Emission Factor Documentation for AP-42
Section 13.2.2

Unpaved Roads

Final Report

For U. S. Environmental Protection Agency
Office of Air Quality Planning and Standards
Emission Factor and Inventory Group

EPA Purchase Order 7D-1554-NALX

MRI Project No. 4864

September 1998

Emission Factor Documentation for AP-42
Section 13.2.2

Unpaved Roads

Final Report

For U. S. Environmental Protection Agency
Office of Air Quality Planning and Standards
Emission Factor and Inventory Group
Research Triangle Park, NC 27711

Attn: Mr. Ron Myers (MD-14)
Emission Factor and Inventory Group

EPA Purchase Order 7D-1554-NALX

MRI Project No. 4864

September 1998

NOTICE

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Contract No. 68-D2-0159 and Purchase Order No. 7D-1554-NALX to Midwest Research Institute. It has been reviewed by the Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, and has been approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

PREFACE

This report was prepared by Midwest Research Institute (MRI) for the Office of Air Quality Planning and Standards (OAQPS), U. S. Environmental Protection Agency (EPA), under Contract No. 68-D2-0159, Work Assignment No. 02 and Purchase Order No. 7D-1554-NALX. Mr. Ron Myers was the requester of the work.

Approved for:

MIDWEST RESEARCH INSTITUTE

Roy Neulicht
Program Manager
Environmental Engineering Department

Jeff Shular
Director, Environmental Engineering
  Department

September 1998

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EMISSION FACTOR DOCUMENTATION FOR AP-42 SECTION 13.2.2
Unpaved Roads

1. INTRODUCTION

The U. S. Environmental Protection Agency (EPA) publishes the document *Compilation of Air Pollutant Emission Factors* (AP-42) as its primary compilation of emission factor information. Supplements to AP-42 have been routinely published to add new emission source categories and to update existing emission factors. AP-42 is routinely updated by EPA to respond to new emission factor needs of EPA, State and local air pollution control programs, and industry.

An emission factor is a value that attempts to relate the representative quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. Emission factors usually are expressed as the weight of pollutant divided by the unit weight, volume, distance, or duration of the activity that emits the pollutant. The emission factors presented in AP-42 may be appropriate to use in a number of situations, such as making source-specific emission estimates for area wide inventories for dispersion modeling, developing control strategies, screening sources for compliance purposes, establishing operating permit fees, and making permit applicability determinations. The purpose of this report is to provide background information from test reports and other information to support revisions to AP-42 Section 13.2.2, Unpaved Roads.

This background report consists of five sections. Section 1 includes the introduction to the report. Section 2 gives a characterization of unpaved road emission sources and a description of the technology used to control emissions resulting from unpaved roads. Section 3 is a review of emission data collection and emission measurement procedures. It describes the literature search, the screening of emission data reports, and the quality rating system for both emission data and emission equations and methods of emission factor determination. Section 4 details how the revised AP-42 section was developed. It includes the review of specific data sets, a description of how candidate the emission equation was developed, and a summary of changes to the AP-42 section. Section 5 presents the AP-42 Section 13.2.2, Unpaved Roads.

Throughout this report, the principal pollutant of interest is PM-10—particulate matter (PM) no greater than 10 μmA (microns in aerodynamic diameter). PM-10 forms the basis for the current National Ambient Air Quality Standards (NAAQS) for particulate matter. PM-10 thus represents the particle size range that is of the greatest regulatory interest. Because formal establishment of PM-10 as the standard basis for the NAAQS occurred in 1987, many earlier emission tests (and in fact the current version of the unpaved road emission factor) have been referenced to other particle size ranges, such as,

TSP Total Suspended Particulate, as measured by the standard high-volume (hi-vol) air sampler. Total suspended particulate, which encompasses a relatively coarse size range, was the basis for the previous NAAQS for PM. Wind tunnel studies have shown that the particle mass capture efficiency curve for the hi-vol sampler is very broad, extending from 100 percent capture of particles smaller than 10 micrometers to a few percent capture of particles as large as 100 micrometers. Also, the capture efficiency curve varies with wind speed and wind direction, relative to roof ridge orientation. Thus, the hi-vol sampler does not provide definitive particle size information for emission factors. However, an effective cutpoint of 30 μm aerodynamic diameter is frequently assigned to the standard hi-vol sampler.

SP Suspended Particulate, which is often used as a surrogate for TSP, is defined as PM with an aerodynamic diameter no greater than 30 μmA. SP may also be denoted as “PM-30.”

PM-2.5 PM with an aerodynamic diameter no greater than 2.5 μmA.

The EPA promulgated new PM NAAQS based on PM-2.5, in July 1997.

Because of the open source nature of unpaved roads, ambient particulate matter samplers are usually most applicable to emission characterization of this source category. Nevertheless, one may adapt traditional stack source sampling methods to unpaved roads. In that case, “total PM” refers to the amount of PM collected in EPA Method 5 plus EPA Method 202 sampling trains. “Total filterable PM” denotes the filter catch in the Method 5 train. Similarly, “PM-10" refers to the sum of the catch in EPA Method 201A and Method 202 trains, while “filterable PM-10" corresponds to the filter catch in Method 201A.

2. SOURCE DESCRIPTION

2.1 SOURCE CHARACTERIZATION[1]

Particulate emissions occur whenever vehicles travel on unpaved roads. Dust plumes trailing behind vehicles on unpaved roads are a familiar sight in rural areas of the United States. Many industrial areas also have active unpaved roads. 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.

2.2 EMISSIONS[1,2]

The emission of concern from unpaved roads is particulate matter (PM) including PM less than 10 microns in aerodynamic diameter (PM-10) and PM less than 2.5 microns in aerodynamic diameter (PM-2.5). 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 correction parameters that characterize (a) the condition of a particular road and (b) the associated vehicle traffic. Parameters of interest in addition to the source activity (number of vehicle passes) include the vehicle characteristics (e.g., vehicle weight), the properties of the road surface material being disturbed (e.g. silt content, moisture content), and the climatic conditions (e.g., frequency and amounts of precipitation).

Dust emissions from unpaved roads have been found to vary directly with the fraction of silt in the road surface material. Silt consists of particles less than 75 μm in diameter, and silt content can be determined by measuring the proportion of loose dry surface dust that passes through a 200-mesh screen, using the ASTM-C-136 method.

2.3 HISTORY OF THE UNPAVED ROAD EMISSION FACTOR EQUATION IN AP-42

The current version of the AP-42 unpaved road emission factor equation for dry conditions has the following form:[1]

$$E = k\ 5.9 \left(\frac{s}{12}\right)\left(\frac{S}{30}\right)\left(\frac{W}{3}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5} \tag{2-1}$$

where:

E = Emission factor, pounds per vehicle-mile-traveled, (lb/VMT)
k = Particle size multiplier (dimensionless)
s = Silt content of road surface material (%)
S = mean vehicle speed, miles per hour (mph)
W = mean vehicle weight, ton
w = mean number of wheels (dimensionless)

The AP-42 discusses how Equation 2-1 can be extrapolated to annual conditions through the simplifying assumption that emissions are present at the “dry” level on days without measurable precipitation and conversely, are absent on days with more than 0.01 in. (0.254 mm) of precipitation. Thus, the emission factor for annual conditions is:

$$E = k\ 5.9 \left(\frac{s}{12}\right)\left(\frac{S}{30}\right)\left(\frac{W}{3}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left(\frac{365-p}{365}\right) \tag{2-1a}$$

where all quantities are as before and:

p = number of days with at least 0.254 mm (0.01 in.) of precipitation per year

The particle size multiplier "k" for different particulate size ranges is shown below.

Aerodynamic Particle Size Multiplier (k) for Equation 2-1

$\leq$30µm[a]	$\leq$30µm	$\leq$15µm	$\leq$10µm	$\leq$5µm	$\leq$2.5µm
1.0	0.80	0.50	0.36	0.20	0.095

[a]Stoke's diameter

The earliest emission factor equation for unpaved roads first appeared in AP-42 in 1975. The current version of the emission factor equation appeared in 1983 as part of Supplement 14 to the third edition of AP-42.

The earliest version of the unpaved road emission factor equation included the first two correction terms shown in Equation 2-1 (i.e., silt content and mean vehicle speed). However, the data base for that version was limited to tests of publicly accessible unpaved roads travelled by light-duty vehicles and had a small range of average travel speeds (30 to 40 mph).[3] Subsequent emission testing (especially roads at iron and steel plants) expanded the ranges for both vehicle weight and vehicle speed. In 1978, a modified equation that included silt, speed, and weight was published in an EPA report.[4] In 1979, the current version (Equation 2-1) was first published;[5] it incorporated a slight reduction in the exponent for vehicle weight and added the wheel correction term.

Although the emission factor equation for unpaved roads has been modified over the past 20 years, all versions have important common features. All were developed using multiple linear regression of the suspended particulate emission factor against correction parameters that describe source conditions. The silt content has consistently been found to be of critical importance in the predictive equation. The first version of the predictive equation (and each subsequent refinement) included a roughly linear (power of 1) relationship between the emission factor and the road surface silt content.[a]

In addition to the unpaved road emission factor equation discussed above, other studies have been undertaken to model emissions from unpaved road vehicular traffic. For example, the 1983 background

---

[a] Note that during the 1970's, the exponent for the silt content was rounded to unity because of the greater computational ease. Recall that this equation predated inexpensive calculators with "x to the y" capability.

document for this section of AP-42 lists three other candidate emission factor equations.[6] Equation 2-1 was recommended over the other candidates on the basis of its wider applicability.

