type j over time period k and area l; R_{jkl}, the rate of emissions (emissions factor) for a specific size fraction per unit of activity for source type j over time period k and area l; K_{jkl}, the particle size modifier applied to R_{jkl} when E_{jkl} is intended to represent a particle size fraction different from that represented by R_{jkl} (e.g., when $PM_{2.5}$ emissions are desired and emissions factors are only available for PM_{10} or TSP); this factor may be different for different source types j, time periods k, and area l; A_{jkl}, the activity

that engenders dust emissions for source type j over time period k and area l; and P_{jkl}, the fractional reduction due to emissions controls applied to source j over time period k and area l.

Subscripts for source type, averaging time, and area are explicit in Eq. 1 to emphasize that these must be specified when estimating emissions. Some form of aggregation is always necessary owing to the static nature of most activity data. Averaging periods and spatial extent are usually much larger than those related to specific emissions events that might affect an ambient concentration. Chemical characterization of source and ambient samples provides an alternative for determining contributions to excessive 24-h PM_{10} or $PM_{2.5}$ concentrations, as discussed below.

U.S. EPA[16] provides regular updates on emissions factors, R_{jkl}, and methods for their application. The factors described below are consistent with 1999 practices, but emissions factors and their methods of application are continually being revised as new information becomes available.

Emissions factors are derived from experiments on specific sources that are believed to represent the general behavior of a source category. Most of the U.S. EPA emissions factors[16] are based on horizontal fluxes from an emitting area such as a road or vacant lot.[101] This is accomplished by locating sampling systems with the desired size-selective inlet (TSP, PM_{10}, or $PM_{2.5}$) at various elevations downwind of the dust-emitting area. Monitors located upwind are used to determine the flux into the emitting domain. This is most easily accomplished along roadways or open areas that have consistent traffic and confined boundaries.

Each of the downwind samplers is used to represent the amount of dust that is carried by the wind component perpendicular to a plane parallel to the source. Both the wind speed and concentration vary with height above ground level; so the horizontal flux is calculated through an area that extends above and below each sampler. These fluxes are added to obtain the aggregate emission rate from the source, after the flux of particles into the emitting area has been subtracted. Figure 5 shows a typical configuration for making these measurements.[102] Sampler elevations, distances from the source, and measurement devices vary among the different studies that have been conducted.

Figures 6 through 8 show the cumulative horizontal emissions fluxes at different elevations above ground level for paved roads, unpaved roads, and bare soil/construction sites.[99] These plots result from many of the same downwind profile tests that were used to derive commonly used PM_{10} emissions factors. The most noticeable feature from these plots is that 60% to 80% of the horizontal emissions flux is detected at elevations less than 1 to 2 m above ground level.

A 10-μm-aerodynamic-diameter particle has a settling velocity of ~0.3 cm/sec, and would therefore deposit to the surface within ~5 min after achieving an elevation of 1 m

