WRAP Fugitive Dust Handbook

Prepared for:

Western Governors’ Association
1515 Cleveland Place, Suite 200
Denver, Colorado 80202

Prepared by:

Countess Environmental
4001 Whitesail Circle
Westlake Village, CA 91361
(WGA Contract No. 30204-83)

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EXECUTIVE SUMMARY

This fugitive dust handbook addresses the estimation of uncontrolled fugitive dust emissions and emission reductions achieved by demonstrated control techniques for eight major fugitive dust source categories. The handbook focuses on fugitive dust emissions “at the source” and does not evaluate factors related to the transport and impact of emissions on downwind locations where ambient air monitoring occurs. The methods for estimating emissions draw (a) from established methods published by the USEPA, specifically AP-42: Compilation of Air Pollutant Emission Factors that are available from the Internet (www.epa.gov/ttn/chief/ap42), and (b) from alternate methods adopted by state and local air control agencies in the WRAP region such as the California Air Resources Board (www.arb.ca.gov/ei/areasrc/areameth.htm), Clark County, Nevada (www.co.clark.nv.us/air_quality), and Maricopa County, Arizona (www.maricopa.gov/envsvc/air). Sources of data are identified and default values for emission factor correction parameters, source extent/activity levels, control efficiencies, and emission reductions by natural mitigation and add-on control measures are provided in tables throughout the handbook.

The handbook has several distinct features that give it a major advantage over the use of AP-42 or other resource documents. The handbook is a comprehensive document that contains all the necessary information to develop control strategies for major sources of fugitive dust. These features include:

- extensive documentation of emission estimation methods adopted by both federal and state agencies as well as methods in the “developmental” stage;
- detailed discussion of demonstrated control measures;
- lists of published control efficiencies for a large number of fugitive dust control measures;
- example regulatory formats adopted by state and local agencies in the WRAP region;
- compliance tools to assure that the regulations are being followed; and
- a detailed methodology for calculating the cost-effectiveness of different fugitive dust control measures, plus sample calculations for control measure cost-effectiveness for each fugitive dust source category.

The handbook and associated website (www.wrapair.org/forums/dejf/fdh) are intended to:

- support technical and policy evaluations by WRAP members, stakeholders, and other interested parties when addressing specific air quality issues and when developing regional haze implementation plans;
- incorporate available information from both the public and private sectors that address options to reduce fugitive dust emissions in areas of the country classified as nonattainment for PM10; and
• provide a comprehensive resource on emission estimation methodologies and control measures for the following eight fugitive dust source categories: agricultural tilling, construction and demolition, materials handling, paved roads, and unpaved roads as well as windblown dust emissions from agricultural fields, material storage piles, and exposed open areas.

The handbook contains separate, stand-alone chapters for each of the eight fugitive dust source categories identified above. Each chapter contains a discussion of characterization of the source emissions, established emissions estimation methodologies, demonstrated control techniques, regulatory formats, compliance tools, a sample control measure cost-effectiveness calculation, and references. A series of appendices are also included in the handbook. Appendix A contains a discussion of test methods used to quantify fugitive dust emission rates. Appendix B includes a summary of emission estimation methods developed by various groups for several fugitive dust source categories not addressed in the main body of the handbook. (Note: These other source categories were not included in the original scope of work, but were added later for completeness.) Appendix B also includes a summary of emission estimation methods for categories addressed in the handbook that either are still in the developmental stage and have not been approved by federal or state agencies, or were developed many years ago and have fallen out of favor. Appendix C contains a step-wise method to calculate the cost-effectiveness of different fugitive dust control measures.

A list of fugitive dust control measures that have been implemented by jurisdictions designated by the USEPA as nonattainment for federal PM10 standards is presented in the table below. The published PM10 control efficiencies for different fugitive dust control measures vary over relatively large ranges as reflected in the table. The user of the handbook is cautioned to review the assumptions included in the original publications (i.e., references identified in each chapter of the handbook) before selecting a specific PM10 control efficiency for a given control measure. It should be noted that Midwest Research Institute found no significant differences in the measured control efficiencies for the PM2.5 and PM10 size fractions of unpaved road emissions based on repeated field measurements of uncontrolled and controlled emissions. Thus, without actual published PM2.5 control efficiencies, the user may wish to utilize the published PM10 values for both size fractions.

Many control cost-effectiveness estimates were reviewed in preparation of this handbook. Some of these estimates contain assumptions that are difficult to substantiate and often appear unrealistic. Depending on which assumptions are used, the control cost-effectiveness estimates can vary by one to two orders of magnitude. Thus, rather than presenting existing cost-effectiveness estimates, the handbook presents a detailed methodology to calculate the cost-effectiveness of different fugitive dust control measures. This methodology is presented in Appendix C. The handbook user is advised to calculate the cost-effectiveness values for different fugitive dust control options based on current cost data and caveats that are applicable to the particular situation.
## Fugitive Dust Control Measures Applicable for the WRAP Region

<table>
<thead>
<tr>
<th>Source Category</th>
<th>Control Measure</th>
<th>Published PM10 Control Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Agricultural Tilling</strong></td>
<td>Reduce tilling during high winds</td>
<td>1 - 5%</td>
</tr>
<tr>
<td></td>
<td>Roughen surface</td>
<td>15 - 64%</td>
</tr>
<tr>
<td></td>
<td>Modify equipment</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Employ sequential cropping</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Increase soil moisture</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>Use other conservation management practices</td>
<td>25 - 100%</td>
</tr>
<tr>
<td><strong>Construction/Demolition</strong></td>
<td>Water unpaved surfaces</td>
<td>10 - 74%</td>
</tr>
<tr>
<td></td>
<td>Limit on-site vehicle speed to 15 mph</td>
<td>57%</td>
</tr>
<tr>
<td></td>
<td>Apply dust suppressant to unpaved areas</td>
<td>84%</td>
</tr>
<tr>
<td></td>
<td>Prohibit activities during high winds</td>
<td>98%</td>
</tr>
<tr>
<td><strong>Materials Handling</strong></td>
<td>Implement wet suppression</td>
<td>50 - 70%</td>
</tr>
<tr>
<td><strong>Paved Roads</strong></td>
<td>Sweep streets</td>
<td>4 - 26%</td>
</tr>
<tr>
<td></td>
<td>Minimize trackout</td>
<td>40 - 80%</td>
</tr>
<tr>
<td></td>
<td>Remove deposits on road ASAP</td>
<td>&gt;90%</td>
</tr>
<tr>
<td><strong>Unpaved Roads</strong></td>
<td>Limit vehicle speed to 25 mph</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>Apply water</td>
<td>10 - 74%</td>
</tr>
<tr>
<td></td>
<td>Apply dust suppressant</td>
<td>84%</td>
</tr>
<tr>
<td></td>
<td>Pave the surface</td>
<td>&gt;90%</td>
</tr>
<tr>
<td><strong>Wind Erosion</strong> (agricultural, open area, and storage piles)</td>
<td>Plant trees or shrubs as a windbreak</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>Create cross-wind ridges</td>
<td>24 - 93%</td>
</tr>
<tr>
<td></td>
<td>Erect artificial wind barriers</td>
<td>4 - 88%</td>
</tr>
<tr>
<td></td>
<td>Apply dust suppressant or gravel</td>
<td>84%</td>
</tr>
<tr>
<td></td>
<td>Revegetate; apply cover crop</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>Water exposed area before high winds</td>
<td>90%</td>
</tr>
</tbody>
</table>
Chapter 1. Introduction

1.1 Background............................................................................................................. 1-1
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This chapter describes the purpose for the preparation of this fugitive dust handbook: presents a brief overview primer on fugitive dust that includes a summary of factors affecting dust emissions, an overview of emission calculation procedures (including a discussion of emission factors), and a discussion of options for controlling emissions; and summarizes the organizational structure of the handbook.

1.1 Background

Most of the more than 70 areas of the United States that have been unable to attain the national ambient-air quality standards (NAAQS) for PM10 (particles smaller than 10 μm in aerodynamic diameter) are in western states with significant emission contributions from fugitive dust sources. Fugitive dust sources may be separated into two broad categories: process sources and open dust sources. Process sources of fugitive emissions are those associated with industrial operations such as rock crushing that alter the characteristics of a feed material. Open dust sources are those that generate non-ducted emissions of solid particles by the forces of wind or machinery acting on exposed material. Open dust sources include industrial sources of particulate emissions associated with the open transport, storage, and transfer of raw, intermediate, and waste aggregate materials, and nonindustrial sources such as unpaved roads and parking lots, paved streets and highways, heavy construction activities, and agricultural tilling.

On a nationwide basis, fugitive dust consists mostly of soil and other crustal materials. However, fugitive dust may also be emitted from powdered or aggregate materials that have been placed in open storage piles or deposited on the ground or roadway surfaces by spillage or vehicle trackout. Dust emissions from paved roadways contain tire and break wear particles in addition to resuspended road surface dust composed mostly of crustal geological material.