Additional studies addressed emissions from restricted classes of unpaved roads. In particular, a 1981 report included separate emission factors for (a) light-to medium-duty traffic, and (b) haul trucks on unpaved roads for use at western surface coal mines.[7] Neither equation bore resemblance to the generic unpaved road emission factor (Equation 2-1). A 1991 study (described in Section 4 of this report) addressed emissions due to relatively high-speed traffic on publicly accessible roads in Arizona.[2] Furthermore, in response to Section 234 of the Clean Air Act Amendments, the western surface coal mining emission factors were reexamined.[8,9] Results from that study are also described in Section 4.

2.4 EMISSION CONTROL TECHNOLOGY[1,10,11]

Controls to reduce particulate emissions from unpaved roads fall into three general categories as follows: source extent reductions, surface improvements, and surface treatment. Each of the categories is discussed below.

Source extent reductions limit the amount of traffic to reduce particulate emissions. The emissions directly correlate to the vehicle miles traveled on the road. An example of limiting traffic is restricting road use to certain vehicle types. The iron and steel industry, for example, has instituted some employee busing programs to eliminate a large number of vehicle passes during shift changes.

Surface improvements offer a long term control technique. Paving is a surface improvement that is a highly effective control, but can be cost prohibitive especially on low volume roads. From past experience, paving has an estimated 99 percent control efficiency for PM-10. 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 AP-42 Section 13.2.1, requires estimation of the silt loading on the traveled portion of the paved surface, which in turn depends on (a) the intensities of deposition processes that add silt to the surface, and (b) whether the pavement is periodically cleaned.

Other surface improvements include covering the road surface with a new material of lower silt content. For example a dirt road could be covered with gravel or slag. Also, regular maintenance practices, such as grading of gravel roads, help to retain larger aggregate sizes on the traveled portion of the road and thus help reduce emissions. The amount of emissions reduction is tied directly to the reduction in surface silt content.

Surface treatments include control techniques that require reapplication such as watering and chemical stabilization. Watering increases the road surface moisture content, which conglomerates the silt particles and reduces their likelihood to become suspended when a vehicle passes over the road surface. The control efficiency of watering depends upon (a) the application rate of the water, (b) the time between applications, (c) traffic volume during the period, and (d) the meteorological conditions during the period.

Chemical stabilization suppresses emissions by changing the physical characteristics of the road surface. Many chemical unpaved road dust suppressants form a hardened surface that binds particles together. As a result of grinding against the improved surface, the silt content of loose material on a highly controlled surface may be substantially higher than when the surface was uncontrolled. Thus, the predictive emission factor equation for unpaved roads usually cannot be used to estimate emissions from chemically stabilized roads.

Although early studies of unpaved road dust control showed a strong correlation between efficiency and the silt content of the surface material, this correlation was based on the very high (e.g., >90 percent) control efficiencies and very low silt values typically found over the first few days after application. Because these conditions represent only a small, restricted portion of the range of possible conditions encountered during a control application cycle, the high degree of correlation was misleading.

Later study of long-term control indicated no significant correlation between silt content and control efficiency. In addition, fairly high (~50 percent) control efficiencies were found to occur with silt contents at or above the uncontrolled level. Because of these findings, attention turned to the use of the amount of silt per unit area (i.e., “silt loading”) as a performance indicator.

A long-term study of the performance of 4 chemical dust suppressants of interest to the iron and steel industry was conducted through EPA in 1985. This study found that although emission factors varied over an order of magnitude, the silt loading values varied over two orders of magnitude, and did not appear to follow a specific trend with time. Furthermore, the results for the different suppressants tended to be clustered together; this indicated that the various suppressant types did not affect silt loading in the same way.

The control effectiveness of chemical dust suppressants depends on the dilution rate, application rate, time between applications, and traffic volume between applications. Other factors that affect the performance of dust suppressants include the vehicle characteristics (e.g., average vehicle weight) and road characteristics (e.g., bearing strength). The variabilities in the above factors and in individual dust control products make the control efficiencies of chemical dust suppressants difficult to calculate. Past field testing of emissions from controlled unpaved roads has shown that chemical dust suppressants provide a PM-10 control efficiency of about 80 percent when applied at regular intervals.

Because no simple relationship of control efficiency with silt or silt loading could be found to successfully model chemical dust suppressant performance, other types of performance models were developed based on the amount of chemical applied to the road surface. Figure 2-1 presents control efficiency relationships for petroleum resins averaged over two common application intervals, 2 weeks and 1 month.[10]

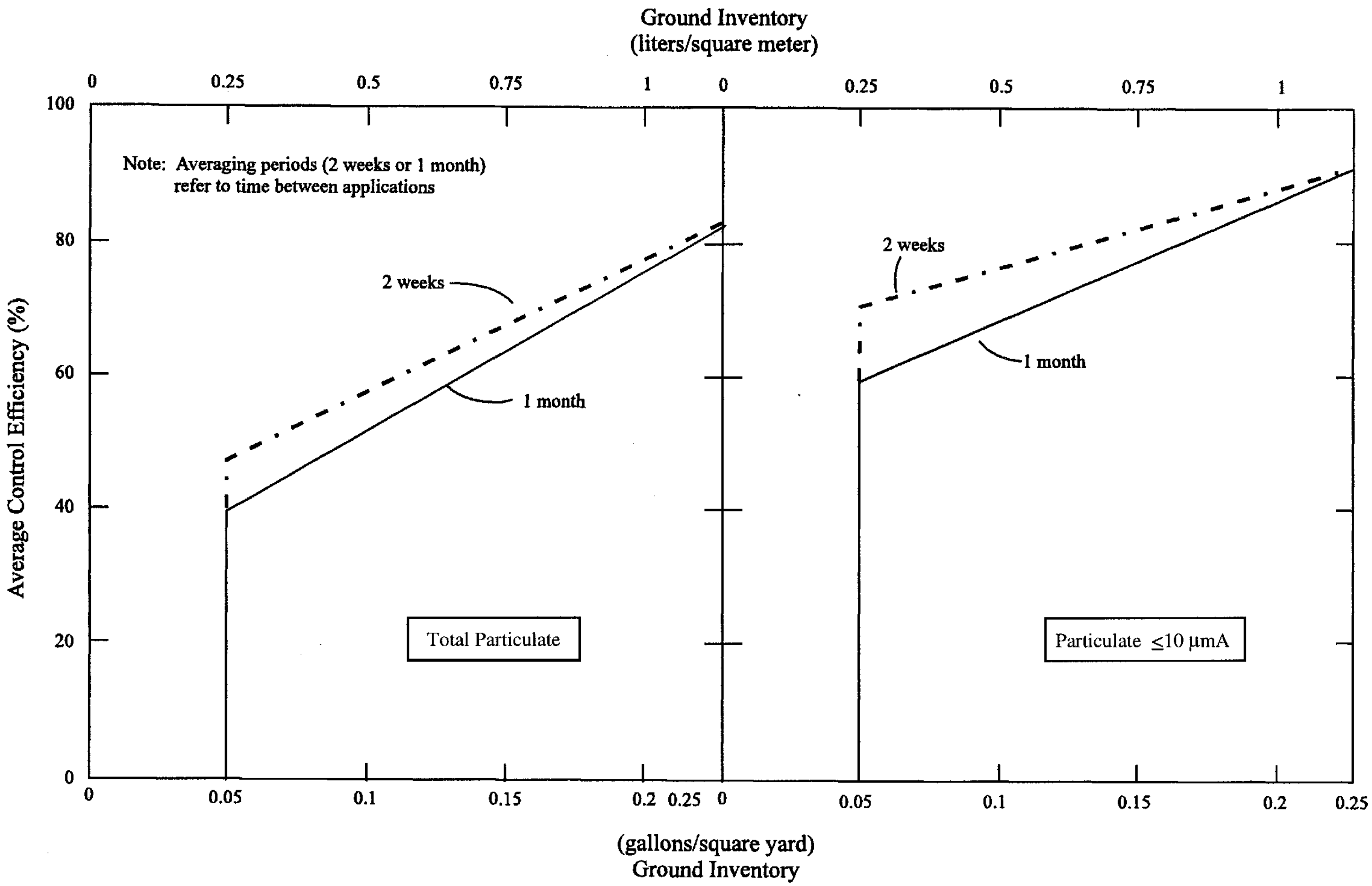


Figure 2-1. Average control efficiencies over common application intervals for chemical dust suppressants.

REFERENCES FOR SECTION 2

1. *Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition,* U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1995.

2. *Unpaved Road Emission Impact, Final Report*, Arizona Department of Environmental Quality, Phoenix, AZ, March 1991.

3. *Development of Emission Factors for Fugitive Dust Sources*, EPA-450/3-74-037, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency , Research Triangle Park, NC, June 1974.