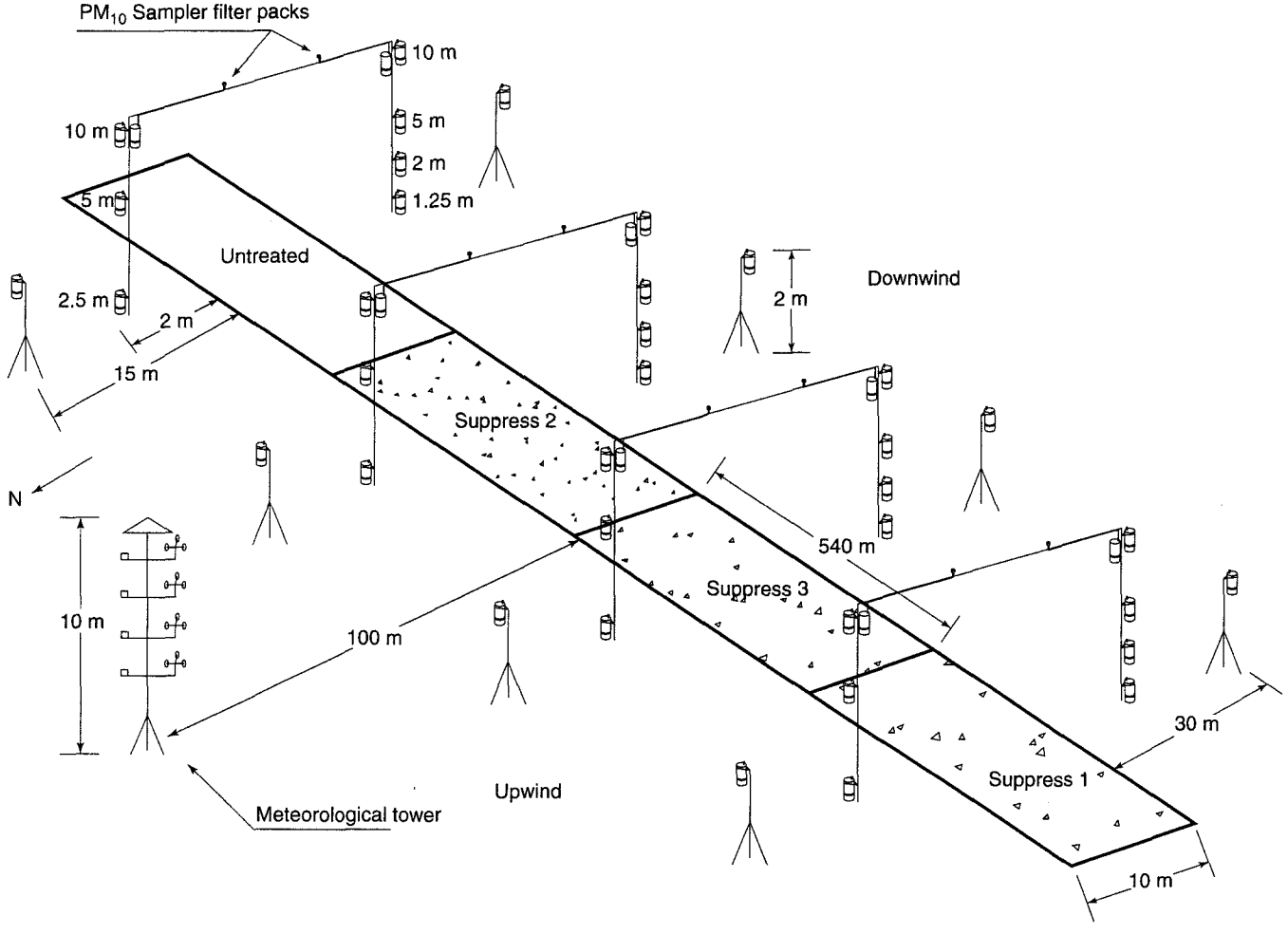


Figure 5. Example of Horizontal Flux Measurement System Around an Unpaved Road Treated with Different Suppressants[102].

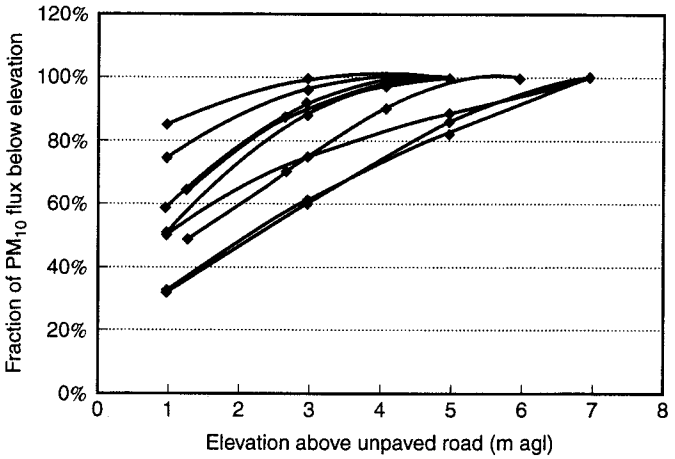


Figure 6. Cumulative Horizontal PM_{10} Flux at Different Downwind Elevations Above Different Unpaved Roads (Data from Cowherd et al.[99]).

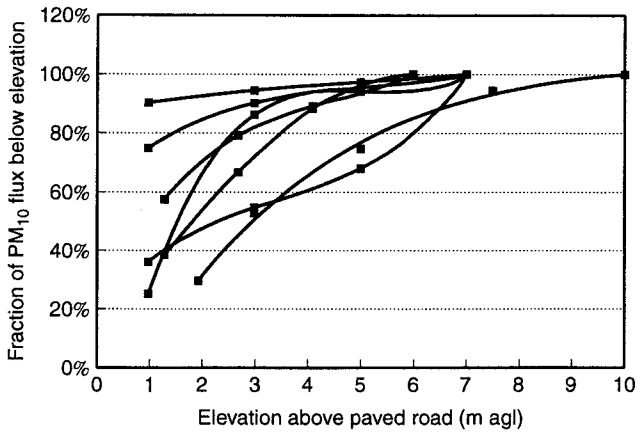


Figure 7. Cumlative Horizontal PM_{10} Flux at Different Elevations Above Different Paved Roads (Data from Cowherd et al.[99]).

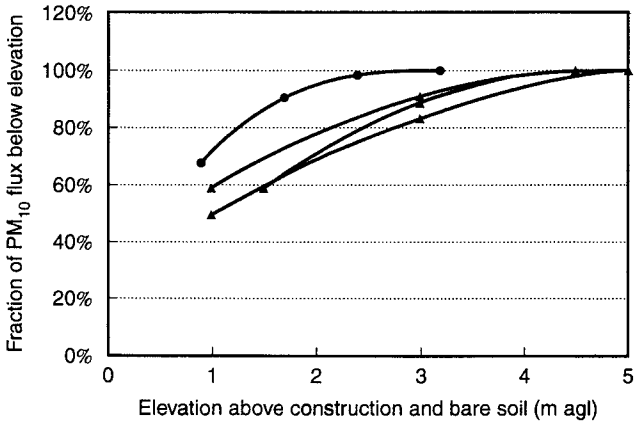


Figure 8. Cumulative Horizontal PM_{10} Flux at Different Downwind Elevations Above Different Construction and Bare Soil Sites. (Data from Cowherd et al.[99]).

above ground level. This corresponds to a travel distance of not more than 1 km in a 3-m/sec wind. Travel distances would be 0.25 km for a 20-μm particle and 4 km for a 5-μm particle under similar wind conditions. This assumes that these near-surface particles do not encounter low-level obstructions in their pathways. The rapid attenuation of PM_{10} concentrations due to deposition and vertical dispersion downwind of an unpaved road is illustrated in Figure 9.[99] While there is substantial scatter in the ratios of downwind to roadside concentrations, it is clear that PM_{10} is attenuated by ~90% within only 50 m from an unpaved roadside.