Generic categories of open dust sources include:

- Agricultural Tilling
- Construction and Demolition
  - Buildings
  - Roads
- Materials Handling
  - Batch drop (dumping)
  - Continuous drop (conveyor transfer, stacking)
  - Pushing (dozing, grading, scraping)
- Paved Travel Surfaces
  - Streets and highways
  - Parking lots and staging areas
- Unpaved Travel Surfaces
  - Roads
  - Parking lots and staging areas
- Wind Erosion of Exposed Areas
  - Agricultural Fields
  - Open Areas (vacant lots, desert land, unpaved surfaces)
  - Storage Piles
1.2 Purpose of the Handbook

In early 2004 the Western Regional Air Partnership’s (WRAP) Dust Emissions Joint Forum (DEJF) selected the Countess Environmental project team composed of senior scientists/consultants from Countess Environmental and Midwest Research Institute to prepare a fugitive dust handbook and a website (www.wrapair.org/forums/dejf/fdh) for accessing the information contained in the handbook. The handbook and website are intended to:

- be used for technical and policy evaluations by WRAP members, stakeholders, and other interested parties when addressing specific air quality issues and when developing regional haze implementation plans;
- incorporate available information from both the public and private sectors that address options to reduce fugitive dust emissions in areas of the country classified as nonattainment for PM10; and
- serve as a comprehensive reference resource tool that will provide technical information on emission estimation methodologies and control measures for the following eight fugitive dust source categories: agricultural tilling, construction and demolition, materials handling, and travel on paved and unpaved roads as well as windblown dust emissions from agricultural fields, open areas of disturbed vacant land, and material storage piles.

The handbook and website will be updated as new information becomes available in the future. Additional fugitive dust source categories will be addressed in these future revisions.

1.3 Factors Affecting Dust Emissions

1.3.1 Mechanically Generated Dust

Mechanically generated emissions from open dust sources exhibit a high degree of variability from one site to another, and emissions at any one site tend to fluctuate widely. The site characteristics which cause these variations may be grouped into (a) properties of the exposed surface material from which the dust originates, and (b) measures of energy expended by machinery interacting with the surface. These site characteristics are discussed below.

**Surface Material Texture and Moisture.** The dry-particle size distribution of the exposed soil or surface material determines its susceptibility to mechanical entrainment. The upper size limit for particles that can become suspended has been estimated at ~ 75 μm in aerodynamic diameter.\(^1\) Conveniently, 75 μm in physical diameter is also the smallest particle size for which size analysis by dry sieving is practical.\(^2\) Particles passing a 200-mesh screen on dry sieving are termed “silt”. Note that for fugitive dust particles, the physical diameter and aerodynamic diameter are roughly equivalent because of the offsetting effects of higher density and irregular shape. Dust emissions are known to be strongly dependent on the moisture level of the mechanically disturbed material.\(^1\)
Water acts as a dust suppressant by forming cohesive moisture films among the discrete grains of surface material. In turn, the moisture level depends on the moisture added by natural precipitation, the moisture removed by evaporation, and moisture movement beneath the surface. The evaporation rate depends on the degree of air movement over the surface, material texture and mineralogy, and the degree of compaction or crusting. The moisture-holding capacity of the air is also important, and it correlates strongly with the surface temperature. Vehicle traffic intensifies the drying process primarily by increasing air movement over the surface.

Mechanical Equipment Characteristics. In addition to the material properties discussed above, it is clear that the physical and mechanical characteristics of materials handling and transport equipment also affect dust emission levels. For example, visual observation suggests (and field studies have confirmed) that vehicle emissions per unit of unpaved road length increase with increasing vehicle speed.\(^1\) For traffic on unpaved roads, studies have also shown positive correlations between emissions and (a) vehicle weight and (b) number of wheels per vehicle.\(^2\) Similarly, dust emissions from materials-handling operations have been found to increase with increasing wind speed and drop distance.

1.3.2 Wind Generated Dust

Wind-generated emissions from open dust sources also exhibit a high degree of variability from one site to another, and emissions at any one site tend to fluctuate widely. The site characteristics which cause these variations may be grouped into (a) properties of the exposed surface material from which the dust originates, and (b) measures of energy expended by wind interacting with the erodible surface. These site characteristics are discussed below.

Surface Material Texture and Moisture. As in the case of mechanical entrainment, the dry-particle size distribution of the exposed soil or surface material determines its susceptibility to wind erosion. Wind forces move soil particles by three transport modes: saltation, surface creep, and suspension. Saltation describes particles, ranging in diameter from about 75 to 500 \(\mu m\), that are readily lifted from the surface and jump or bounce within a layer close to the air-surface interface. Particles transported by surface creep range in diameter from about 500 to 1,000 \(\mu m\). These large particles move very close to the ground, propelled by wind stress and by the impact of small particles transported by saltation. Particles smaller than about 75 \(\mu m\) in diameter move by suspension and tend to follow air currents. As stated above, the upper size limit of silt particles (75 \(\mu m\) in physical diameter) is roughly the smallest particle size for which size analysis by dry sieving is practical. The threshold wind speed for the onset of saltation, which drives the wind erosion process, is also dependent on soil texture, with 100-150 \(\mu m\) particles having the lowest threshold speed. Saltation provides energy for the release of particles in the PM10 size range that typically are bound by surface forces to larger clusters. Dust emissions from wind erosion are known to be strongly dependent on the moisture level of the erodible material.\(^3\) The mechanism of moisture mitigation is the same as that described above for mechanical entrainment.
**Nonerodible Elements.** Nonerodible elements, such as clumps of grass or stones (larger than about 1 cm in diameter) on the surface, consume part of the shear stress of the wind which otherwise would be transferred to erodible soil. Surfaces impregnated with a large density of nonerodible elements behave as having a “limited reservoir” of erodible particles, even if the material protected by nonerodible elements is itself highly erodible. Wind-generated emissions from such surfaces decay sharply with time, as the particle reservoir is depleted. Surfaces covered by unbroken grass are virtually nonerodible.

**Crust Formation.** Following the wetting of a soil or other surface material, fine particles will move to form a surface crust. The surface crust acts to hold in soil moisture and resist erosion. The degree of protection that is afforded by a soil crust to the underlying soil may be measured by the modulus of rupture (roughly a measure of the hardness of the crust) and thickness of the crust. Exposed soil that lacks a surface crust (e.g., a disturbed soil or a very sandy soil) is much more susceptible to wind erosion.

**Frequency of Mechanical Disturbance.** Emissions generated by wind erosion are also dependent on the frequency of disturbance of the erodible surface. A disturbance is defined as an action which results in the exposure of fresh surface material. This would occur whenever a layer of aggregate material is either added to or removed from the surface. The disturbance of an exposed area may also result from the turning of surface material to a depth exceeding the size of the largest material present. Each time that a surface is disturbed, its erosion potential is increased by destroying the mitigative effects of crusts, vegetation, and friable nonerodible elements, and by exposing new surface fines.

**Wind Speed.** Under high wind conditions that trigger wind erosion by exceeding the threshold velocity, the wind speed profile near the erodible surface is found to follow a logarithmic distribution:

\[
  u(z) = \frac{u^*}{0.4} \ln \frac{z}{z_0} \quad (z > z_0)
\]

where: 
- \( u \) = wind speed (cm/s)
- \( u^* \) = friction velocity (cm/s)
- \( z \) = height above test surface (cm)
- \( z_0 \) = roughness height (cm)
- 0.4 = von Karman's constant (dimensionless)

The friction velocity (\( u^* \)) is a measure of wind shear stress on the erodible surface, as determined from the slope of the logarithmic velocity profile. The roughness height (\( z_0 \)) is a measure of the roughness of the exposed surface as determined from the \( y \)-intercept of the velocity profile (i.e., the height at which the wind speed is zero) on a logarithmic-linear graph. Agricultural scientists have established that total soil loss by continuous wind erosion of highly erodible fields is dependent roughly on the cube of wind speed above the threshold velocity. More recent work has shown that the loss of particles in suspension mode follows a similar dependence. Soils protected by
nonerodible elements or crusts exhibit a weaker dependence of suspended particulate emissions on wind speed.

Wind Gusts. Although mean atmospheric wind speeds may not be sufficient to initiate wind erosion from a particular "limited-reservoir" surface, wind gusts may quickly deplete a substantial portion of its erosion potential. In addition, because the erosion potential (mass of particles constituting the "limited reservoir") increases with increasing wind speed above the threshold velocity, estimated emissions should be related to the gusts of highest magnitude. The current meteorological variable which appropriately reflects the magnitude of wind gusts is the fastest 2-minute wind speed from the "First Order Summary of the Day," published by the U.S. Weather Service for first order meteorological stations. The quantity represents the wind speed corresponding to the largest linear passage of wind movement during a 2-minute period. Two minutes is approximately the same duration as the half-life of the erosion process (i.e., the time required to remove one-half the erodible particles on the surface). It should be noted that instantaneous peak wind speeds can significantly exceed the fastest 2-minute wind speed. Because the threshold wind speed must be exceeded to trigger the possibility of substantial wind erosion, the dependence of erosion potential on wind speed cannot be represented by any simple linear function. For this reason, the use of an average wind speed to calculate an average emission rate is inappropriate.

Wind Accessibility. If the erodible material lies on an exposed area with little penetration into the surface wind layer, then the material is uniformly accessible to the wind. If this is not the case, it is necessary to divide the erodible area into subareas representing different degrees of exposure to wind. For example, the results of physical modeling show that the frontal face of an elevated materials storage pile is exposed to surface wind speeds of the same order as the approach wind speed upwind of the pile at a height matching the top of the pile; on the other hand, the leeward face of the pile is exposed to much lower wind speeds.