4. *Fugitive Emissions from Integrated Iron and Steel Plants,* EPA-600/2-78-050, Office of Research and Development, U. S. Environmental Protection Agency , Research Triangle Park, NC, March 1978.

5. *Iron and Steel Plant Open Source Fugitive Emission Evaluation*, EPA-600/2-79-103, Office of Energy, Minerals, and Industry, U. S. Environmental Protection Agency , Research Triangle Park, NC, May 1979.

6. *Fugitive Dust Emission Factor Update for AP-42*, EPA Contract No. 68-02-3177, Assignment 25, Industrial Environmental Research Laboratory, U. S. Environmental Protection Agency , Research Triangle Park, NC, September 1983.

7. *Improved Emission Factors for Fugitive Dust from Western Surface Coal Mining Sources,* U. S. Environmental Protection Agency , Research Triangle Park, NC, EPA Contract No. 68-03-2924, Assignment 1, July 1981.

8. *Review of Surface Coal Mining Emission Factors*, EPA-454/R-95-007, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 1991.

9. *Surface Coal Mine Emission Factor Study*, U. S. Environmental Protection Agency, EPA Contract No. 68-D2-0165, Assignment I-06, Research Triangle Park, NC, January 1994.

10. *Fugitive Dust Background Document and Technical Information Document for Best Available Control Measures*, EPA-450/2-92-004, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1992.

11. *Control of Open Fugitive Dust Sources,* EPA-68-02-4395, Assignment 14, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1988.

3. GENERAL DATA REVIEW AND ANALYSIS PROCEDURES

3.1 LITERATURE SEARCH AND SCREENING

To reduce the amount of literature collected to a final group of references from which emission factors could be developed, the following general criteria were used.

1. Emissions data must be from a primary reference.

a. Source testing must be from a referenced study that does not reiterate information from previous studies.

b. The document must constitute the original source of test data. For example, a technical paper was not included if the original study was contained in the previous document. If the exact source of the data could not be determined, they were eliminated.

2. The referenced study must contain test results based on more than one test run.

3. The report must contain sufficient data to evaluate the testing procedures and source operating conditions.

A final set of reference materials was compiled after a thorough review of the pertinent reports, documents, and information according to these criteria.

3.2 METHODS OF EMISSION FACTOR DETERMINATION[2]

Fugitive dust emission rates and particle size distributions are difficult to quantify because of the diffuse and variable nature of such sources and the wide range of particle size involved including particles which deposit immediately adjacent to the source. Standard source testing methods, which are designed for application to confined flows under steady state, forced-flow conditions, are not suitable for measurement of fugitive emissions unless the plume can be drawn into a forced-flow system. The following presents a brief overview of applicable measurement techniques.

3.2.1 Mass Emission Measurements

Because it is usually impractical to enclose open dust sources or to capture the entire emissions plume, only the upwind-downwind and exposure profiling methods are suitable for measurement of particulate emissions from most open dust sources.[3] These two methods are discussed separately below.

The basic procedure of the upwind-downwind method involves the measurement of particulate concentrations both upwind and downwind of the pollutant source. The number of upwind sampling instruments depends on the degree of isolation of the source operation of concern (i.e., the absence of interference from other sources upwind). Increasing the number of downwind instruments improves the reliability in determining the emission rate by providing better plume definition. In order to reasonably define the plume emanating from a point source, instruments need to be located at two downwind distances and three crosswind distances, at a minimum. The same sampling requirements pertain to line sources except that measurement need not be made at multiple crosswind distances.

Net downwind (i.e., downwind minus upwind) concentrations are used as input to dispersion equations (normally of the Gaussian type) to back calculate the particulate emission rate (i.e., source strength) required to generate the pollutant concentration measured. Emission factors are obtained by dividing the calculated emission rate by a source activity rate (e.g., number of vehicles, or weight of material transferred per unit time). A number of meteorological parameters must be concurrently reported for input to the dispersion equations. The test report should describe what constitutes acceptable meteorological conditions.

At a minimum, the wind direction and speed must be recorded on-site and should remain within acceptable ranges. When the upwind/downwind technique is applied to unpaved roads, the test report must describe the mean angle of the wind relative to the road centerline.

As part of a sound test methodology, source activity parameters should be recorded, including the vehicle weights and vehicle speeds. The surface material at the test location (specifically, its silt and moisture contents) should also be characterized following guidance of AP-42 Appendicies C.1 and C.2.

While the upwind-downwind method is applicable to virtually all types of sources, it has significant limitations with regard to development of source-specific emission factors. The major limitations are as follows:

1. In attempting to quantify a large area source, overlapping of plumes from upwind (background) sources may preclude the determination of the specific contribution of the area source.

2. Because of the impracticality of adjusting the locations of the sampling array for shifts in wind direction during sampling, it cannot be assumed that plume position is fixed in the application of the dispersion model.

3. The usual assumption that an area source is uniformly emitting does not allow for realistic representation of spatial variation in source activity.

4. The typical use of uncalibrated atmospheric dispersion models introduces the possibility of substantial error (a factor of three according to Reference 4) in the calculated emission rate, even if the stringent requirement of unobstructed dispersion from a simplified (e.g., constant emission rate from a single point) source configuration is met.

On an even more fundamental level, typical traffic volumes on unpaved roads are far too low to represent the road as a steady, uniformly emitting line source for dispersion analysis purposes. A far better representation (but one which, unfortunately, is not available at this time) would view the unpaved road source as a series of discrete moving point sources.

Just as importantly, it is not clear that “cosine correction” used to account for the effect that an oblique wind direction has on line sources is applicable to the case of an unpaved road. As the plume is released, dispersion occurs in all three cartestian coordinate directions. Only dispersion in the direction parallel to the plume centerline would be negligible. Depending on the direction a vehicle is traveling, an oblique wind would appear to dilute or "concentrate" the plume mass seen by the samplers, as compared to the case of a perpendicular wind. Correction for each plume depends upon the magnitude and direction of the wind relative to vehicle velocity vector.

The other measurement technique, exposure profiling, offers some distinct advantages for source-specific quantification of fugitive emissions from open dust sources. The method uses the isokinetic profiling concept that is the basis for conventional (ducted) source testing. The passage of airborne pollutant immediately downwind of the source is measured directly by means of simultaneous multipoint sampling over the effective cross section of the fugitive emissions plume. This technique uses a mass-balance calculation scheme similar to EPA Method 5 stack testing rather than requiring indirect calculation through the application of a generalized atmospheric dispersion model. As with other testing methodologies, source activity must be recorded as part of a sound exposure profiling program.

For measurement of nonbuoyant fugitive emissions, profiling sampling heads are distributed over a vertical network positioned just downwind (usually 5 m) from the source. If total particulate emissions are to be measured, sampling intakes are pointed into the wind and sampling velocity is adjusted to match the local mean wind speed, as monitored by anemometers distributed over heights above ground level.

Note that, because the test method relies on ambient winds to carry emissions to the sampling array, acceptance criteria for wind speed/direction are necessarily based on antecedent monitoring. That is, the immediate past record is used to determine acceptability for the current or upcoming period of time. As a practical matter, this means that wind monitoring must be conducted immediately before starting an exposure profiling test. The test methodology must also present what guidelines govern stopping/suspending a test for unacceptable wind conditions. For example, testing should be suspended if the angle between the mean wind direction and the perpendicular to the road centerline exceeds 45° for two consecutive 3- to 10-min averaging period. Similarly, testing should be suspended if the mean wind speed falls below 4 mph or exceeds 20 mph for more than 20 percent of the test duration.

The size of a sampling grid needed to conduct exposure profiling tests of an unpaved road depends on several factors, including size/speed of the vehicles traveling the road; expected wind speed; width of the road; and the sampler separation distance from the road. Particulate sampling heads should be symmetrically distributed over the concentrated portion of the plume containing roughly 90 percent of the total mass flux (exposure). In general, the best way to judge the sampling height is to view the plumes being generated from vehicle passes over the road. Past field studies using exposure profiling also provide a good means to establish the necessary size for the sampling grid.

Grid size adjustments may be required based on the results of preliminary testing. To be reasonably certain that one is capturing the entire plume, one needs to demonstrate that the concentration (or, more to the point, the mass flux) decreases near the top of the sampling array. As a practical matter, this means that individual samplers be deployed so that results can be compared from one height to the next. Specifically, use of a manifold to (a) collect air samples at different heights but (b) to route the emissions to a common duct for measurement cannot provide direct evidence of the sufficient height of the sampling array.

Use of dispersion algorithms to determine sampling heights suffers from the same limitations as noted earlier in connection with the upwind/downwind method. That is, typical traffic volumes on unpaved roads are far too low to represent the road as a steady, uniformly emitting line source for dispersion purposes. Just as importantly, it is not clear that "cosine correction" used to account for the effect that an oblique wind direction has on line sources is applicable to the case of an unpaved road.

To calculate emission rates using the exposure profiling technique, a conservation of mass approach is used. The passage of airborne particulate (i.e., the quantity of emissions per unit of source activity) is obtained by spatial integration of distributed measurements of exposure (mass/area) over the effective cross section of the plume. The exposure is the point value of the flux (mass/area/time) of airborne particulate integrated over the time of measurement.