Dispersion models usually consider fugitive dust emissions at elevations higher than 2 m agl. Effective emissions heights of 5 to 10 m agl are often used so that a plume can develop downwind of a site. Most models are unable to resolve terrain variations of 1 to 2 m, and are therefore unable to account for the effects of horizontal impaction on gently rolling terrain and obstructions such as trees, shrubbery, and buildings.

There is little published information on the quantitative effect of nearby obstructions on low-level dust emissions, but it is common practice to place obstructions such as greenbelts[103,104] near visible dust emitters. Slinn[80] shows that dust deposition velocities through eucalyptus forest can be five to ten times higher than gravitational settling velocities with wind speeds of 5 to 10 m/sec.

Vertical flux is an alternative to horizontal flux as a method to estimate fugitive dust emissions.[105,106] Vertical flux is proportional to particle density, surface friction velocity, and the difference between particle concentrations at different elevations above ground level. Only a fraction of the horizontal flux moves upward, depending on meterological, aerosol, and surface variables. These variables can be obtained with a configuration similar to that of Figure 5.

Currently used emissions factors based on integrated horizontal flux adequately represent suspendable dust, the amount that leaves a dust-generating surface. These factors do not adequately represent transportable dust, the fraction of suspendable dust that is likely to travel more than a few hundred meters from the emitter. Future revisions to AP-42 may consider factors for horizontal fluxes above certain elevations that can be associated with appropriate zones of influence. For example, fluxes below 2 m would not be used to estimate impacts at distances larger than 1 to 10 km from the source, but would be available to estimate impacts on nearby receptors. Vertical flux estimates might be more appropriate for determining fugitive dust impacts over urban and larger spatial scales.

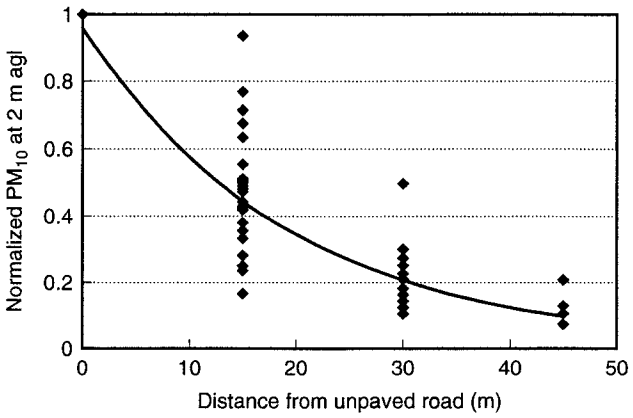


Figure 9. Attenuation of PM_{10} Concentrations with Distance from an Unpaved Road.[102].

Unpaved Road Dust Emissions

Results from 180 PM_{10} and 92 TSP field tests were used to develop unpaved road emissions factors. The PM_{10} emissions factor for unpaved roads is:

$$R_{ur,PM_{10}} = 2.6(silt/12)^{0.8}(weight/3)^{0.4}(moisture/3)^{-0.3} \quad (2)$$

where $R_{ur,PM_{10}}$ is the PM_{10} unpaved road dust emission factor for all vehicle classes combined (pounds/vehicle mile traveled); silt, the silt content of the surface material (% mass); weight, the average weight of all vehicle types combined (tons); and moisture, the surface moisture content (%).

Particle size modifiers are $K_{ur,PM_{10}} = 1.0$ and $K_{PM_{2.5}} = 0.146$. For conversion to metric units of grams per vehicle kilometer traveled, multiply $R_{ur,PM_{10}}$ by 281.9.

Earlier emissions factors included variables for speed and number of wheels contacting the unpaved road surface, but these were not found to be statistically significant in the reanalysis of test data. U.S. EPA[16] provides ranges of average silt loadings for different source types from 5.1% to 24%. Individual sample silt loadings range from 0.1% to 68%. Equation 2 overestimates average emissions for vehicle speeds lower than 24 km/h.

A control effectiveness modifier due to rain is often appended to Eq. 2 to estimate annual averages: $P_{annual,county} =$ precidays/365, where precidays is the number of precipitation days per year with greater than 0.01 in. of rain as determined by the National Climatic Data Center. These data are usually sufficient to obtain spatial resolution for different counties within a state. This modifier assumes a 100% emissions reduction effectiveness for each day with more than 0.01 in. of precipitation.

Paved Road Dust

Results from regression analysis on data from 65 paved road dust tests that measured PM_{10} were used to derive the following paved road dust emissions factor:[3]

$$R_{pr,PM_{10}} = 0.016(siltload/2)^{0.065}(weight/3)^{1.5} \quad (3)$$

where $R_{pr,PM_{10}}$ is the PM_{10} paved road dust emission factor for all vehicle classes combined (pounds per vehicle mile traveled); siltload, the silt loading of the surface material (g/m^2); and weight, the average weight of all vehicle types combined (tons).