1.4 Emission Calculation Procedure

A calculation of the estimated emission rate for a given source requires data on source extent, uncontrolled emission factor, and control efficiency. The mathematical expression for this calculation is given as follows:

\[ R = SE \cdot e \cdot (1 - c) \]  

where:
- \( R \) = estimated mass emission rate in the specified particle size range
- \( SE \) = source extent
- \( e \) = uncontrolled emission factor in the specified particle size range (i.e., mass of uncontrolled emissions per unit of source extent)
- \( c \) = fractional efficiency of control

The source extent (activity level) is the appropriate measure of source size or the level of activity which is used to scale the uncontrolled emission factor to the particular source in question. For process sources of fugitive particulate emissions, the source
extent is usually the production rate (i.e., the mass of product per unit time). Similarly, the source extent of an open dust source entailing a batch or continuous drop operation is the rate of mass throughput. For other categories of open dust sources, the source extent is related to the area of the exposed surface which is disturbed by either wind or mechanical forces. In the case of wind erosion, the source extent is simply the area of erodible surface. For emissions generated by mechanical disturbance, the source extent is also the surface area (or volume) of the material from which the emissions emanate. For vehicle travel, the disturbed surface area is the travel length times the average daily traffic (ADT) count, with each vehicle having a disturbance width equal to the width of a travel lane.

If an anthropogenic control measure (e.g., treating the surface with a chemical binder which forms an artificial crust) is applied to the source, the uncontrolled emission factor in Eq. 1-2 must be multiplied by an additional term to reflect the resulting fractional control. In broad terms, anthropogenic control measures can be considered as either continuous or periodic, as the following examples illustrate:

<table>
<thead>
<tr>
<th>Continuous controls</th>
<th>Periodic controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet suppression at conveyor transfer points</td>
<td>Watering or chemical treatment of unpaved roads</td>
</tr>
<tr>
<td>Enclosures/wind fences around storage piles</td>
<td>Sweeping of paved travel surfaces</td>
</tr>
<tr>
<td>Continuous vegetation of exposed areas</td>
<td>Chemical stabilization of exposed areas</td>
</tr>
</tbody>
</table>

The major difference between the two types of controls is related to the time dependency of performance. For continuous controls, efficiency is essentially constant with respect to time. On the other hand, the efficiency associated with periodic controls tends to decrease (decay) with time after application until the next application, at which time the cycle repeats but often with some residual effects from the previous application.

In order to quantify the performance of a specific periodic control, two measures of control efficiency are required. The first is “instantaneous” control efficiency and is defined by:

$$c(t) = \left(1 - \frac{e_c(t)}{e_u}\right) \times 100$$  

where:

- $c(t)$ = instantaneous control efficiency (percent)
- $e_c(t)$ = instantaneous emission factor for the controlled source
- $e_u$ = uncontrolled emission factor
- $t$ = time after control application

The other important measure of periodic control performance is average efficiency, defined as:

$$C(T) = \frac{1}{T} \int_0^T c(t) dt$$

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where: $c(t) = \text{instantaneous control efficiency at time } t \text{ after application (percent)}$

$T = \text{time period over which the average control efficiency is referenced}$

The average control efficiency is needed to estimate the emission reductions due to periodic applications.

1.5 Emission Factors

Early in the USEPA field testing program to develop emission factors for fugitive dust sources, it became evident that uncontrolled emissions within a single generic source category may vary over two (or more) orders of magnitude as a result of variations in source conditions (equipment characteristics, material properties, and climatic parameters). Therefore, it would not be feasible to represent an entire generic source category in terms of a single-valued emission factor, as traditionally used by the USEPA to describe average emissions from a narrowly defined ducted source operation. In other words, it would take a large matrix of single-valued factors to adequately represent an entire generic fugitive dust source category. In order to account for emissions variability, therefore, the approach was taken that fugitive dust emission factors be constructed as mathematical equations for sources grouped by the dust generation mechanisms. The emission factor equation for each source category would contain multiplicative correction parameter terms that explain much of the variance in observed emission factor values on the basis of variances in specific source parameters. Such factors would be applicable to a wide range of source conditions, limited only by the extent of experimental verification. For example, the use of the silt content as a measure of the dust generation potential of a material acted on by the forces of wind or machinery proved to be an important step in extending the applicability of the emission factor equations to a wide variety of aggregate materials of industrial importance.

A compendium of emission factors (referred to as AP-42) is maintained on a CD-ROM (Air Chief Version 11. 2004) by the U.S. Environmental Protection Agency. Chapter 13 of AP-42 contains the predictive emission factor equations for fugitive dust sources. Also with each equation is provided a set of particle size multipliers for adjusting the calculated emission factors to specific particle size fractions. The ratios of PM2.5 to PM10 published in AP-42 typically range from 0.15 to 0.25; however, recent field studies indicate that the ratios may be as low as 0.06 to 0.10. The DEJF plans to fund a series of controlled laboratory tests during 2005 to quantify the PM2.5 PM10 ratio for several resuspended soils.

Example: Vehicle Traffic on Unpaved Roads. For the purpose of estimating uncontrolled emissions, the AP-42 emission factor equation applicable to vehicle traffic on publicly accessible unpaved roads takes source characteristics into consideration:

$$E = 1.8 \times 12 \times S^{0.12} \times M^{0.5} - C$$

(5)

where: $E = \text{PM10 emission factor (lb VMT)}$

$s = \text{surface material silt content (}\%)$

$S = \text{mean vehicle speed (mph)}$

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M = surface material moisture content (%)
C = emission factor for 1980's vehicle fleet exhaust, plus break/tire wear

The denominators in each of the multiplicative terms of the equation constitute normalizing default values, in case no site-specific correction parameter data are available. The default moisture content represents dry (worst-case) road conditions. Extrapolation to annual average uncontrolled emission estimates (including natural mitigation) is accomplished by assuming that emissions are occurring at the estimated rate on days without measurable precipitation and, conversely, are absent on days with measurable precipitation.

1.6 Emission Control Options

Typically, there are several options for the control of fugitive particulate emissions from any given source. This is clear from Equation 1-2 used to calculate the emission rate. Because the uncontrolled emission rate is the product of the source extent and the uncontrolled emission factor, a reduction in either of these two variables produces a proportional reduction in the uncontrolled emission rate. In the case of open sources, the reduction in the uncontrolled emission factor may be achieved by adjusted "work practices". The degree of the reduction of the uncontrolled emission factor can be estimated from the known dependence of the factor on source conditions that are subject to alteration. For open dust sources, this information is embodied in the predictive emission factor equations for fugitive dust sources as presented in Section 13 of AP-42. The reduction of source extent and the incorporation of adjusted work practices which reduce the amount of exposed dust-producing material are preventive measures for the control of fugitive dust emissions.

Add-on controls can also be applied to reduce emissions by reducing the amount (areal extent) of dust-producing material, other than by cleanup operations. For example, the elimination of mud/dirt carryout onto paved roads at construction and demolition sites is a cost-effective preventive measure. On the other hand, mitigative measures involve the periodic removal of dust-producing material. Examples of mitigative measures include: cleanup of spillage on travel surfaces (paved and unpaved) and cleanup of material spillage at conveyor transfer points. Mitigative measures tend to be less favorable from a cost-effectiveness standpoint.

Periodically applied control techniques for open dust sources begin to decay in efficiency almost immediately after implementation. The most extreme example of this is the watering of unpaved roads, where the efficiency decays from nearly 100% to 0% in a matter of hours. On the other hand, the effects of chemical dust suppressants applied to unpaved roads may last for several months. Consequently, to describe the performance of most intermittent control techniques for open dust sources, the "time-weighted average" control efficiency must be reported along with the time period over which the value applies. For continuous control systems (e.g., wet suppression for continuous drop materials transfer), a single control efficiency is usually appropriate.
Table 1-1 lists fugitive dust control measures that have been judged to be generally cost-effective for application to metropolitan areas unable to meet PM10 standards. The most highly developed performance models available apply to application of chemical suppressants on unpaved roads. These models relate the expected instantaneous control efficiency to the application parameters (application intensity and dilution ratio) and to the number of vehicle passes (rather than time) following the application. More details on available dust control measure performance and cost are presented by Cowherd et al. (1988) and Cowherd (1991).

<table>
<thead>
<tr>
<th>Source category</th>
<th>Control action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural Tilling</td>
<td>Conservation management practices</td>
</tr>
<tr>
<td>Construction/Demolition</td>
<td>Paving permanent roads early in project</td>
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<tr>
<td></td>
<td>Covering haul trucks</td>
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<tr>
<td></td>
<td>Access apron construction and cleaning</td>
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<tr>
<td></td>
<td>Watering of gravelled travel surfaces</td>
</tr>
<tr>
<td>Materials Handling</td>
<td>Wet suppression</td>
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<tr>
<td>Paved Roads</td>
<td>Water flushing/sweeping</td>
</tr>
<tr>
<td></td>
<td>Improvements in sanding/salting applications and materials</td>
</tr>
<tr>
<td></td>
<td>Covering haul trucks</td>
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<tr>
<td></td>
<td>Prevention of trackout</td>
</tr>
<tr>
<td></td>
<td>Curb installation</td>
</tr>
<tr>
<td></td>
<td>Shoulder stabilization</td>
</tr>
<tr>
<td>Unpaved Roads</td>
<td>Paving</td>
</tr>
<tr>
<td></td>
<td>Chemical stabilization</td>
</tr>
<tr>
<td></td>
<td>Surface improvement (e.g., gravel)</td>
</tr>
<tr>
<td></td>
<td>Vehicle speed reduction</td>
</tr>
<tr>
<td>Wind Erosion (agricultural, open area, and storage pile)</td>
<td>Revegetation</td>
</tr>
<tr>
<td></td>
<td>Limitation of off-road vehicle traffic</td>
</tr>
</tbody>
</table>