3.2.2 Emission Factor Derivation

Usually the final emission factor for a given fugitive source operation, as presented in a test report, is derived simply as the arithmetic mean of the individual emission factors calculated from each test of that source. Frequently, test reports present the range of individual emission factor values.

Although test reports often present an arithmetic mean emission factor for a single specific source, it is important to recognize that the population of all unpaved road emission factors is better characterized as log-normally than as (arithmetic) normally distributed. That is to say, the logarithms of the emission factor are themselves normally distributed. This can be seen in Figures 3-1 and 3-2, which present normal probability plots for both a set of PM-10 unpaved road emission factors and the logarithms of the factors. Note that the plot of the log-transformed data results in a straight line, which indicates normality. In Figures 3-1 and 3-2 the ordinate (y-axis) is sometimes termed the "z-score." The z-score is found by ranking the data in ascending order and dividing each value's rank by the total number N of data points:

Proportion = (RANK - 0.5)/N

The z-score represents the value of the standard normal distribution (i.e., mean equal to 0 and a standard deviation of 1) whose cumulative frequency equals the proportion found. In practical terms, a sample from a normally distributed population will exhibit a reasonably straight line in this type of plot.

To characterize emissions from unpaved roads, one could use the geometric mean emission factor (i.e., the arithmetic mean of the log-transformed data). However, attempting to characterize emissions from data spanning several orders of magnitude, from extremely large mine haul trucks to light-duty vehicles on county roads, with a single valued emission factor would be futile. Alternatively, one could construct a series of different single-valued mean emission factors, with each mean corresponding to a different category of unpaved roads. For example, one might derive a factor for use with passenger cars on rural roads, another factor for haul trucks, and a third for plant traffic at an industrial facilities. This "subcategory mean" approach, as applied to emissions from unpaved roads, has several drawbacks.

The approach ignores the similarities in the dust-emitting process between subcategories of unpaved road travel. Despite the contrast in scale between haul trucks and small vehicles, the general physical process is the same. The vehicle's tires interact with the surface material, directly injecting particles into the atmosphere while at the same time pulverizing the material. Furthermore, the passage of the vehicle results

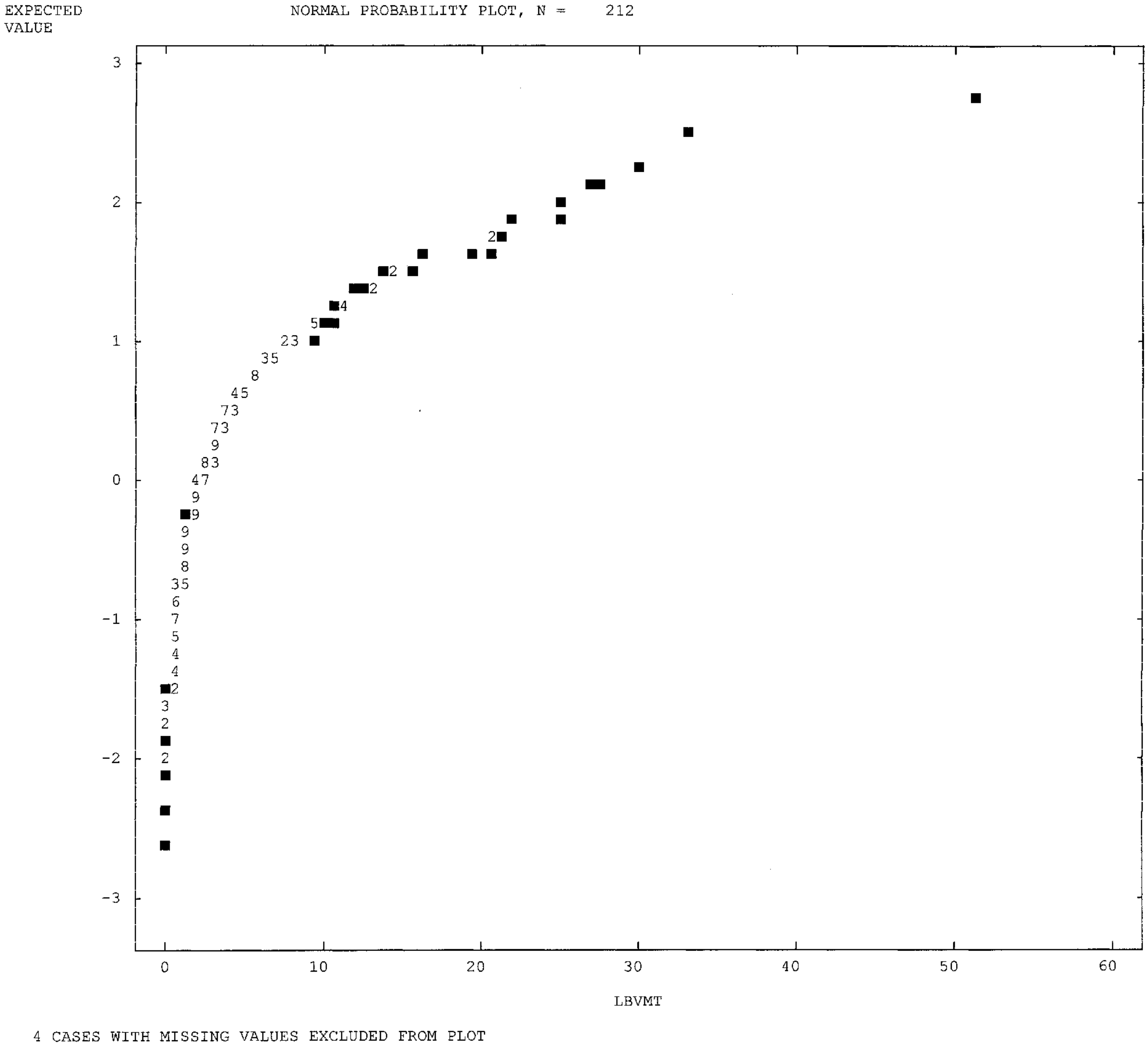
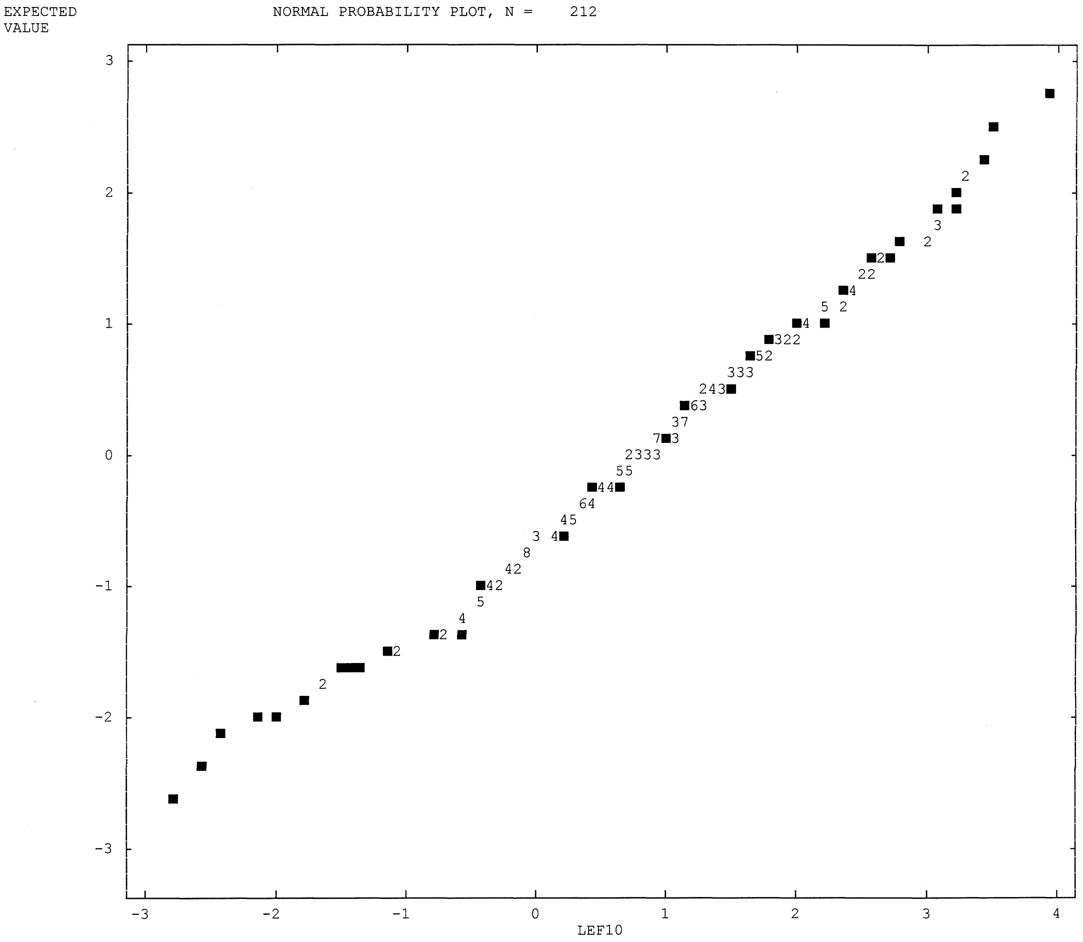


Figure 3-1. Normal probability plot for PM-10 unpaved road emission factors.