Particle size modifiers are $K_{pr,PM_{10}} = 1.0$ and $K_{pr,PM_{2.5}} = 0.247$. For conversion to metric units of grams per vehicle kilometer traveled, multiply $R_{ur,PM_{10}}$ by 287.5. Equation 3 is qualified for the range of variables that encompasses the tests from which it was derived. These are silt loadings between 0.02 and 400 g/m^2, mean vehicle weights of 2 to 42 tons, and mean vehicle speeds of 10 to 55 mph. Default silt loadings for normal roads are 0.1 g/m^2 for roads with more than 5,000 vehicles per day and 0.4 g/m^2 for roads with less than 5,000 vehicles per day. For dirty roads, such as those with visible carryout or road sand on them, the default values are 0.5 g/m^2 for more than 5,000 vehicles per day and 3 g/m^2 for fewer than 5,000 vehicles per day. These defaults may differ widely from actual values; great improvements in emissions estimates are gained with a few simple silt loading measurements.

Construction

The only available construction emission factor is a fixed value for total suspended particulate matter (TSP):

$$R_{const,TSP} = 1.2 \text{ tons/acre/month of activity} \quad (4)$$

Multiply $R_{const,TSP}$ by 2.24 to obtain emissions in mg/hectare/mo. No particle size modifiers are available. The acres of land under construction are usually estimated from the dollars spent on construction. The construction dust source category includes the building of residential structures, commercial structures, and roads. Emissions result from individual construction operations such as scraping, grading, loading, digging, compacting, light-duty vehicle travel, and other operations. Only the heavy earthmoving portion of a construction project approaches the emissions indicated by Eq. 4.[107] A better approach to estimating construction emissions is to break the project into its composite operations and apply individual emissions factors for unpaved roads, paved roads, and wind erosion.

Active Storage Piles

Active storage piles generate dust when material in dropped onto them from above in an unenclosed area. Material can be added in batches or continuously. The material is carried away from the pile by wind; so this is an important variable in emissions estimation. The emission factor for storage piles is:

$$R_{pile,PM_{10}} = 0.0011(windspeed/5)^{1.3}(moisture/2)^{-1.4} \quad (5)$$

where $R_{pile,PM_{10}} = PM_{10}$ storage pile emission factor (pounds/ton of material dropped); windspeed, the mean wind speed (mph); and moisture, the material moisture content (%).

Particle size modifiers are $K_{pile,PM_{10}} = 1.0$ and $K_{pile,PM_{2.5}} = 0.314$. Multiply $R_{pile,PM_{10}}$ by 0.5 to obtain units of kg/Mg of material dropped. Silt content was not found to be a significant variable in the regression analysis used to generate Eq. 5. The range of conditions for the emissions tests that generated Eq. 5 were silt contents of 0.44% to 19%, moisture contents of 0.25% to 4.8%, and wind speeds of 1.3 to 15 mph (21 to 24 km/h).

Wind Erosion

Since wind erosion depends on wind speeds at the surface exceeding the threshold velocity, hourly wind speed measurements at a known height above ground level are needed. Gusts or "fastest mile" winds are used in the estimation method. Gusts are the highest speed recorded for 60 sec or less during an hour. The fastest mile is reported by the National Weather Service as the speed corresponding to the fastest wind within an hour to traverse a full mile. The emission factor for wind erosion is:

$$R_{eros,PM_{10}} = 0.5\Sigma(58(u^* - u_t^*)^2 25(u^* - u_t^*) \quad (6)$$

Sum only for $(u^* - u_t^*) > 0$, and where $R_{eros,PM_{10}}$ is the PM_{10} emission factor (g/m^2 of available reservoir); u^*, the friction velocity at the surface (m/sec); and u_t^* the threshold suspension velocity at the surface (m/sec).

For a typical configuration with 0.05 surface roughness and measurements from a 10-m meteorological tower, the surface friction velocity is ~0.053 times the gust or fastest mile speed

measured at 10 m. U.S. EPA[16] provides several examples and default values for surface roughnesses that can be used to adapt Eq. 6 to a variety of landforms. Particle size modifiers are $K_{eros,PM_{10}} = 1.0$ and $K_{pr,PM_{2.5}} = 0.30$.

CHEMICAL COMPOSITION

Fugitive dust contributions to PM_{10} and $PM_{2.5}$ concentrations in ambient air are easily distinguished from other source contributions by their chemical compositions. Hundreds of fugitive dust source profiles from many different areas have been measured.[108] Chemical source profiles are the fractional mass abundances of measured chemical species relative to primary PM_{10} or $PM_{2.5}$ mass in source emissions.

Source profile compilations (e.g., Watson and Chow,[4] Cowherd et al.,[99] Watson,[109] Sheffield and Gordon,[110] Core and Houck,[111] Cooper et al.,[112] Houck et al.,[17,113–115] Chow and Watson,[63,116,117] and Watson et al.[118–120]) include chemical abundances of elements, ions, and carbon for geological material (e.g., paved and unpaved road dust, soil dust, storage pile), motor vehicle exhaust (e.g., diesel-, leaded-gasoline-, and unleaded-gasoline-fueled vehicles), vegetative burning (e.g., wood stoves, fireplaces, forest fires, and prescribed burning), industrial boiler emissions, and other aerosol sources. More modern, research-oriented profiles include specific organic compounds or functional groups, elemental isotopes, and microscopic characteristics of single particles.[121,122]

Chow et al.[123] found that geological profiles typically contain large abundances of aluminum (Al), silicon (Si), potassium (K), calcium (Ca), and iron (Fe). The abundance of total potassium (K) is six to ten times the abundance of soluble potassium (K^+). The abundances of aluminum (Al), silicon (Si), potassium (K), and iron (Fe) are similar among fugitive dust profiles. Lead (Pb) is often enriched in paved road dust, even though leaded fuels are no longer used in the United States. Carbon constitutes 5% to 15% of road dust and some agricultural soils. Soluble ions such as sulfate (SO_4^{2-}), nitrate (NO_3^-), and ammonium (NH_4^+) are generally low, in the range of 0.1% to 0.2%. Sodium (Na) and chloride (Cl^-) are also low, except for situations when salt is used as a deicing agent.