1.7 Document Organization

The handbook contains separate, stand-alone chapters for each fugitive dust source category with the chapters grouped into two broad categories, mechanically generated fugitive dust and wind generated fugitive dust, as follows:

- **Group I. Mechanically Generated Fugitive Dust**
  - Agricultural Tilling (Chapter 2)
  - Construction and Demolition (Chapter 3)
  - Materials Handling (Chapter 4)
  - Paved Roads (Chapter 5)
  - Unpaved roads (Chapter 6)

- **Group II. Wind Generated Fugitive Dust**
  - Agricultural Wind Erosion (Chapter 7)
  - Open Area Wind Erosion (Chapter 8)
  - Storage Pile Wind Erosion (Chapter 9)
Each chapter contains the following subsections:
- Characterization of Source Emissions
- Emissions Estimation: Primary Methodology (generally from AP-42)
- Emissions Estimation: Alternate Methodology (if available; e.g., CARB)
- Demonstrated Control Techniques
- Regulatory Formats
- Compliance Tools
- Sample Cost-Effectiveness Calculation
- References

A glossary and a series of Appendices are included in the handbook. Appendix A contains a discussion of two basic test methods used to quantify fugitive dust emission rates, namely:
- The upwind-downwind method that involves the measurement of upwind and downwind particulate concentrations, utilizing ground-based samplers under known meteorological conditions, followed by a calculation of the source strength (mass emission rate) with atmospheric dispersion equations; and
- The exposure-profiling method that involves simultaneous, multipoint measurements of particulate concentration and wind speed over the effective cross section of the plume, followed by a calculation of the net particulate mass flux through integration of the plume profiles.

Appendix B includes a summary of emission estimation methods developed by various groups for several fugitive dust source categories not addressed in the main body of the handbook. It also includes a summary of emission estimation methods for categories addressed in the handbook that are still in the "developmental" stage and have not been approved by federal or state agencies, or were developed many years ago and have fallen out of favor. The emission estimation methods discussed in Appendix B include:
- an early USEPA method for agricultural tilling,
- an early USEPA method and a California Air Resources Board (CARB) method for agricultural harvesting,
- a CARB method for cattle feedlots,
- emission estimation methods developed by AeroVironment for miscellaneous minor fugitive dust sources (leaf blowers, equestrian centers, landfills, and truck wake turbulence of unpaved shoulders),
- an early USEPA method for active storage pile wind erosion,
- an early USEPA method for uncovered haul trucks,
- a Desert Research Institute (DRI) method for unpaved shoulders, and
- four methods for open area wind erosion: the Draxler method, the UNLV method, the Great Basin Unified APCD method, and the DEJF method.

Appendix B also includes a discussion of a method developed by DRI to measure the silt content for paved roads. Because many of these methods have not been peer-reviewed, the reader is cautioned against the use of the emission factors included in these methods.
Appendix C contains a step-wise methodology to calculate the cost-effectiveness of different fugitive dust control measures. In compiling information regarding control cost-effectiveness estimates (i.e., $ per ton of PM10 reduction) of different control options for the fugitive dust handbook, we discovered that many of the estimates provided in contractor reports prepared for air quality agencies for PM10 SIPs contain either hard to substantiate assumptions or unrealistic assumptions. Depending on what assumptions are used, the control cost-effectiveness estimates can range over one to two orders of magnitude. Consequently, the end user of the handbook would get a distorted view if we published these estimates. Rather than presenting these published cost-effectiveness estimates, we have prepared a detailed methodology containing the steps to calculate cost-effectiveness that is included in Appendix C. We recommend that the handbook user calculate the cost-effectiveness values for different fugitive dust control options based on current cost data and assumptions that are applicable for their particular situation.

1.8 References


Chapter 6. Unpaved Roads

6.1 Characterization of Source Emissions ....................................................... 6-1
6.2 Emission Estimation: Primary Methodology ............................................ 6-1
6.3 Emission Estimation: Alternate Methodology for Non-Farm Roads .......... 6-7
6.4 Emission Estimation: Alternative Methodology for Farm Roads .............. 6-8
6.5 Demonstrated Control Techniques ......................................................... 6-9
6.6 Regulatory Formats .............................................................................. 6-15
6.7 Compliance Tools .................................................................................. 6-17
6.8 Sample Cost-Effectiveness Calculation .................................................. 6-17
6.9 References ............................................................................................. 6-20
6.1 Characterization of Source Emissions

When a vehicle travels an unpaved road, the force of the wheels on the road surface causes pulverization of surface material. Particles are lifted and dropped from the rolling wheels, and the road surface is exposed to strong air currents in turbulent shear with the surface. The turbulent wake behind the vehicle continues to act on the road surface after the vehicle has passed. The quantity of dust emissions from a given segment of unpaved road varies linearly with the volume of traffic. Field investigations also have shown that emissions depend on source parameters that characterize the condition of a particular road and the associated vehicle traffic. Characterization of these source parameters allow for "correction" of emission estimates to specific road and traffic conditions present on public and industrial roadways.

6.2 Emission Estimation: Primary Methodology

This section was adapted from Section 13.2.2 of EPA's Compilation of Air Pollutant Emission Factors (AP-42). Section 13.2.2 was last updated in December 2003.

Dust emissions from unpaved roads have been found to vary directly with the fraction of silt (particles smaller than 75 micrometers [μm] in physical diameter) in the road surface materials. The silt fraction is determined by measuring the proportion of loose dry surface dust that passes a 200-mesh screen using the ASTM-C-136 method. A summary of this method is contained in Appendix C of AP-42. Table 6-1 summarizes measured silt values for industrial unpaved roads. Table 6-2 summarizes measured silt values for public unpaved roads. It should be noted that the ranges of silt content for public unpaved roads vary over two orders of magnitude. Therefore, the use of data from this table can potentially introduce considerable error. Use of this data is strongly discouraged when it is feasible to obtain locally gathered data.

Since the silt content of a rural dirt road will vary with geographic location, it should be measured for use in projecting emissions. As a conservative approximation, the silt content of the parent soil in the area can be used. Tests, however, show that road silt content is normally lower than in the surrounding parent soil, because the fines are continually removed by the vehicle traffic, leaving a higher percentage of coarse particles. Other variables are important in addition to the silt content of the road surface material. For example, at industrial sites, where haul trucks and other heavy equipment are common, emissions are highly correlated with vehicle weight. On the other hand, there is far less variability in the weights of cars and pickup trucks that commonly travel publicly accessible unpaved roads throughout the United States. For those roads, the moisture content of the road surface material may be more dominant in determining differences in emission levels between a hot desert environment and a cool moist location.

6-1
Table 6-1. Typical Silt Content Values of Surface Material on Industrial Unpaved Roads

<table>
<thead>
<tr>
<th>Industry</th>
<th>Road use or surface material</th>
<th>Plant sites</th>
<th>No. of samples</th>
<th>Silt content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Range</td>
</tr>
<tr>
<td>Copper smelting</td>
<td>Plant road</td>
<td>1</td>
<td>3</td>
<td>16-19</td>
</tr>
<tr>
<td>Iron and steel production</td>
<td>Plant road</td>
<td>19</td>
<td>135</td>
<td>0.2-19</td>
</tr>
<tr>
<td>Sand and gravel processing</td>
<td>Plant road</td>
<td>1</td>
<td>3</td>
<td>4.1-6.0</td>
</tr>
<tr>
<td></td>
<td>Material storage area</td>
<td>1</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Stone quarry and processing</td>
<td>Plant road</td>
<td>2</td>
<td>10</td>
<td>2.4-16</td>
</tr>
<tr>
<td></td>
<td>Haul road to/from pit</td>
<td>4</td>
<td>20</td>
<td>5.0-15</td>
</tr>
<tr>
<td>Taconite mining and processing</td>
<td>Service road</td>
<td>1</td>
<td>8</td>
<td>2.4-7.1</td>
</tr>
<tr>
<td></td>
<td>Haul road to/from pit</td>
<td>1</td>
<td>12</td>
<td>3.9-9.7</td>
</tr>
<tr>
<td>Western surface coal mining</td>
<td>Haul road to/from pit</td>
<td>3</td>
<td>21</td>
<td>2.8-18</td>
</tr>
<tr>
<td></td>
<td>Plant road</td>
<td>2</td>
<td>2</td>
<td>4.9-5.3</td>
</tr>
<tr>
<td></td>
<td>Scraper route</td>
<td>3</td>
<td>10</td>
<td>7.2-25</td>
</tr>
<tr>
<td></td>
<td>Haul road (freshly graded)</td>
<td>2</td>
<td>5</td>
<td>18-29</td>
</tr>
<tr>
<td>Construction sites</td>
<td>Scrapper routes</td>
<td>7</td>
<td>20</td>
<td>0.56-23</td>
</tr>
<tr>
<td>Lumber sawmills</td>
<td>Log yards</td>
<td>2</td>
<td>2</td>
<td>4.8-12</td>
</tr>
<tr>
<td>Municipal solid waste landfills</td>
<td>Disposal routes</td>
<td>4</td>
<td>20</td>
<td>2.2-21</td>
</tr>
</tbody>
</table>

*a References 1, 5-15.