4 CASES WITH MISSING VALUES EXCLUDED FROM PLOT

Abscissa consists of natural logarithm of emission factor in lb/vmt.

Figure 3-2. Normal probability plot for logarithms of PM-10 unpaved road emission factors.

in a wake which also entrains particulate matter. Admittedly, the intensity of any process will depend on many factors, such as: vehicle weight, number of wheels, tread design, tire footprint pressure, clearance height, vehicle speed. The approach undertaken in this study (as described later in this section) attempts to capture the essential traffic differences in a few easily quantified vehicle parameters.

Beyond variations in vehicle scale, unless one devises many different classifications, the "subcategory mean" technique cannot capture important regional or other differences. For example, an emission factor applied throughout the United States for passenger cars on rural roads would necessarily smear any differences in emissions between arid western states and those in the wetter, eastern part of the country. Beside "east" and "west," one could also distinguish between: improved/unimproved and well/poorly maintained road surfaces. No matter how many classifications are chosen, partitioning emission test data into finely divided categories reduces the amount of data available to develop each factor. The practical result from this fine subdivision is to lower the confidence in any result obtained from the analysis.

As an alternative to a single valued mean, an emission factor may be presented in the form of a predictive equation derived by regression analysis of test data. The general method employed in regression anlaysis is to first examine the physical forces that affect the dependent variable, to construct an empirical model reflective of those forces, then to use regression to provide a best fit. Such an equation mathematically relates emissions to parameters which characterize those measurable physical parameters having the most affect on the emissions. Possible parameters considered may be grouped into three categories:

1. Measures of source activity or energy expended (e.g., the speed, number of wheels, and weight of vehicles traveling on an unpaved road). As a practical matter useful vehicle-related parameters should be observable at a distance under normal traffic conditions. Most secondary parameters such as tire size, pressure, etc., are correlated with gross vehicle characteristics such as vehicle weight as related to the type of vehicle (light duty automobile, tractor trailer, etc.).

2. Properties of the material being disturbed (e.g., the content of suspendable fines in the surface material on an unpaved road or the moisture content of the surface material).

3. Climatic parameters (e.g., number of precipitation-free days per year during which emissions tend to be at a maximum).

An emission factor equation is useful if it is successful in “explaining” much of the observed variance in emission factor values on the basis of corresponding variances in specific source parameters. This enables more reliable estimates of source emissions on a site-specific basis. In general, an equation’s success in explaining variance is gauged by the R-squared value. If an equation has an R-squared value of 0.47, then it is said to “explain” 47 percent of the variance in the set of emission factors.

It should be noted, however, that a high value of R^2 may sometimes prove misleading in developing an emission factor equation for a particular data set. For example, an equation may be “fine tuned” to the developmental data set by including an additional correction parameter, but in a manner that is contrary to the physical phenomena of the dust generation process. This was illustrated in a field study conducted for the Arizona Department of Environmental Quality (as described in Section 4) that found that inclusion of moisture and silt content as correction parameters would require that they enter into the equation in a manner opposite to common sense. That is to say, emissions would increase with increasing moisture content and would decrease with increasing silt content. In that instance, it is important to recognize that the goal of an emission factor equation is not to provide a near-perfect fit to the emission measurements in the developmental data base, but rather to provide reasonably reliable estimates of emissions for situations where no test data are available.

A generic emission factor equation is one that is developed for a source operation defined on the basis of a single dust generation mechanism that crosses industry lines. Clearly, vehicle travel over unpaved roads is not only a common operation in almost all industries but also represents a general, public source of particulate emissions.

Unpaved road source conditions encompass extreme variations. For example, average vehicle weights on unpaved roads (ranging from country roads to mining haul roads) easily span two orders of magnitude. Furthermore, there is also a wide range in surface material properties. Values for silt and moisture content from the available test data span one and two orders of magnitude, respectively. Not surprisingly, these correction parameters (like the emission factor values) are better characterized by a log-normal rather than (arithmetic) normal distribution.

Furthermore, normal and log-normal distributions appear to fit other vehicle-related variables (speed and number of wheels) equally well. Because standard tests of significance assume normal parent populations, regression of log-transformed data is far more appropriate than regression of untransformed values. The log-linear regression results in a multiplicative model.

To establish its applicability, a generic equation should be developed from test data obtained in different industries. As will be discussed in Section 4, the approach taken to develop a new unpaved road equation has been to combine (to the extent possible) all emission tests of vehicles traveling over an unpaved surface. The combination is made without regard to previous groupings in AP-42. In particular, tests at surface coal mines are combined with tests of unpaved roads within other industries and tests of publicly accessible unpaved roads.

3.3 EMISSION DATA AND EMISSION FACTOR QUALITY RATING SCHEME USED FOR THIS SOURCE CATEGORY[1,2,5]

As part of the analysis of the emission data, the quantity and quality of the information contained in the final set of reference documents were evaluated. The uncontrolled emission factor quality rating scheme used for this source category represents a refinement of the rating system developed by EPA for AP-42 emission factors. The scheme entails the rating of test data quality followed by the rating of the emission factor(s) developed from the test data, as described below.

In the past, test data that were developed from well documented, sound methodologies were viewed equally and assigned an A rating. Although side-by-side studies would better define the differences in precision between upwind/downwind and profiling methodologies, historical experience has granted a greater degree of confidence in the ability of profiling to characterize the full particulate emissions plume. In this document, test data using sound, well documented profiling methodologies were assigned an A rating. Test data using sound, well documented upwind/downwind methodologies were assigned a B rating.

In evaluating whether an upwind-downwind sampling strategy qualifies as a sound methodology, the following minimum test requirements are used. At least five particulate measuring devices must be operated during a test, with one device located upwind and the others located at two downwind and three crosswind distances. The requirement of measurements at crosswind distances is waived for the case of line sources. Also wind direction and speed must be monitored concurrently on-site.

For upwind/downwind testing, it is generally assumed wind speed and direction are constant. To maintain a likeness of constant conditions, the downwind sampler should be shut down when the wind speed drops below 75 percent or raises above 125 percent of the predetermined design speed for periods longer than 3 minutes. Once the wind speed has returned to the acceptble range of 90 percent to 110 percent for 2 minutes, the downwind sampler should be restarted. Samplers should also be shut down when the wind direction varies by 10° or more from the predetermined design direction for longer than 3 minutes. Once the wind direction has returned to the acceptable range for two minutes, the samplers should be restarted. General procedure includes shutting down the upwind sampler during the same periods the downwind samples are shut down.[5]

The minimum requirements for a sound exposure profiling program are the following. A one-dimensional, vertical grid of at least three samplers is sufficient for measurement of emissions from an unpaved road. At least one upwind sampler must be operated to measure background concentration, and wind speed must be measured on-site.

As an alternative to discrete downwind sampling units, a manifold system comprising several sampling points may be used. The mass collected at different heights is ducted to a common tube where stack sampling methods can be applied. A fundamental difference between the use of discrete samplers and a manifold is the need in the latter case to demonstrate plume capture. In other words, the discrete sampling approach directly demonstrates that concentration (or, more to the point, the mass flux) decreases near the top of the sampling array. Because the manifold approach, on the other hand, integrates samples collected at different heights, it cannot provide direct evidence of plume capture. Should the manifold approach be adopted, a minimum of 4 sampling heights should be used for unpaved road testing. In addition, the test report must address the issues related to capture of the entire plume. Furthermore, because wind speed increases with height, the test report must also discuss isues of how intake velocities at different points were selected and controlled to account for the variation in mass flux due simply to wind speed.

For a sound exposure profile operation, several test parameters must remain in predetermined ranges including wind direction, wind speed, precipitation, and source conditions. Mean wind direction during sampling should remain within 45° of perpendicular to the path of the moving point source for 90 percent of the 10 min averaging periods. The mean wind speed should not move outside of the 4 to 20 mph range more than 20 percent of the sampling period. Rainfall must not ensue during the equipment set-up or during sampling for uncontrolled conditions. The predetermined criteria for source conditons (e.g., uncontrolled surface conditions, change from normally maintained road, unusual traffic, truck spill) should be maintained.

Neither the upwind-downwind method nor the exposure profiling method can be expected to produce A-rated emissions data when applied to large, poorly defined area sources, or under very light and variable wind flow conditions. In these situations, data ratings based on degree of compliance with minimum test system requirements were reduced one letter.

It is critically important in either the upwind/downwind or exposure profiling method that the unpaved road is uniformly emitting along the length of the road. In practical terms, this generally requires that

* The road is straight or very gently curving over a distance that is much greater than the distance to the downwind samplers.

* Vehicles do not typically start or stop moving in the general vicinity of the sampling array.

* In the case of heavy-duty vehicles, there is no need to downshift or otherwise cause substantial diesel emissions near the test site.