Vehicle exhaust and burning are constituted mostly by carbonaceous material with elemental levels much less than 1% of mass emissions. Soluble potassium (K^+/K) ratios[124] are typically 0.80 to 0.90 in vegetative burning profiles, in contrast to the low soluble-to-total potassium ratios found in geological material.

Ducted industrial source emissions often contain a variety of different elements. Primary particle emitted by coal-fired power generators have the largest overlap in composition with fugitive dust sources. Crustal element abundances for silicon (Si), calcium (Ca), and iron (Fe) in coal-fired boiler profiles are 30% to 50% of the corresponding abundances in geological material. Aluminum (Al) abundances are similar to or higher than those found in geological material. Other elements such as phosphorus (P), potassium (K), titanium (Ti), chromium (Cr), manganese (Mn), strontium (Sr), zirconium (Zr), and barium (Ba) may be found in coal and certain soils. Selenium (Se) is not common in soils, but is usually found in coal-fired boiler emissions that do not pass through dry sulfur dioxide scrubbers. Watson[119] found that limestone scrubbers processing hot exhaust gases removed selenium vapor before it could condense on fly ash particles.

The different sources of fugitive dust are not easily separated from each other because their chemical profiles are similar, but some attempts have been made to do so. Gatz and Prospero[125] applied Si/Al, Ca/Al ratios to separate transported North African dust from other sources. Gatz[126] and Gatz et al.[127] separated agricultural soil and unpaved roads based on their Ca/K ratios. Bruns et al.[128] identify different microbial species in different types of agricultural soils. Houck et al.[17] showed clear distinctions in Na, Cl, SO_4^{2-}, CO_3^{2-} abundances for alkaline lake beds relative to other sources. Davis et al.[129] identified clay and other specific minerals in a variety of soils. Finding additional markers that help to distinguish among fugitive dust emitters would improve source contribution estimates.

AIR POLLUTION CONTROL MEASURES

Mitigation measures include some combination of reducing suspendable dust reservoirs, preventing its deposit, stabilizing it, enclosing it, and reducing the activities that suspend it. These methods are applied with various degrees of effectiveness and diligence, often in response to local nuisance complaints rather than as part of a comprehensive emissions reduction strategy. Control effectiveness estimates, P_{jkl} in Eq. 1, vary considerably, and there is no single value appropriate for all situations. Table 1 summarizes several of these measures and the dust sources to which they can be applied. Ranges of effectiveness are discussed below.

Surface Watering

Surface watering is often applied on disturbed land such as construction sites or unpaved surfaces to reduce particle resuspension by vehicles. Flocchini et al.[33] found that the addition of sufficient water to increase the surface moisture content from 0.56% to 2% can achieve greater than 86% reduction in PM_{10} emissions. Kinsey and Cowherd[86] found immediate dust reductions at construction sites as a result of surface watering; however, the effectiveness of this measure did not increase as more water was applied to the site.

Chemical Suppression

The application of chemical suppressants on unpaved surfaces can reduce fugitive dust emissions. Watson et al.[102] enumerate commercially available dust suppressants. These products are classified into six categories according to their chemical composition and the suppressant mechanism they employ:

- Surfactants. Chemicals that reduce water surface tension and allow available moisture to more effectively wet the particles and aggregates in the surface layer.
- Salts. Hygroscopic compounds such as magnesium chloride or calcium chloride that adsorb water as ambient relative humidity exceeds 50%. Since salts are water soluble, precipitation tends to wash them away.
- Polymers. Long-chain molecular compounds that act as adhesives to bond soil particles together. Polymers may be able to stick to more particles than ordinary resins.
- Resin or petroleum emulsions. Non-water-soluble organic carbon compounds that are emulsified or suspended in water. When these emulsions are sprayed onto soil, they