Table 6-2. Typical Silt Content Values of Surface Material on Public Unpaved Roads

<table>
<thead>
<tr>
<th>Industry</th>
<th>Road use or surface material</th>
<th>Plant sites</th>
<th>No. of samples</th>
<th>Silt content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Range</td>
</tr>
<tr>
<td>Publicly accessible roads</td>
<td>Gravel/crushed limestone</td>
<td>9</td>
<td>46</td>
<td>0.1-15</td>
</tr>
<tr>
<td></td>
<td>Dirt (i.e., local material compacted, bladed, and crowned)</td>
<td>8</td>
<td>24</td>
<td>0.83-68</td>
</tr>
</tbody>
</table>

*a References 1, 5-16.

6.2.1 Emission Factors

The PM10 emission factors presented below are the outcomes from stepwise linear regressions of field emission test results of vehicles traveling over unpaved surfaces. Due to a limited amount of information available for PM2.5, the expression for that particle size range has been scaled against the PM10 results. Consequently, the quality rating for the PM2.5 factor is lower than that for the PM10 expression. The following empirical expressions may be used to estimate the quantity of size-specific particulate emissions.
from an unpaved road in pounds (lb) per vehicle mile traveled (VMT). For vehicles traveling on unpaved surfaces at industrial sites, emissions are estimated from the following equation:

\[ E = k (s^{12})^{(W^{3})} \]  

and, for vehicles traveling on publicly accessible roads, dominated by light duty vehicles, emissions may be estimated from the following equation:

\[ E = \frac{k (s^{12})^{(S^{30})}}{(M^{0.5})} - C \]  

where \( k, a, b, c \) and \( d \) are empirical constants given below in Table 6-3, and

- \( E \) = size-specific emission factor (lb VMT)
- \( s \) = surface material silt content \( (\% \) )
- \( W \) = mean vehicle weight (tons)
- \( M \) = surface material moisture content \( (\% \) )
- \( S \) = mean vehicle speed (mph)
- \( C \) = emission factor for 1980’s vehicle fleet exhaust, brake wear and tire wear.

The source characteristics \( s, W \) and \( M \) are referred to as correction parameters for adjusting the emission estimates to local conditions. The metric conversion from lb VMT to grams (g) per vehicle kilometer traveled (VKT) is as follows:

\[ 1 \text{ lb VMT} = 281.9 \text{ g VKT} \]

The constants for Equations 1a and 1b based on the stated aerodynamic particle sizes are shown in Table 6-3. Table 6-3 also contains the quality ratings for the various size-specific versions of Equations 1a and 1b. The equations retain the assigned quality rating, if applied within the ranges of source conditions, shown in Table 6-4, that were tested in developing the equations.

### Table 6-3. Constants for Equations 1a and 1b

<table>
<thead>
<tr>
<th>Constant</th>
<th>Industrial roads (Equation 1a)</th>
<th>Public roads (Equation 1b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM2.5</td>
<td>PM10</td>
</tr>
<tr>
<td>( k ) (lb/VMT)</td>
<td>0.23</td>
<td>1.5</td>
</tr>
<tr>
<td>( a )</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>( b )</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>( c )</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( d )</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Quality rating</td>
<td>C</td>
<td>B</td>
</tr>
</tbody>
</table>

* Assumed equivalent to total suspended particulate matter (TSP).
* * = Not used in the emission factor equation.
As noted earlier, the models presented as Equations 1a and 1b were developed from tests of traffic on unpaved surfaces, mostly performed in the 1980s. Unpaved roads have a hard, generally nonporous surface that usually dries quickly after a rainfall or watering, because of traffic-enhanced natural evaporation. Factors influencing how fast a road dries are discussed in Section 6.5 below. The quality ratings given above pertain to the mid-range of the measured source conditions for the equations. A higher mean vehicle weight and a higher than normal traffic rate may be justified when performing a worst-case analysis of emissions from unpaved roads.

The emission factor for the exhaust, brake wear, and tire wear of a 1980’s vehicle fleet (C) was obtained from EPA’s MOBILE6.2 model. The emission factor also varies with aerodynamic size range as shown in Table 6-5.

A PM10 emission factor for the resuspension of fugitive dust from unpaved shoulders created by the wake of high-profile vehicles such as tractor-trailers traveling on paved roads at high speed has been developed by Desert Research Institute (DRI). A discussion of the emissions estimation methodology for fugitive dust originating from unpaved shoulders is presented in Appendix B.

### Table 6-4. Range of Source Conditions Used in Developing Equations 1a and 1b

<table>
<thead>
<tr>
<th>Emission factor</th>
<th>Surface silt content, %</th>
<th>Mean vehicle weight</th>
<th>Mean vehicle speed</th>
<th>Mean No. of wheels</th>
<th>Surface moisture content, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial roads (Equation 1a)</td>
<td>1.8-25.2</td>
<td>1.8-260</td>
<td>2-290</td>
<td>8-69</td>
<td>5-43</td>
</tr>
<tr>
<td>Public roads (Equation 1b)</td>
<td>1.8-35</td>
<td>1.4-2.7</td>
<td>1.5-3</td>
<td>16-88</td>
<td>10-55</td>
</tr>
</tbody>
</table>

* See discussion in text.

### Table 6-5. Emission Factor for 1980’s Vehicle Fleet Exhaust, Brake Wear, and Tire Wear

<table>
<thead>
<tr>
<th>Particle size range</th>
<th>C, Emission factor for exhaust, brake wear, and tire wear lb/VMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM25</td>
<td>0.00036</td>
</tr>
<tr>
<td>PM10</td>
<td>0.00047</td>
</tr>
<tr>
<td>PM30</td>
<td>0.00047</td>
</tr>
</tbody>
</table>

6.2.2 Source Extent

It is important to note that the vehicle-related source conditions refer to the average weight, speed, and number of wheels for all vehicles traveling the road. For example, if
98\% of the traffic on the road are 2-ton cars and trucks while the remaining 2\% consists of 20-ton trucks, then the mean weight is 2.4 tons. More specifically, Equations 1a and 1b are not intended to be used to calculate a separate emission factor for each vehicle class within a mix of traffic on a given unpaved road. That is, in the example, one should not determine one factor for the 2-ton vehicles and a second factor for the 20-ton trucks. Instead, only one emission factor should be calculated that represents the "fleet" average of 2.4 tons for all vehicles traveling the road. Moreover, to retain the quality ratings when addressing a group of unpaved roads, it is necessary that reliable correction parameter values be determined for the road in question. The field and laboratory procedures for determining road surface silt and moisture contents are given in Appendices C.1 and C.2 of AP-42. Vehicle-related parameters should be developed by recording visual observations of traffic. In some cases, vehicle parameters for industrial unpaved roads can be determined by reviewing maintenance records or other information sources at the facility.

In the event that site-specific values for correction parameters cannot be obtained, then default values may be used. In the absence of site-specific silt content information, an appropriate mean value from Tables 6-1 and 6-2 may be used as a default value, but the quality rating of the equation is reduced by two letters. Because of significant differences found between different types of road surfaces and between different areas of the country, use of the default moisture content value of 0.5 percent in Equation 1b is discouraged. The quality rating should be downgraded two letters when the default moisture content value is used. It is assumed that readers addressing industrial roads have access to the information needed to develop average vehicle information for their facility.

### 6.2.3 Natural Mitigation

The effect of routine watering to control emissions from unpaved roads is discussed below in Section 6.5. However, all roads are subject to some natural mitigation because of rainfall and other precipitation. The Equation 1a and 1b emission factors can be extrapolated to annual average uncontrolled conditions (but including natural mitigation) under the simplifying assumption that annual average emissions are inversely proportional to the number of days with measurable (more than 0.254 mm [0.01 inch]) precipitation:

\[
E_{ev} = E[(365 - P) / 365]
\]

where,

- \( E_{ev} \) = annual size-specific emission factor extrapolated for natural mitigation (lb VMT)
- \( E \) = emission factor from Equation 1a or 1b
- \( P \) = number of days in a year with at least 0.254 mm (0.01 in) of precipitation

Maps showing the geographical distribution of "wet" days on an annual basis for the United States based on meteorological records on a monthly basis are available in the
Equation 2 provides an estimate that accounts for precipitation on an annual average basis for the purpose of inventoring emissions. It should be noted that Equation 2 does not account for differences in the temporal distributions of the rain events, the quantity of rain during any event, or the potential for the rain to evaporate from the road surface. In the event that a finer temporal and spatial resolution is desired for inventories of public unpaved roads, estimates can be based on a more complex set of assumptions. These assumptions include:

1. The moisture content of the road surface material is increased in proportion to the quantity of water added;
2. The moisture content of the road surface material is reduced in proportion to the Class A pan evaporation rate;
3. The moisture content of the road surface material is reduced in proportion to the traffic volume; and
4. The moisture content of the road surface material varies between the extremes observed in the area.

The CHIEF Web site (www.epa.gov/ttn/chief/ap42/ch13/related/cl13s02-2) has a file which contains a spreadsheet program for calculating emission factors which are temporally and spatially resolved. Information required for use of the spreadsheet program includes monthly Class A pan evaporation values, hourly meteorological data for precipitation, humidity and snow cover, vehicle traffic information, and road surface material information.

It is emphasized that the simple assumption underlying Equation 2 and the more complex set of assumptions underlying the use of the procedure which produces a finer temporal and spatial resolution have not been verified in any rigorous manner. For this reason, the quality ratings for either approach should be downgraded one letter from the rating that would be applied to Equation 1.
6.3 Emission Estimation: Alternate Methodology for Non-Farm Roads

This section was adapted from Section 7.10 of CARB's Emission Inventory Methodology. Section 7.10 was last updated in August 1997.