It is also important to note that neither upwind-downwind nor exposure profiling interfere with plume development or dispersion by forcing or blocking the air flow. Instead, the PM travels "naturally due to vehicle wakes and ambient winds toward the sampling array

After the test data supporting a particular single-valued emission factor are evaluated, the criteria presented in Table 3-1 are used to assign a quality rating to the resulting emission factor. The collection and reporting of activity and process information such as road surface silt content, moisture content, and average vehicle weight are also considered in the evaluation. These criteria were developed to provide objective definition for (a) industry representativeness and (b) levels of variability within the data set for the source category. The rating system obviously does not include estimates of statistical confidence, nor does it reflect the expected accuracy of fugitive dust emission factors relative to conventional stack emission factors. It does, however, serve as a useful tool for evaluation of the quality of a given set of emission factors relative to the entire available fugitive dust emission factor data base.

TABLE 3-1. QUALITY RATING SCHEME FOR SINGLE-VALUED EMISSION FACTORS

Code	No. of test sites	No. of tests per site	Total No. of tests	Test data variability[a]	Adjustment for EF rating[b]
1	≥3	≥3	-	< F2	0
2	≥3	≥3	-	> F2	-1
3	2	≥2	≥5	< F2	-1
4	2	≥2	≥5	> F2	-2
5	-	-	≥3	< F2	-2
6	-	-	≥3	> F2	-3
7	1	2	2	> F2	-3
8	1	2	2	> F2	-4
9	1	1	1	-	-4

[a] Data spread in relation to central value. F2 denotes factor of two.

[b] Difference between emission factor rating and test data rating.

Minimum industry representativeness is defined in terms of number of test sites and number of tests per site. These criteria were derived from two principles:

1. Traditionally, three tests of a source represent the minimum requirement for reliable quantification.
2. More than two plant sites are needed to provide minimum industry representativeness.

The level of variability within an emission factor data set is defined in terms of the spread of the original emission factor data values about the mean or median single-valued factor for the source category. The fairly rigorous criterion that all data points must lie within a factor of two of the central value was adopted. It is recognized that this criterion is not insensitive to sample size in that for a sufficiently large test series, at least one value may be expected to fall outside the factor-of-two limits. However, this is not considered to be a problem because most of the current single-valued factors for fugitive dust sources are based on relatively small sample sizes.

Development of quality ratings for emission factor equations also requires consideration of data representativeness and variability, as in the case of single-value emission factors. However, the criteria used to assign ratings (Table 3-2) are different, reflecting the more sophisticated model being used to represent the test data. As a general principle, the quality rating for a given equation should lie between the test data rating and the rating that would be assigned to a single-valued factor based on the test data. The following criteria are used to determine whether an emission factor equation has the same rating as the supporting test data:

1. At least three test sites and three tests per site, plus an additional three tests for each independent parameter (P) in the equation.
2. Quantitative indication that a significant portion of the emission factor variation is attributable to the independent parameter(s) in the equation.

TABLE 3-2. QUALITY RATING SCHEME FOR EMISSION FACTOR EQUATIONS

Code	No. of test sites	No. of tests per site	Total No. of tests[a]	Adjustment for EF rating[b]
1	≥3	≥3	≥(9 + 3P)	0
2	≥2	≥3	≥3P	-1
3	≥1	-	<3P	-1

[a] P denotes the number of correction parameters in the emission factor equation.
[b] Difference between emission factor rating and test data rating.

Loss of quality rating in the translation of these data to an emission factor equation occurs when these criteria are not met. In practice, the first criterion is far more influential than the second in rating an emission factor equation, because development of an equation implies that a substantial portion of the emission factor variation is attributable to the independent parameter(s). As indicated in Table 3-2, the rating is reduced by one level below the test data rating if the number of tests does not meet the first criterion, but is at least three times greater than the number of independent parameters in the equation. The rating is reduced two levels if this supplementary criterion is not met.

The rationale for the supplementary criterion follows from the fact that the likelihood of including false relationships between the dependent variable (emissions) and the independent parameters in the equation increases as the ratio of the number of independent parameters to sample size increases. For example, a four parameter equation based on five tests would exhibit perfect explanation ($R^2 = 1.0$) of the emission factor data, but the relationships expressed by such an equation cannot be expected to hold true in independent applications.

REFERENCES FOR SECTION 3

1. *Procedures for Preparing Emission Factor Documents*, EPA-454/R-95-015, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1997.

2. *Emission Factor Documentation for AP-42, Section 11.2.5 and 11.2.6, Paved Roads*, EPA-68-D0-0123, Assignment 44, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1993.

3. *Fugitive Dust Emissions Factor Update for AP-42*, EPA 68-02-3177, Assignment 25, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1970.

4. *Workbook of Atmospheric Dispersion Estimates, AP-26*, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1970.

5. *Protocol for the Measurement of Inhalable Particulate Fugitive Emissions from Stationary Industrial Sources*, EPA Contract 68-02-3115, Task 114, Process Measurements Branch, Industrial Environmental Research Laboratory, Environmental Protection Agency, Research Triangle Park, NC, March 1980.

4. REVIEW OF SPECIFIC TEST REPORTS

4.1 INTRODUCTION

A total of 12 field test reports were identified as sources of either potentially directly useful data on PM-10 emissions from unpaved roads or data that could be used to interpolate the necessary PM-10 information. These reports are described in Section 4.2.

4.2 REVIEW OF SPECIFIC DATA SETS

Profiling methodologies are generally used for these tests and include the following test parameters: (a) downwind test equipment should be located approximately 5 meters from the source, (b) background equipment should be placed approximately 15 meters upwind of the source, (c) wind direction should remain within 45° of perpendicular to the path of the moving point source for 90 percent of the 10 min averaging periods during testing, (d) mean wind speed should not move outside of the 4 to 20 mph range more than 20 percent of the sampling period, (e) and no wind flow disturbances should exist immediately upwind or downwind of the testing location. When following standard testing methodologies some vehicle heights may exceed the height of the sampling equipment typically about 7 m; however, the fact that the emissions originate at the road surface and the emission plume density can be characterized as decreasing with height indicates the total plume can be estimated. Vehicle heights are not generally reported in the source test reports. Analysis for silt content and moisture content of the road surface follow methodologies described in Appendix C.1 and Appendix C.2 of the AP-42. Variations from these generally accepted test parameters or any other nontraditional testing parameters are discussed within the individual test report reviews.

For this study, a well documented report not only discussed the test methodology but also included source condition and activity information. With each report description both a summary of all reported particulate sizes and individual PM-10 test data are presented. From these test reports, all uncontrolled tests and all water tests were included in the emission equation development unless noted otherwise. Chemical stabilizers were not included in the emission equation development discussed in Section 4-3.

4.2.1 Reference 1

Midwest Research Institute, "Letter Report of Field Tests, Road Sampling," for Washoe County District Health Department, Reno, NV, August 1996.

This letter report presents results of sampling of an unpaved road and a paved road in Washoe County, Nevada, in May and June of 1996. The study was undertaken to provide site-specific PM-10 test data to supplement a yearlong road surface sampling program. Also, the study supported ongoing EPA reviews of the PM-2.5 fraction of PM-10 emissions from paved and unpaved roads.

Exposure profiling was employed downwind to measure particulate emissions. For the unpaved road tests, three hi-vol samplers each fitted with a cyclone preseparator were located downwind of the test road at heights of 1, 3, and 5 m. Reference method PM-10 samplers were located upwind and downwind of the roadway as well. Road widths were not reported. Wind speed was also recorded at heights of 1, 3, and 5 m.

Four unpaved road tests and three paved road tests were completed. The unpaved road tests used only lightweight captive vehicles at low vehicle speeds. Although the testing methodology was sound, the conciseness of the letter report warranted a “B” rating of the test data. Table 4-1 presents summary test data and Table 4-2 presents detailed test information.

4.2.2 Reference 2

Midwest Research Institute, “Improvement of Specific Emission Factors (BACM Project No. 1)” for South Coast AQMD, California, March 1996.

This study developed improved particulate emission factors for construction activities and paved roads in western States. Sampling results for PM-10 are reported from testing in June and July, 1995, at three construction sites located in Nevada and California. Also, surface silt loading measurements were taken from paved roads in four separate areas in Nevada and California.

Exposure profiling was employed for the emission measurements. The downwind profiling arrays contained three high volume air samplers fitted with cyclone preseparators at heights of 1, 3, and 5 m. One high volume air sampler with a cyclone preseparator measured upwind concentrations at a 2 m height. Warm wire anemometers, located at heights of 1 and 5 m, measured wind speed. Road widths were not reported.

The unpaved road testing focused on particulate emissions from scraper travel and light-duty vehicles. Six uncontrolled scraper tests and three uncontrolled light duty vehicle tests were completed. In addition, watering was utilized as a control for two controlled scraper tests. The test data were assigned an “A” rating. Table 4-3 presents summary test data and Table 4-4 presents detailed test information.

4.2.3 Reference 3

Air Control Techniques, “PM10, PM2.5, and PM1 Emission Factors for Haul Roads at Two Stone Crushing Plants,” for National Stone Association, Washington, D.C., November 1995.

This test program presents the results of sampling at two stone crushing plant quarries in August 1995. This study was undertaken to accurately measure PM-10, PM-2.5, and PM-1 emissions from a controlled haul road at a stone quarry. Testing occurred at Martin Marietta’s Garner and Lemon Springs quarries in North Carolina.