Table 1. Fugitive Dust Emissions Control Methods

Control Method	Sources Controlled	Description
Street cleaning	Paved roads	Uses mechanical brushes, vacuum suction, regenerative-air suction, or blow-air/suction recirculation to remove street debris, litter, and dirt
Water flashing	Paved roads	Uses pressurized sprays of water or water with added surfactant to dislodge road dust and transport it into a drain system
Resurfacing	Paved roads	Repaving with nonerodible materials minimizes pavement cracks which trap and accumulate dust and minimizes pavement abrasion
Wet suppression	Unpaved roads	Water agglomerates small dust particles into larger entities that adhere to the surface, resist resuspension, or rapidly deposit after suspension
Windscreens	Disturbed open fields, storage piles, construction	Fabric, wood, or other light-weight material is placed upwind of an area to reduce surface winds, or downwind to intercept particles
Traffic controls	Paved roads, unpaved roads	Lower vehicle travel speeds, limited road usage, restriction of heavy-duty vehicle traffic, and providing parking opportunities and public transit reduces emissions levels
Carryout reduction	Construction, unpaved roads, paved roads	Wheel and truck washing on leaving a dusty site limits distribution of suspendable particles
Enclosures	Storage piles, open-haul trucks	Covering piles with tarps or building structures limits wind erosion
Chemical Stabilization	Unpaved roads, construction/demolition sites, storage piles, open fields	Surfactant or foaming agents bind fine particles into larger aggregates that reduce surface resuspension; some chemicals increase the surface dust moisture content to enhance particle agglomeration and fallout
Vegetative cover/ stabilization	Open fields	Vegetation reduces wind velocity at the surface and binds soil particles to the surfaces
Tilling implements, orientations, and frequencies	Agricultural fields	Wide-span planting equipment, no-till and minimum till planting procedures, land leveling, and sprinkler irrigation limit suspension of surface dust
Electrostatic fogger	Agricultural tilling, industrial processes	Electrostatically charged water droplets agglomerate suspended particles, thereby increasing particle size and deposition velocity
Skilled planting	Agricultural fields	Plug or punch planting, aerial seeding, and double cropping limit disturbance of surface materials

stick the soil particles together, and eventually harden to form a solid mass. Several emulsion products are based on tree resin, petroleum, or asphalt compounds.

- Bitumens. Materials such as asphalt or road oil that act as adhesives to bond soil particles together.
- Lignin sulfonate. A wood by-product from paper manufacture that forms a sticky but water-soluble layer on unpaved surfaces.

Most suppressants require repeated application at frequencies on the order of weeks or months. The effectiveness of chemical suppressants depends on road surface conditions, soil composition, application intensity, traffic volume, vehicle weight, and environmental factors such as precipitation and temperature. Prior to suppressant application, the road surface often needs to be graded or wetted. Most products can be dispensed as liquids by a truck equipped with a tank and spray bar. The spraying process injects the suppressant into the road material. Solid materials can be spread and mixed into the soil or road bed with a grader.

Several studies have examined the effectiveness of different chemical suppressants on various types of unpaved roads.[51,102] Rosbury and Zimmer[30] found considerable variability in dust emission rates for untreated and chemical-suppressant-treated surfaces. Much of this variation was attributed to the effects of ambient meteorological conditions (especially precipitation), the types of vehicles traveling on the road, and the initial road conditions. Control efficiency varied from 7% to 54% for well-mixed suppressant applications, from insignificant to 80% for topical suppressant applications.

Muleski and Cowherd[130] evaluated the effectiveness of chemical suppressants on unpaved roads and found emission rates similar to those found by Rosbury and Zimmer.[32] Average control efficiencies of ~50% or more were found within the first 30 days after suppressant application.

Grau[131] prepared suppressant-treated soil specimens under controlled laboratory conditions to determine their performance when subjected to simulated field conditions. The screening tests included repeated air impingement tests (1-min blasts from 80- and 160-km/h air jets at 20° from the horizontal) with simulated rainfall or jet fuel spills. Fortynine suppressants were tested, and suppressant effectiveness was determined based on visual observations. Only eleven suppressants were found acceptable.

Flocchini et al.[33] found that surface watering and road oiling reduced PM_{10} emissions by $87 \pm 6\%$ and $59 \pm 12\%$, respectively. Reducing vehicle travel speeds on unpaved roads from 40 to 16–24 km/h can effectively reduce PM_{10} emissions by $58 \pm 3\%$ and $42 \pm 35\%$, respectively.

Few studies evaluate the effectiveness of chemical suppressants over a long time period. Gillies et al.[51] and Watson et al.[102] describe a year-long study to assess changes in suppressant effectiveness in reducing PM_{10} emissions from

unpaved public roads in the San Joaquin Valley, CA. Vehicle-induced vertical PM_{10} concentration profiles were measured. Three different types of chemical suppressants were applied on the unpaved roads: an acrylic co-polymer, a bitumen with copolymer additive, and a "biocatalyst." Gillies et al.[51] found that within a week of application the bitumen and acrylic copolymer showed over 95% emission reduction as compared to the untreated surface. The "biocatalyst" had an effectiveness of only 39%. After 3 months, the efficiency of the bitumen and biocatalyst had decreased by 20% and 30%, respectively, while the efficiency of the acrylic copolymer remained constant. After 11 months, the control effectiveness had been reduced to 53% for the bitumen, 85% for the acrylic copolymer and 0% for the "biocatalyst."[102]

Moosmüller et al.[92] applied several chemical suppressants to unpaved shoulders that were intended for stabilizing surfaces with minimal activity. They found that unpaved shoulders experience at least as much activity as unpaved roads, owing to vehicles leaving the roadway, mail carriers and school buses, and driveway entrances. None of the applied suppressants was effective a week after they were applied.

Street Sweeping

Mechanical broom and vacuum street sweeping have been applied in urban areas to remove street debris, litter, and dirt. Water droplets are often sprayed onto the road surface prior to sweeping to minimize dust resuspension induced by the sweeper. Sweeping schedules vary from weekly to monthly. Sweeping for aesthetic purposes is confined to the curb lanes in commercial and/or residential areas. Major highways and freeways are rarely swept.

Mechanical broom sweepers use large rotating brooms to lift the material from the street onto a conveyer belt. The conveyer discharges street debris into a collection hopper. Circular gutter brooms direct the debris into the path of the rotating broom. Mechanical broom sweeping has been questioned as a means of air pollution control on paved urban streets.[94,132,133] Chow et al.[93] found that the brushes resuspend as many small particles as they remove.