This source category provides estimates of the entrained geologic particulate matter emissions that result from vehicular travel over non-agricultural unpaved roads. The emissions are estimated separately for three major unpaved road categories: city and county roads, U.S. forests and park roads, and Bureau of Land Management (BLM) and Bureau of Indian Affairs (BIA) roads. The emissions result from the mechanical disturbance of the roadway and the vehicle generated air turbulence effects. Agricultural unpaved road estimates are computed in a separate methodology; see Section 6.4.

6.3.1 Emission Factor

The PM10 emission factor used for estimates of geologic dust emissions from vehicular travel on unpaved roads is based on work performed by UC Davis and the Desert Research Institute. The emission factor used for all unpaved roads statewide is 2.27 lbs PM10 VMT. The PM2.5 PM10 ratio for unpaved road dust published by CARB is 0.212. Because the emission measurements were performed in California, this emission factor was used to replace the previous generic emission factor provided in EPA's AP-42 document. The new emission factor is slightly smaller than the factors derived with the AP-42 methodology.

6.3.2 Source Extent (Activity Level)

For the purpose of estimating emissions, it is assumed that the unpaved road dust emissions are primarily related to the vehicle miles traveled (VMT) on the roads. State highway data are used to estimate unpaved road miles for each roadway category in each county. It is assumed that 10 daily VMT (DVMT) are traveled on unpaved city and county roads as well as U.S. forest and parks roads and BLM and BIA roads. Road mileage, if needed, can be simply computed by dividing the annual VMT values by 3650 (which is 10 DVMT x 365 days).

Daily activity on unpaved roads occurs primarily during daylight hours. Activity is assumed to be the same each day of the week. Monthly activity varies by county and is based on estimates of monthly rainfall in each county. This is to reflect that during wet months there is less unpaved road traffic, and there are also lower emissions per mile of road when the road soils have a higher moisture content. Unpaved road growth is tied to on-road VMT growth for many counties. For other counties, growth is set to zero and VMT is not used.

6.3.3 Assumptions and Limitations

This alternative methodology is subject to the following assumptions and limitations:
1. This methodology assumes that all unpaved roads emit the same levels of PM10 per VMT during all times of the year for all vehicles and conditions.

2. It is assumed that all unpaved roads receive 10 VMT per day.

3. This methodology assumes that no controls are used on the roads.

4. It is assumed that the emission factors derived in a test county are applicable to the rest of the State.

6.4 Emission Estimation: Alternative Methodology for Farm Roads

This section was adapted from Section 7.11 of CARB's Emission Inventory Methodology. Section 7.11 was last updated in August 1997.

This source category provides estimates of the entrained geologic particulate matter emissions that result from vehicular travel over unpaved roads on agricultural lands. The emissions result from the mechanical disturbance of the roadway and the vehicle generated air turbulence effects. This emission factor used is oriented towards dust emissions from light duty vehicle use, but the activity data implicitly include some larger vehicle use for harvest and other operations.

6.4.1 Emission Factor

The PM10 emission factor used for estimates of geologic dust emissions from vehicular travel on unpaved roads is based on work performed by UC Davis\(^{27}\) and the Desert Research Institute.\(^{28}\) The emission factor used for all unpaved roads statewide is 2.27 lbs PM10/VMT.\(^{29}\) The PM2.5/PM10 ratio for unpaved road dust published by CARB is 0.212.\(^{30}\) Because the emission measurements were performed in California, this emission factor was used to replace the previous generic emission factor provided in U.S. EPA's AP-42 document.\(^{31}\) The new emission factor is slightly smaller than the factors derived with the AP-42 methodology.

6.4.2 Source Extent (Activity Level)

For the purpose of estimating emissions, it is assumed that the unpaved road dust emissions are primarily related to the vehicle miles traveled (VMT) on the roads. In 1976 an informal survey was made of several county agricultural commissioners in the San Joaquin Valley, who estimated that each 40 acres of cultivated land receives approximately 175 vehicle passes per year on the unpaved farm roads.\(^{32}\) This value is used in the emission estimates. The crop acreage data used to estimate the road dust emissions are from the state agency summary of crop acreage harvested.\(^{33,34}\) The acreage estimates do not include pasture lands because it is thought that the quantity of vehicular travel on these lands is minimal.

Daily activity on unpaved roads occurs primarily during daylight hours. Activity is assumed to be the same each day of the week. Monthly activity varies by county and is
based on estimates of monthly rainfall in each county. This is to reflect that during wet months there is less unpaved road traffic, and there are also lower emissions per mile of road when the road soils have a higher moisture content. Unpaved road growth for farm roads is based on agricultural crop acreage or agricultural production. This value is set to zero for many counties.

6.4.3 Assumptions and Limitations

This alternative methodology is subject to the following assumptions and limitations:

1. This methodology assumes that all unpaved farm roads emit the same levels of PM10 per VMT during all times of the year for all vehicles and conditions.
2. It is assumed that all unpaved farm roads receive 175 VMT per 40 acres per year for all crops and cultivation practices.
3. This methodology assumes that no controls are used on the roads.
4. It is assumed that the emission factors derived in the test area are applicable to the rest of the State.
5. This methodology assumes that unpaved road travel associated with pasture lands is negligible.

6.5 Demonstrated Control Techniques

A wide variety of options exist to control emissions from unpaved roads. Options fall into the following three groupings:

1. **Vehicle restrictions** that limit the speed, weight or number of vehicles on the road
2. **Surface improvement** by measures such as (a) paving or (b) adding gravel or slag to a dirt road
3. **Surface treatment** such as watering or treatment with chemical dust suppressants

Available control options span broad ranges in terms of cost, efficiency, and applicability. For example, traffic controls provide moderate emission reductions (often at little cost) but are difficult to enforce. Although paving is highly effective, its high initial cost is often prohibitive. Furthermore, paving is not feasible for industrial roads subject to very heavy vehicles and or spillage of material in transport. Watering and chemical suppressants, on the other hand, are potentially applicable to most industrial roads at moderate to low costs. However, these require frequent reapplication to maintain an acceptable level of control. Chemical suppressants are generally more cost-effective than water but not in cases of temporary roads (which are common at mines, landfills, and construction sites). In summary, then, one needs to consider not only the type and volume of traffic on the road but also how long the road will be in service when developing control plans.
Vehicle restrictions. These measures seek to limit the amount and type of traffic present on the road, or to lower the mean vehicle speed. For example, many industrial plants have restricted employees from driving on plant property and have instead instituted bussing programs. This eliminates emissions due to employees traveling to/from their worksites. Although the heavier average vehicle weight of the busses increases the base emission factor, the decrease in vehicle-miles-traveled results in a lower overall emission rate.

Surface improvements. Control options in this category alter the road surface. As opposed to “surface treatments” discussed below, improvements are relatively “permanent” and do not require periodic retreatment. The most obvious surface improvement is paving an unpaved road. This option is quite expensive and is probably most applicable to relatively short stretches of unpaved road with at least several hundred vehicle passes per day. Furthermore, if the newly paved road is located near unpaved areas or is used to transport material, it is essential that the control plan address routine cleaning of the newly paved road surface. The control efficiencies achievable by paving can be estimated by comparing emission factors for unpaved and paved road conditions. The predictive emission factor equation for paved roads, given in Chapter 5, requires estimation of the silt loading on the traveled portion of the paved surface, which in turn depends on whether the pavement is periodically cleaned. Unless curbing is to be installed, the effects of vehicle excursion onto unpaved shoulders (berms) also must be taken into account in estimating the control efficiency of paving.

Other surface improvement methods involve covering the road surface with another material that has a lower silt content. Examples include placing gravel or slag on a dirt road. The control efficiency can be estimated by comparing the emission factors obtained using the silt contents before and after improvement. The silt content of the road surface should be determined after 3 to 6 months rather than immediately following placement. Control plans should address regular maintenance practices, such as grading, to retain larger aggregate on the traveled portion of the road.

Surface treatments. These measures refer to control options which require periodic reapplication. Treatments fall into the two main categories of:

- wet suppression (i.e., watering, possibly with surfactants or other additives), which keeps the road surface wet to control emissions, and
- chemical stabilization which attempts to change the physical characteristics of the surface.

The necessary reapplication frequency varies from minutes or hours for plain water under summertime conditions to several weeks or months for chemical dust suppressants.

Wet Suppression. Watering increases the moisture content, which in turn causes particles to conglomerate and reduces their likelihood of becoming suspended when vehicles pass over the surface. The control efficiency depends on how fast the road dries after water is added. This in turn depends on: (a) the amount (per unit road surface area) of water added during each application; (b) the period of time between applications; (c)
the weight, speed and number of vehicles traveling over the watered road during the period between applications; and (d) meteorological conditions (temperature, wind speed, cloud cover, etc.) that affect evaporation during the period. Figure 6-1 presents a simple bilinear relationship between the instantaneous control efficiency due to watering and the resulting increase in surface moisture. The moisture ratio “M” (i.e., the x-axis in Figure 6-1) is found by dividing the surface moisture content of the watered road by the surface moisture content of the uncontrolled road. As the watered road surface dries, both the ratio M and the predicted instantaneous control efficiency (i.e., the y-axis in the figure) decrease. The figure shows that between the uncontrolled moisture content (M = 1) and a value twice as large (M = 2), a small increase in moisture content results in a large increase in control efficiency. Beyond that, control efficiency grows slowly with increased moisture content.