The study used what was termed “an upwind-downwind profiling technique.” The test approach relied on the use of a manifold to sample at several heights (up to 30 feet), which constitutes a profiling method. Downwind samples were drawn (approximately isokinetically) into 10 sample nozzles 8 to 10 inches in diameter that joined a single downcomer connected to an 18 in. horizontal duct. The vertical sampling occurred approximately 3 m downwind of the source. The system maintained a total gas flow rate of approximately 2,500 acfm. Sampling occurred along the 18 in. horizontal duct using EPA Method 201A for in-stack measurements of PM-10. Particle distribution measurements were collected with a cascade impactor and a nephelometer. Upwind measurements were made using a hi-vol sampler at a height of 15 ft, a cascade impactor, and a nephelometer placed only a few meters upwind. The roads were 30 ft wide at both test sites. Analysis included polarizing light microscopy (PLM) that measured particles of combustion products. Wind direction was required to be ±60° of perpendicular to the line source.

Three emission tests were completed at both Garner and Lemon Springs. All samples were considered controlled through water application during the test periods. Road watering occurred approximately every 2.5 to 3 hours. The amount of water applied per unit road surface area is not stated. Table 4-5 presents summary test data and Table 4-6 presents detailed test information. Emissions are presented in Table 4-5 as reported in the study; however, the emissions calculation in the study did not adjust for combustion product particles in the upwind measurements. For the development of the AP-42 emission equation, all particulate matter was factored into the emissions.

Although the sampling methodology varied from the more common exposure profiling methods, it was judged satisfactory to capture and measure a representative mass emission from the road. As a result, the Lemon Springs test was assigned an “A” rating. At the Garner test location, a large rock wall that stood immediately behind the downwind sampling site may have interrupted natural wind flows and/or created a local recirculation event. The potential wind obstruction accounted for a “B” rating of the test data at the Garner quarry.

4.2.4 Reference 4

Midwest Research Institute, “Surface Coal Mine Emission Factor Study,” for U. S. EPA, January 1994.

This test report presents results of sampling during September and October 1992 at a surface coal mine near Gillette, Wyoming. This study was undertaken to address issues identified in the Clean Air Act Amendments of 1990 regarding the potential overestimation of the air quality impacts of western surface coal mining. The principal objective was to compare PM-10 field measurements against available emission factors for surface coal mines and revise the factors as necessary.

The study focused on characterizing particulate emissions from line sources such as haul roads and scrapers at a surface mining site. Four haul road sites (No. 1, 1B, 2, and 4) and one scraper site (No. 5) were characterized using downwind exposure profilers for PM-10 fitted with cyclone preseparators, a Wedding PM-10 sampler, and two hi-vol samplers for TSP. The exposure profiling arrays consisted of four samplers located from 1 m to 7 m in height. Upwind concentrations were monitored with a Wedding PM-10 sampler and one cyclone preseparator. Wind direction at one height (3 m) and wind speed at three heights (1 m, 3 m, and 5 m) were recorded at the downwind sites. Additional sampling studies included measuring the near-source particle size distributions using a combination cyclone preseparator and a cascade impactor.

At the five sites a total of 36 PM-10 emission tests were completed. A majority of the tests (34 PM-10 tests) were performed on haul roads. The road width was not reported. The haul road tests spanned a large range of wind speeds from 4.5 mph to 22 mph. Approximately half of these tests were controlled by use of water/surfactant. The water/surfactant provided a control efficiency from 40 to 70 percent for PM-10 and from 30 to 60 percent for TSP. A summary of emissions data is presented in Table 4-7 and detailed test information is presented in Table 4-8. The test data were assigned a rating of A. The report included adequte detail and the methodology meets the requirements for a sound exposure profiling system.

The study also presented an evaluation of the performance of emission factor models in predicting independent emission test data. An emission factor developed specifically for haul roads in the surface coal mining industry (see Equation 4-1) was compared against the "generic" AP-42 unpaved road emission factor (Equation 2-1). The Fourth Edition of AP-42 (September 1988) presented the following PM-30 emission factor for haul trucks in Section 8.24, "Western Surface Coal Mining:"

$$E30 = 0.0067 (w)3.4 (L)0.2 \tag{4-1}$$

where:

E30 = TSP emission factor (lb/vmt)
w = mean number of wheels
L = road surface silt loading (g/m2)

In addition, the performance of an emission factor developed specifically for light-/medium-duty traffic at surface coal mines was also compared against that of the generic model. Section 8.24 in the Fourth Edition of AP-42 (September 1988) presented the following equation (Equation 4-2) for estimating PM-30 emission from light-/medium-duty traffic on unpaved roads at surface coal mines.

$$E30 = 5.79 / (M)4.0 \tag{4-2}$$

where:
E30 = TSP emission factor (lb/vmt)
M = road surface moisture content (%)

It is important to note that, when Equation 2-1 was applied to independent emission test data, the generic emission factor performed as well as or better than emission factors developed specifically for the mining industry. For haul trucks, Equation 4-1 severely underpredicted the measured emission factors. On average, Equation 4-1 underpredicted the independent test data by a factor greater than 5. In contrast, Equation 2-1 tended to overpredict the independent test data, but by a factor of less than 2 on average.

Equation 2-1 also performed reasonably well (within 20 percent on average) when applied to independent tests of light-duty traffic emissions. Although the AP-42 light/medium duty factor provided reasonably accurate (within a factor of 2) estimates in two of three cases, the industry-specific factor overpredicted a third independent test result by a factor of 20. In summary, then, the generic AP-42 emission factor performed at least as well as the industry-specific factors on average and performed substantially better in terms of extreme over/underprediction. As will be discussed in Section 4.3, these findings led to combining emission tests collected over a broad range of source conditions into a single large data set for emission factor development.

4.2.5 Reference 5

Entropy, "PM10 Emission Factors for a Haul Road at a Granite Stone Crushing Plant," for National Stone Association, Washington, D.C., December 1994.

This test report presents test data from measurements at a granite quarry in Knightdale, North Carolina. The testing program occurred in October 1994 and focused on PM-10 emissions from an unpaved haul road.

The testing protocols followed what the report termed a "push-pull method." Four 36-inch diameter circulating fans were utilized on the upwind side of the road and large hoods were located downwind to capture particulate emissions. Two sets of two hoods stacked vertically were located side-by-side. A set of hoods consisted of two hoods each four ft high by seven ft wide with one located 2 ft and the other seven ft above the ground. The road width was 40 ft. Emissions captured in a set of hoods were drawn through a common 12 inch duct and sampled for PM-10 using EPA Method 201A. One hi-vol PM-10 ambient sampler was located upwind of the circulating fans. Wind speed and wind direction were also monitored.

Three controlled tests and four uncontrolled tests were performed. All seven tests utilized both sets of hoods and the results from both sets were averaged for the emission factor calculations. Testing was discontinued when wind speeds exceeded 3 mph. Controlled tests utilized water as the dust suppressant. For the controlled tests, watering occurred on average every 3.6 hr. The water application rate in terms of volume of water applied per unit road surface area was not reported. Table 4-9 presents summary test data and Table 4-10 presents detailed test information.

The push-pull method as described in Reference 5 does not correspond directly to any of the test methods presented in Section 3 of this report. Furthermore, the data reported provide strong evidence that some basic premises underlying unpaved road testing were not met. For example, in three of the seven tests, the concentrations measured by the side-by-side hood differed by a factor of 5 to 7, strongly suggesting either a lack of precision in the testing methodology or that the road under consideration could not be reasonably represented as a uniformly emitting line source.

There are additional concerns about operational features of the push-pull method. Reference 5 describes wind directions up to 80° from perpendicular as acceptable and testing was interrupted if the wind velocity exceeded 3 mph. Testing under low-speed winds or winds with very oblique directions promotes the passage of PM-10 over the short sampling array. In other words, the wind speed/direction acceptance criteria established for the push-pull method actually promote incomplete plume capture, thus resulting in a low bias in the reported emission factors.

Because of the deviations from established acceptable sample methodology and the lack of precision of the push-pull method, the quality highest rating the data could receive (following guidance given in EPA-454/R-95-015, Procedures for Preparing Emission Factor Documents) is "C." Nevertheless, because the operational parameters associated with the method would bias results low, a final quality rating of "D" was assigned.

4.2.6 Reference 6

Midwest Research Institute, "Unpaved Road Emission Impact,"for Arizona Department of Environmental Quality, March 1991.

This study performed field sampling on Arizona rural roads in Pima, Pinal, and Yuma counties. The study also recommended a mathematical model to estimate emissions from unpaved rural roads for arid and semiarid regions, based on a review of historical data as well as Arizona-specific field sampling results. Particle emission sizes of interest in this study were TSP and PM-10. Contrary to expectation, the examination of the historical data base did not find a systematic underprediction of emissions from unpaved roads in the arid portions of the Western United States.