Commercially available vacuum sweepers use pure vacuum suction, regenerative-air suction, or blow-air/suction recirculation.[90,134–136] Vacuum sweepers use a gutter broom to loosen dirt and debris from the road surface and direct this material to a vacuum nozzle that sucks it into a hopper. The hopper usually consists of a chamber into which particles are collected by gravitational settling. The air passing through this chamber can be exhausted directly to the environment, through a bag-filter or precipitator, or to the collection nozzle for recirculation.

Pure vacuum sweepers create a strong vacuum within the pickup head that draws air from outside the head, through a duct, and into a hopper. The air movement across the road surface removes particles from the pavement and entrains them in the air flow. The vacuumed air is exhausted to ambient air after a brief residence time in the hopper. This residence time is usually insufficient to allow gravitational settling of PM_{10} or $PM_{2.5}$.

Regenerative-air vacuum sweepers direct the exhaust air back to one end of the pickup head at velocities between 50 and 200 m/sec. This blast air is directed perpendicular to the pavement where it is intended to dislodge particles. The blast air and its entrained particles move across the pickup head to a suction nozzle that transports the debris to the collection hopper. The pickup head must seal with the pavement using a flexible rubber curtain to prevent blast air from escaping the collection nozzle and to maintain a negative air pressure within the nozzle.

The blow-air/suction recirculation sweeper directs a portion of the exhaust air to a blast nozzle located immediately behind the pickup head. This blast air is directed at an angle to the pavement to blow particles from the road surface into the airstream caused by suction through the head. The suction flow rate exceeds the blast flow rate so that ambient air is always being drawn into the pickup head, thereby minimizing the escape of recirculated particles to the air. The nonrecirculated portion of the exhaust air is vented into a separate settling chamber before it escapes to ambient air.

Seton et al.[137] described a 6-month street-sweeping study conducted in Portland, OR. Geological source contributions to chemically speciated TSP, PM_{15}, and $PM_{2.5}$ concentrations at a nearby sampling site were compared for sweeping and nonsweeping periods. No reductions in geological source contributions were detected with daily vacuum sweeping of the curb lane of industrial-area streets.

Hewitt[138] reported a 4-year study conducted in Bangor, ME, where ambient particle concentrations measured for 2 years without sweeping were compared with measurements from 2 years with sweeping. Nearly 800 TSP measurements were obtained and a 20% reduction in TSP as a result of vacuum street cleaning was reported. PEDCo Environmental[139] also measured TSP, PM_{15}, and $PM_{2.5}$ concentrations near paved roads in Denver, CO, at two sites that had been sanded during snowstorms. One site had the sand removed by sweeping, while the other site had no sand removal. Though a slight decrease in TSP and $PM_{2.5}$ was observed at the site where sand was removed, the difference was not statistically significant.

Cuscino et al.[140] made size-resolved vertical profile measurements near paved roads before and after sweeping. For PM_{15} mass concentrations, emissions reductions were estimated to be 16% 2 hours after sweeping, 51% 3 hours after sweeping, 0% 4 hours after sweeping, and 58% 24 h after sweeping. Cuscino et al.[140] note that meteorological variability may have played a large role in the differences in ambient mass concentrations among the measurement periods. In earlier studies, Cowherd[141] reported efficiencies of about 45% for PM_{15} and 35% for $PM_{2.5}$ when vacuum sweeping was used. Both of these vacuum-sweeping studies were performed on industrial paved roads, where initial street loadings and amount of material tracked on is typically much higher than on public streets.

Chow et al.[93] applied a receptor model to separate the contributions from fugitive road dust and vehicle exhaust. The ratio of these two contributions is less sensitive to meteorological and emission rate differences between sweeping and nonsweeping study periods than the absolute source contributions from either source. Chow et al.[93] found that daily street sweeping with a regenerative-air vacuum sweeper resulted in no detectable reductions in geological contributions to ambient PM_{10} measured in the sweeping area and that the street-sweeper design used in this study could not possibly reduce PM_{10} on pavements.

Fitz and Bumiller[142] investigated the effectiveness of street sweepers in reducing loose "blowsand" (material deposited on roadways after large-scale wind erosion events) on paved roads. They found that some street sweepers can successfully

remove 97% to 99% of the loose surface material, whereas other sweepers resuspended as much PM_{10} as they removed.

While recently improved sweepers seem effectively to deplete the reservoir of material from which particles can be generated, none of these studies conclusively demonstrates the effectiveness of street sweeping on ambient concentrations of suspended PM_{10}. Suspended particle concentrations are affected by many variables, and differences caused by street sweeping may not be detectable at nearby monitoring sites. The variables that appear to influence emissions reduction efficiencies are: (1) loading of dirt on the street before and after sweeping; (2) particle size distribution of dirt on the street; (3) sweeper efficiency in removing dust from the street surface; (4) sweeper exhaust emission rates for small particles; (5) portion of roadway that is swept; (6) length of roadway that is swept; (7) sweeping frequency; and (8) meteorological variables such as precipitation, wind speed, wind direction, and relative humidity.

Water Flushing

Water flushing uses pressurized sprays from a water truck to dislodge road dust and transport it to the curb, where much of the particulate is washed into storm drains. A combination of water flushing followed immediately by broom sweeping has been used as a means of street cleaning.