![Figure 6-1. Watering Control Effectiveness for Unpaved Travel Surfaces](image)

Given the complicated nature of how the road dries, characterization of emissions from watered roadways is best done by collecting road surface material samples at various times between water truck passes. AP-42 Appendices C.1 and C.2 present the recommended sampling and analysis procedures, respectively, for determining the surface bulk dust loading. The moisture content measured can then be associated with a control efficiency by use of Figure 6-1. Samples that reflect average conditions during the watering cycle can take the form of either a series of samples between water applications or a single sample at the midpoint. It is essential that samples be collected during periods with active traffic on the road. Finally, because of different evaporation rates, it is recommended that samples be collected at various times during the year. If
only one set of samples is to be collected, these must be collected during hot, summertime conditions.

When developing watering control plans for roads that do not yet exist, it is strongly recommended that the moisture cycle be established by sampling similar roads in the same geographic area. If the moisture cycle cannot be established by similar roads using established watering control plans, the more complex methodology used to estimate the mitigation of rainfall and other precipitation can be used to estimate the control provided by routine watering. An estimate of the maximum daytime Class A pan evaporation (based upon daily evaporation data published in the monthly Climatological Data for the state by the National Climatic Data Center) should be used to insure that adequate watering capability is available during periods of highest evaporation. Hourly precipitation values are replaced by the equivalent inches of precipitation resulting from watering. 1 inch of precipitation is equivalent to an application of 5.6 gallons of water per square yard of road. Information on the long term average annual evaporation and on the percentage that occurs between May and October is available in the Climatic Atlas. This methodology should be used only for prospective analyses and for designing watering programs for existing roadways. The quality rating of an emission factor for a watered road that is based on this methodology should be downgraded two letters.

Periodic road surface samples should be collected and analyzed to verify the efficiency of the watering program.

Chemical Dust Suppressants. As opposed to wet suppression (i.e., watering), chemical dust suppressants have much less frequent reappplication requirements. These materials suppress emissions by changing the physical characteristics of the existing road surface material. Many chemical dust suppressants applied to unpaved roads form a hardened surface that binds particles together. After several applications, a treated unpaved road often resembles a paved road except that the surface is not uniformly flat. Because the improved surface results in more grinding of small particles, the silt content of loose material on a highly controlled surface may be substantially higher than when the surface was uncontrolled. For this reason, the models presented as Equations 1a and 1b cannot be used to estimate emissions from chemically stabilized roads. Should the road be allowed to return to an uncontrolled state with no visible signs of large-scale cementing of material, the Equation 1a and 1b emission factors could then be used to obtain conservatively high emission estimates.

The control effectiveness of chemical dust suppressants appears to depend on: (a) the dilution rate used in the mixture; (b) the application rate (volume of solution per unit road surface area); (c) the time between applications; (d) the size, speed and amount of traffic during the period between applications; and (e) meteorological conditions (rainfall, freeze/thaw cycles, etc.) during the period. Other factors that affect the performance of chemical dust suppressants include other traffic characteristics (e.g., cornering, track-out from unpaved areas) and road characteristics (e.g., bearing strength, grade). The variability in these factors and differences between individual dust control products make the control efficiencies of chemical dust suppressants difficult to estimate. Past field testing of emissions from controlled unpaved roads has shown that chemical dust
suppressants provide a PM10 control efficiency of about 80% when applied at regular intervals of 2 weeks to 1 month.

Petroleum resin products historically have been the dust suppressants (besides water) most widely used on industrial unpaved roads. Figure 6-2 presents a method to estimate average control efficiencies associated with petroleum resins applied to unpaved roads. The following items should be noted:

1. The term “ground inventory” represents the total volume (per unit area) of petroleum resin concentrate (not solution) applied since the start of the dust control season.

2. Because petroleum resin products must be periodically reapplied to unpaved roads, the use of a time-averaged control efficiency value is appropriate. Figure 6-2 presents control efficiency values averaged over two common application intervals, 2 weeks and 1 month. Other application intervals will require interpolation.

3. Note that zero efficiency is assigned until the ground inventory reaches 0.05 gallon per square yard (gal yd²). Requiring a minimum ground inventory ensures that one must apply a reasonable amount of chemical dust suppressant to a road before claiming credit for emission control. Recall that the ground inventory refers to the amount of petroleum resin concentrate rather than the total solution.

As an example of the application of Figure 6-2, suppose that Equation 1a was used to estimate an emission factor of 7.1 lb VMT for PM10 from a particular road. Also, suppose that, starting on May 1, the road is treated with 0.221 gal yd² of a solution (1 part petroleum resin to 5 parts water) on the first of each month through September. The average controlled emission factors calculated from Figure 6-2 are shown in Table 6-6.

Besides petroleum resins, other newer dust suppressants have also been successful in controlling emissions from unpaved roads. Specific test results for those chemicals, as well as for petroleum resins and watering, are provided in References 18 through 21.
Figure 6-2. Average TSP and PM10 Control Efficiencies for Two Common Application Intervals
Table 6-6. Example of Average Controlled Emission Factors for Specific Conditions

<table>
<thead>
<tr>
<th>Period</th>
<th>Ground inventory, gal/yd²</th>
<th>Average control efficiency, %</th>
<th>Average controlled emission factor, lb/VMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>0.037</td>
<td>0</td>
<td>7.1</td>
</tr>
<tr>
<td>June</td>
<td>0.073</td>
<td>62</td>
<td>2.7</td>
</tr>
<tr>
<td>July</td>
<td>0.11</td>
<td>68</td>
<td>2.3</td>
</tr>
<tr>
<td>August</td>
<td>0.15</td>
<td>74</td>
<td>1.8</td>
</tr>
<tr>
<td>September</td>
<td>0.18</td>
<td>80</td>
<td>1.4</td>
</tr>
</tbody>
</table>

* From Figure 6-5. Zero efficiency assigned if ground inventory is less than 0.05 gal/yd². 1 lb/VMT = 281.9 g/VKT. 1 gal/yd² = 4.531 L/m².

Table 6-7 summarizes tested control measures and reported control efficiencies for measures that reduce the generation of fugitive dust from unpaved roads.

Table 6-7. Control Efficiencies for Control Measures for Unpaved Roads

<table>
<thead>
<tr>
<th>Control measure</th>
<th>PM10 control efficiency</th>
<th>References/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limit maximum speed on unpaved roads to 25 miles per hour</td>
<td>44%</td>
<td>Assures linear relationship between PM10 emissions and vehicle speed and an uncontrolled speed of 45 mph.</td>
</tr>
<tr>
<td>Pave unpaved roads and unpaved parking areas</td>
<td>99%</td>
<td>Based on comparison of paved road and unpaved road PM10 emission factors.</td>
</tr>
<tr>
<td>Implement watering twice a day for industrial unpaved road</td>
<td>55%</td>
<td>MRI, April 2001</td>
</tr>
<tr>
<td>Apply dust suppressant annually to unpaved parking areas</td>
<td>84%</td>
<td>CARB April 2002</td>
</tr>
</tbody>
</table>

6.6 Regulatory Formats

Fugitive dust control options have been embedded in many regulations for state and local agencies in the WRAP region. Regulatory formats specify the threshold source size that triggers the need for control application. Example regulatory formats downloaded from the Internet for several local air quality agencies in the WRAP region are presented in Table 6-8. The website addresses for obtaining information on fugitive dust regulations for local air quality districts within California, for Clark County, NV, and for Maricopa County, AZ, are as follows:

- Districts within California: www.arb.ca.gov/drd/drdb.htm
- Clark County, NV: www.co.clark.nv.us/air_quality_regs.htm
- Maricopa County, AZ: www.maricopa.gov/envsvc/air_rule_desc.asp
<table>
<thead>
<tr>
<th>Control Measure</th>
<th>Goal</th>
<th>Threshold</th>
<th>Agency</th>
<th>Control Measure</th>
<th>Goal</th>
<th>Threshold</th>
<th>Agency</th>
<th>Control Measure</th>
<th>Goal</th>
<th>Threshold</th>
<th>Agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requires annual treatment of unpaved public roads beginning in 1998 and continuing for each of 8 years thereafter by implementing one of the following: paving at least one mile with typical roadway material, applying chemical stabilizers to at least two miles to maintain stabilized surface, implementing at least one of the following on at least three miles of road surface: installing signage at 1/4 mile intervals, limiting speed to 15 mph, installing speed control devices every 500 ft, or maintaining roadway to limit speed to 15 mph</td>
<td>Set applicability standard: unpaved road must be more than 50 ft wide at all points or must not be within 25 ft of property line, or have more than 20 vehicle trips per day. All roads with average daily traffic greater than average of all unpaved roads within its jurisdiction must be treated</td>
<td>SCAQMD Rule 1186</td>
<td>9/10/1999</td>
<td>Control measures implemented by June 1, 2003: pave, apply dust palliative, or other</td>
<td>Complies with stabilization standard; limit visible dust emissions to 20% opacity, limit silt loading to 0.33 oz/ft², and limit silt content to 6%</td>
<td>All unpaved roads with vehicular traffic 150 vehicles or more per day</td>
<td>Hydrographic Basins 212, 216, 217 Sect. 91 Air Quality Reg. 06/22/2000</td>
<td>Limit vehicle spd &lt;=15mph and &lt;=20 trips/day; BACM: watering, paving, apply/maintain gravel, asphalt, or dust suppressant; Dust ctrl plan for constr site roads</td>
<td>Limit VDE to 20% opacity; limit silt loading to 0.33oz/ft², limit silt content to 6%</td>
<td>Constr site roads, inactive/active; limiting vehicle spd and trips is alt to stabilization regs and max number of trips each day in ctrl plan (also number of vehicles, earthmoving equip, etc.); for roads with &gt;=150 vehicles/day implement BACM by 06/10/2004; same for &gt;=250 vehicles day (existing roads by 06/10/2000)</td>
<td>Maricopa County Rule 310 and 310.01 04/07/2004 and 02/16/2000</td>
</tr>
</tbody>
</table>
6.7 Compliance Tools

Compliance tools assure that the regulatory requirements, including application of dust controls, are being followed. Three major categories of compliance tools are discussed below.

Record keeping: A compliance plan is typically specified in local air quality rules and mandates record keeping of source operation and compliance activities by the source owner operator. The plan includes a description of how a source proposes to comply with all applicable requirements, log sheets for daily dust control, and schedules for compliance activities and submittal of progress reports to the air quality agency. The purpose of a compliance plan is to provide a consistent reasonable process for documenting air quality violations, notifying alleged violators, and initiating enforcement action to ensure that violations are addressed in a timely and appropriate manner.

Site inspection: This activity includes (1) review of compliance records, (2) proximate inspections (sampling and analysis of source material), and (3) general observations. An inspector can use photography to document compliance with an air quality regulation.

On-site monitoring: EPA has stated that "An enforceable regulation must also contain test procedures in order to determine whether sources are in compliance." Monitoring can include observation of visible plume opacity, surface testing for crust strength and moisture content, and other means for assuring that specified controls are in place.

The following table summarizes the compliance tools that are applicable for unpaved roads.

<table>
<thead>
<tr>
<th>Record keeping</th>
<th>Site inspection/monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road map; traffic volumes, speeds, and patterns; dust suppression equipment and maintenance records; frequencies, amounts, times, and rates for watering and dust suppressants (type); use of water surfactants; calculated control efficiencies; regrading. graveling, or paving of unpaved road segments; control equipment downtime and maintenance records; meteorological log</td>
<td>Observation of water truck operation and inspection of sources of water; observation of dust plume opacity exceeding a standard; counting of traffic volumes; surface material sampling and analysis for silt and moisture contents; real-time portable monitoring of PM.</td>
</tr>
</tbody>
</table>

6.8 Sample Cost-Effectiveness Calculation

This section is intended to demonstrate how to select a cost-effective control measure for fugitive dust originating from unpaved roads. A sample cost-effectiveness calculation is presented below for a specific control measure (watering) to illustrate the procedure. The sample calculation includes the entire series of steps for estimating...
uncontrolled emissions (with correction parameters and source extent), controlled emissions, emission reductions, control costs, and control cost-effectiveness values for PM10 and PM2.5. In selecting the most advantageous control measure for construction and demolition, the same procedure is used to evaluate each candidate control measure (utilizing the control measure specific control efficiency and cost data), and the control measure with the most favorable cost-effectiveness and feasibility characteristics is identified.

Sample Calculation for Unpaved Roads
(Industrial Facility)

Step 1. Determine source activity and control application parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road length (mile)</td>
<td>10</td>
</tr>
<tr>
<td>Vehicles/day</td>
<td>100</td>
</tr>
<tr>
<td>Wet days/year</td>
<td>20</td>
</tr>
<tr>
<td>Number of workdays/year</td>
<td>260</td>
</tr>
<tr>
<td>Number of emission days/yr (workdays without rain)</td>
<td>240</td>
</tr>
<tr>
<td>Control Measure</td>
<td>Watering</td>
</tr>
<tr>
<td>Control Application/Frequency</td>
<td>Twice daily*</td>
</tr>
<tr>
<td>Economic Life of Control System (year)</td>
<td>10</td>
</tr>
<tr>
<td>Control Efficiency</td>
<td>55%</td>
</tr>
</tbody>
</table>

* No nighttime traffic.

The number of vehicles per day, wet days per year, workdays per year, and the economic life of the control are determined from climatic and industrial records. The number of emission days per year are calculated by subtracting the number of annual wet days from the number of annual workdays:

\[
\text{Number of workdays/yr} - \text{Wet days/yr} = 260 - 20 = 240
\]

Watering has been chosen as the applied control measure. The control application/frequency and control efficiency are default values provided by MRI, 2001.35

Step 2. Calculate Emission Factor. The PM2.5 and PM10 emission factors are calculated from the AP-42 equation utilizing the appropriate correction parameters.

\[
E = k(s/12)^a(W/3)^b
\]

- \(k\)—PM2.5 (Ib/VMT) = 0.23
- \(k\)—PM10 (lb/VMT) = 1.5
- \(s\)—silt content (%) = 15
- \(a\)—PM2.5 (dimensionless) = 0.9
- \(a\)—PM10 (dimensionless) = 0.9
- \(W\)—vehicle weight (tons) = 15
- \(b\)—vehicle weight (dimensionless) = 0.45

- \(E_{PM10} = 3.8 \text{ lb/VMT}\)
- \(E_{PM2.5} = 0.6 \text{ lb/VMT}\)

Step 3. Calculate Uncontrolled PM Emissions. The emission factors (calculated in Step 2) are multiplied by the number of vehicles per day and by the number of emission days per year (both under activity data) and divided by 2,000 lb/ton to compute the annual PM emissions, as follows:
Annual emissions = (Emission Factor x Vehicles/day x Number of emission days yr
developed 2,000

- Annual PM10 Emissions = (3.8 x 100 x 240)/2,000 = 45.4 tons
- Annual PM2.5 Emissions = (0.6 x 100 x 240)/2,000 = 7.0 tons

**Step 4. Calculate Controlled PM Emissions.** The uncontrolled emissions (calculated in Step 3) are multiplied by the percentage that uncontrolled emissions are reduced, as follows:

Controlled emissions = Uncontrolled emissions x (1 - Control efficiency fraction), where CE = 55% (as seen under activity data)

For this example, we have selected watering as our control measure. Based on a control efficiency estimate of 55% for the application of water to unpaved roads, the annual controlled emissions estimate are calculated to be:

Annual Controlled PM10 emissions = (45.4 tons) x (1 - 0.55) = 20.4 tons
Annual Controlled PM2.5 emissions = (7.0 tons) x (1 - 0.55) = 3.1 tons

**Step 5. Determine Annual Cost to Control PM Emissions.**

<table>
<thead>
<tr>
<th>Cost</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs ($)</td>
<td>6,000</td>
</tr>
<tr>
<td>Operating/Maintenance costs ($)</td>
<td>8,000</td>
</tr>
<tr>
<td>Overhead costs ($)</td>
<td>4,000</td>
</tr>
<tr>
<td>Enforcement/Compliance costs ($)</td>
<td>500</td>
</tr>
<tr>
<td>Annual Interest Rate</td>
<td>3%</td>
</tr>
<tr>
<td>Capital Recovery Factor</td>
<td>0.12</td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>18,500</td>
</tr>
<tr>
<td>Annualized Cost ($-yr)</td>
<td>13,203</td>
</tr>
</tbody>
</table>

The Capital costs, the Operating/Maintenance costs, and the Enforcement/Compliance costs are default values determined from current sources (e.g. Sierra Research, 2003). The Overhead costs are typically one-half of the Operating/Maintenance costs. Overhead costs = $8,000/2 = $4,000.

The Annual Interest Rate (AIR) is based on the most up to date information and sources.

The Capital Recovery Factor (CRF) is figured by multiplying AIR by 1 plus AIR, raised to the exponent of the Economic life of the control system, and then dividing by 1 plus AIR to the Economic life minus 1, as follows:

\[ \text{Capital Recovery Factor} = \text{AIR} \times (1 + \text{AIR})^{Economic\ life} / (1 + \text{AIR})^{Economic\ life} - 1 \]

\[ \text{Capital Recovery Factor} = 3\% \times (1 + 3\%)^{10} / (1 + 3\%)^{10} - 1 = 0.12 \]

The Total Cost is the sum of the Capital costs, Operating/Maintenance costs, Overhead costs, and the Enforcement/Compliance costs.
Total Cost = Capital costs + Operating/Maintenance costs + Overhead + Enforcement/Compliance costs

Total Cost = 6,000 + 8,000 + 4,000 + 500 = $18,500

The Annualized Cost is calculated by adding the product of the Capital Recovery Factor and the Capital costs to the Operating/Maintenance costs and the Overhead costs and the Enforcement/Compliance costs:

Annualized Cost = (CRF x Capital costs) + Operating/Maintenance + Overhead costs + Enforcement/Compliance costs

Annualized Cost = (0.12 x 6,000) + 8,000 + 4,000 + 500 = $13,200

**Step 6. Calculate Cost Effectiveness.** Cost effectiveness is calculated by dividing the annualized cost by the emissions reduction. The emissions reduction is determined by subtracting the controlled emissions from the uncontrolled emissions:

Cost effectiveness = Annualized Cost/ (Uncontrolled emissions – Controlled emissions)

Cost effectiveness for PM10 emissions = $13,203/ (45.4 – 20.4) = $530/ton
Cost effectiveness for PM2.5 emissions = $13,203/ (7.0 – 3.1) = $3,450/ton

**6.9 References**


32. Bill Roddy. Fresno County Air Pollution Control District. personal communication, 1976.