Water flushing generally results in more consistent and higher efficiencies than sweeping, with 30% to 80% control effectiveness and 0 to 18 $\mu g/m^3$ reduction in nearby TSP measurements.[94,132,140,141] Flushing can be expected to reduce particle resuspension dramatically while the road surface is still wet, but its effect on average emissions during a typical cleaning cycle cannot be ascertained from the data reported.

The combination of water flushing and sweeping has the highest reported control effectiveness, from 47% to 90% for PM_{15} and 48% to 83% for $PM_{2.5}$.[140,141,143] The time frame of these measurements is either not specified or very short — less than 3 hours, when the road surface may still be wet. Large changes in control effectiveness over a short time period (e.g., 30% difference over a 12-min period) suggest that measurement uncertainty is high. Measurements were made on industrial paved roads; applicability to public roads has not been demonstrated.

Vehicle Washing

Washing vehicles as they depart from work areas can minimize dust trackout and carryout.[94,144] Carryout is the sediment attached to the vehicle that may eventually fall off and become resuspended by other vehicles. Axetell and Zell[94] found that TSP concentrations (~84 $\mu g/m^3$) increased by 40 to 60 $\mu g/m^3$ due to uncontrolled mud trackout. Immediate cleanup with shovel and broom reduced TSP by 10 to 20 $\mu g/m^3$, and daily cleanup reduced TSP by about 5 to 10 $\mu g/m^3$. These values correspond to control efficiencies of about 30% for immediate cleanup and 15% for daily cleanup.

Surface Roughness Alterations

Wind erosion emissions can be mitigated by: (1) altering the surface (such as increasing its roughness with tillage implements and practices), (2) vegetative stubble or mulch coverage, or (3) windbreaks. Applying tillage implements to ridge the soil or create large nonerodible clods is a standard practice in wind erosion control where the establishment of vegetative cover is difficult. This method results in large nonerodible roughness elements that absorb momentum from the erodible soil and trap the erodible soil in larger cracks and crevices.

No-till and minimum-till planting procedures minimize topsoil erosion, conserve water, and reduce dust emissions.[145] New seeds can be planted into stubble from the last crop or into a cropped field by cutting through the surface vegetation and inserting the seed directly into the ground. This type of low- or no-till farming reduces wind-generated fugitive emissions because vegetative cover (e.g., standing stubble or mulch) is left on the soil surface. The fraction of vegetative cover along with its shape and density of coverage determine the effectiveness of dust control.[146] Annual crops can be interplanted in narrow strips or rows to minimize ground-level soil movement. Interplanting is often supplemented with other practices such as protecting the strips with other vegetative coverage more efficiently to reduce dust emissions.

Windbreaks or other surface barriers absorb or deflect wind energy and minimize soil movement or particle resuspension from unprotected surfaces.[103,104,147] The length of a windbreak needs to be six to ten times its height to mitigate dust emissions effectively. In general, the shape, width, height, and porosity of the barrier, along with the surface wind speed and wind direction, affect the efficiency of the windbreak.

Minimization of Activity

Fugitive emissions caused by construction and agricultural activity can be reduced by minimizing activity levels. Vehicle-related resuspended dust can be reduced by regulating vehicle travel speeds, prohibiting road use by vehicles with more than four wheels, and reducing vehicle volume by providing perimeter parking and mass transit to industrial sites. Traffic controls are often supplemented with other control measures, such as surface watering and wheel washing.

SUMMARY AND CONCLUSIONS

Nonducted fugitive dust emissions arise from multiple sources that are often intermittent. National estimates show that unpaved roads, paved roads, construction projects, agricultural operations, and wind erosion are the largest contributors to fugitive dust. Industrial fugitive dust emissions are relatively small on a national basis, but they may be important in local circumstances.

The variables that affect emissions are complex and interrelated. Lacking a quantitative theoretical basis, emissions factors have been derived from empirical tests on representative sources that are intended to represent the entire population of emitters. The emission factors derived from these tests are applied to variables and activities that are specific to a source area. These variables include measures of surface particle loading, particle size, moisture content, and the type of activity.

Suspendable particles are not transportable particles. Sixty to ninety percent of PM_{10} mass is suspended within 1 to 2 m above ground level. These particles deposit to the surface or impact on nearby vertical structures within a few minutes after suspension. Although horizontal fluxes commonly used in empirically derived emission factors represent the mass of dust particles suspended from a surface, they do not represent

the mass entrained into the atmosphere and transported over relevant distances of 0.1 to >10 km. The fraction of dust within the lowest 2 m above ground level probably deposits the surface or horizontally impacts on nearby obstructions and does not travel far from its source.

Fugitive dust control measures involve combinations of reducing suspendable dust reservoirs, preventing its deposit, stabilizing it, enclosing it, and reducing the activities that suspend it. Demonstrations studies on representative emitters provide a wide range of control effectiveness. The effectiveness of controls depends on the specific situation as well as the diligence with which it is applied. Tests are needed to demonstrate fugitive dust control effectiveness for specific circumstances.

DISCLAIMER

The material presented here represents the research and interpretation of the authors and does not represent the policy of the Desert Research Institute, the University and Community College System of Nevada, or the U.S. Environmental Protection Agency. The mention of commercial products does not constitute an endorsement or recommendation of those products.

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