Exposure profiling formed the basis of the measurement technique used at the Arizona sampling sites. For this study, two downwind arrays were deployed 5 m from the road. Each array had three sampling heads located at heights of 1, 3, and 5 m. One downwind unit was fitted with cyclone preseparators. The other downwind unit was equipped with cyclones for half the sampling periods and with standard high volume roofs for the other sampling periods. In addition, one pair each of high volume and dichotomous samplers were operated at a 100 ft downwind distance. No road widths were reported. Upwind measurements were obtained with a vertical array containing two sampling heads, a standard hi-vol sampler, and a dichotomous sampler. Wind speed was measured with warm wire anemometers at two heights (1 and 5 m), and wind direction was measured at a single height.

Vehicle passes were controlled during testing periods and three vehicle speeds were tested (35, 45, and 55 mph). The test data were assigned an "A" rating. Table 4-11 presents summary test data and Table 4-12 presents detailed test information. The report examined how well the data developed in the field tests agreed with the current version of the AP-42 emission factor.

Although the AP-42 equation provided reasonably accurate results when applied to the field tests conducted in this study, another emission factor model was developed. This was justified in the report by differences between typical traffic conditions in Arizona and the basis of the existing AP-42 emission factor. Common travel speeds on rural unpaved roads in Arizona generally fall outside the range of values in the AP-42 model's underlying data base. As a result of the numerous industrial road tests, the data base generally reflected heavier vehicles than are common on rural roads.

4.2.7 Reference 7

Midwest Research Institute, "Roadway Emissions Field Tests at US Steels Fairless Works," for U.S. Steel Corporation, May 1990.

This testing program focused on paved and unpaved road particulate emissions at an integrated iron and steel plant near Philadelphia, Pennsylvania, in November 1989. Exposure profiling was used to characterize one unpaved road (Site "X") located near the center of the facility and used principally as a "shortcut" by light-duty vehicles.

Two tests were conducted using a profiling array, with sample heights from 1.5 m to 6.0 m, that measures downwind mass flux. A high-volume, parallel-slot cascade impactor was employed to measure the downwind particle distribution and a hi-vol sampler was utilized to determine the downwind TSP mass fraction. Road width was not reported. The upwind particle size distribution was determined with a standard high-volume/impactor combination.

Unpaved roads at the plant had been treated with dust suppressant several years before the test program started. As a result, only controlled unpaved road emissions were tested. In other words, this test program did not produce data that could be used for an uncontrolled unpaved road emission equation. The control efficiencies for PM-10 were estimated to be 80 to 90 percent. Control efficiencies for TSP were estimated at 70 percent to 80 percent for the unpaved road chemical suppressants. Table 4-13 presents summary information and Table 4-14 presents detailed test information.

4.2.8 Reference 8

Midwest Research Institute, "Evaluation of the Effectiveness of Chemical Dust Suppressants on Unpaved Roads," for U. S. EPA, EPA-600/2-87-102, November 1987.

This study obtained data on the control effectiveness of common dust suppressants used in the iron and steel industry. Tests were conducted from May through November, 1985, at LTV's Indiana Harbor Works in East Chicago, Indiana, and at Armco's Kansas City Works in Missouri. The testing program measured control performance for five chemical dust suppressants including two petroleum resin products (Coherex® and Generic 2), a emulsified asphalt (Petro Tac), an acrylic cement (Soil Sement), and a calcium chloride solution.

The exposure profiling methodology was utilized for all testing. The downwind exposure profiler contained sampling heads at 1.5, 3.0, 4.5, and 6.0 m. Particle size distribution was determined both upwind and downwind with high volume cascade impactors. Wind speed was monitored at two heights and wind direction was monitored at a single height. Road width was not reported.

A total of 64 tests were completed with seven uncontrolled tests and 57 controlled tests. Suppressants tested at Indiana Harbor Works were initially applied as follows: Petro Tac at 0.44 gal/yd^2, Coherex® at 0.56 gal/yd^2, and calcium chloride at 0.25 gal/yd^2. All five suppressants were tested at the Kansas City Works facility and were initially applied at the following rates: Petro Tac at 0.21 gal/yd^2, Coherex® at 0.21 gal/yd^2, Soil Sement at 0.16 gal/yd^2, Generic at 0.14 gal/yd^2, and calcium chloride at 0.24 gal/yd^2. A rating of "A" was assigned to the data. Testing followed an acceptable methodology and the test report was reasonably well documented.

Total particulate, IP, PM-10, and PM-2.5 were measured during this study. A control efficiency of 50 percent or greater was measured for all chemicals tested. Reapplication of the suppressant resulted in a notably higher level of control. A cost-effectiveness comparison found little variation between suppressants under the test conditions with the exception of a nonfavorable comparison of calcium chloride. Table 4-15 presents summary test data and Table 4-16 presents detailed test information.

The report also discussed the development of models to estimate the control efficiency of different chemical dust suppressants. As was discussed at the end of Section 2, various suppressants do not appear to affect the road surface characteristics in the same way. As a result, this makes performance models based on surface physical parameters unfeasible.

4.2.9 Reference 9

Midwest Research Institute, "Fugitive Emission Measurement of Coal Yard Traffic at a Power Plant," for Confidential Client, December 1985.

This study included seven tests of controlled, unpaved surfaces and four tests of uncontrolled, unpaved surfaces at a power plant. Airborne particle size fractions of interest in this study are total particulate, TSP, IP, PM-10, and PM-2.5. A section of road within the facility's coal yard was tested in August 1985. The road was a permanent ramp up the main stockpile and is used by scrapers for both stockpiling and reclaiming operations.

Particulate emissions were characterized using three downwind exposure profilers, each consisting of four profiling heads at heights of 1.5, 3.0, 4.5 and 6.0 m. (The use of three profiling systems allowed continuous testing after water application by staggering the operation of the samplers.) Three high-volume, parallel-slot cascade impactors equipped with cyclone preseparators were used to characterize the downwind particle size distribution at a height of 2.2 m. One cyclone/impactor combination was used to characterize the upwind particle size distribution and total particulate concentration. Wind speed was measured with warm-wire anemometers at two heights (3 and 6 m) and wind direction was measured at a single height (4.5 m). Also, incoming solar radiation was measured with a mechanical pyranograph. Road width was not reported.

For the controlled tests, the road and surrounding areas were watered for approximately 30 minutes before the start of air sampling. Water was applied to the surface in two passes with a total mean of 0.46 gal/yd^2 (which is equivalent to approximately 0.08 in. of precipitation). The watering was found to provide effective control for 3 to 4 hours with 35 vehicle passes/hr. The control efficiency for TSP and PM-10 averaged 74 and 72 percent over 3 hours, respectively. The control efficiency closely correlated to the surface moisture content, with a higher moisture content increasing the control efficiency. A summary of the emissions data is presented in Table 4-17 and detailed test information is presented in Table 4-18. Because testing followed an accepted test methodology and the results were reasonably well documented, data were rated "A."

4.2.10 Reference 10

Midwest Research Institute, "Critical Review of Open Source Particulate Emission Measurements--Part II - Field Comparison," for Southern Research Institute, August 1984.

This report presents test results from a June, 1984, test at U.S. Steel's Gary Works in Gary, Indiana. The study was conducted to compare exposure profiling methodologies as used by five independent testing organizations to characterize fugitive emissions originating from vehicular traffic. The source tested was a paved road simulated as an unpaved road through the addition of exceptionally high road surface loading (600,000 lb/mile).

An exposure profiler with 5 sampling heads (located at heights of 1.5, 3.0, 4.5, 6.0, and 7.5 m) was used to characterize downwind emissions. Particle sizing was determined using cyclone/impactors located alongside the exposure profiler. Particle sizes of interest in this study included total particulate (TP), <30 μm, <15 μm, <10 μm , and <2.5μm in aerodynamic diameter. One cyclone/impactor and one cyclone were deployed upwind for background measurements. Warm wire anemometers measured wind speed at two heights (1.5 and 4.5 m). The road was reported to be 30 ft wide.

The material used to cover the road surface was a mixture of clay, iron ore and boiler ash. Reasonably good agreement was found between the AP-42 unpaved road model (Equation 2-1) and the emission data collected for the simulated unpaved road. However, the report noted that this was a surprising result for a number of reasons. First, the material (a mixture of clay, iron ore and boiler ash) used to simulate the surface is not typical of unpaved roads. There were also concerns about the homogeneity of the material spread over the five test sections. These problems were further complicated by the fact that the source conditions were not at a steady-state. Instead, the surface loading (mass of material per unit area) steadily decreased throughout the week of emission testing.

4.2.11 Reference 11

Midwest Research Institute "Size Specific Particulate Emission Factors for Uncontrolled Industrial and Rural Roads" for U. S. EPA, January 1983.

This study reports the results of testing conducted in 1981 and 1982 at industrial unpaved and paved roads and at rural unpaved roads. Unpaved industrial roads were tested at a stone crushing facility in Kansas, a sand and gravel processing facility in Kansas, and a copper smelting facility in Arizona. The rural unpaved road testing occurred in Colorado, Kansas, and Missouri. The study was conducted to increase the existing data base for size-specific particulate emissions. The following particle sizes were of specific interest for the study: IP, PM-10, and PM-2.5.

Exposure profiling was utilized to characterize particulate emissions. Five sampling heads, located at heights of up to 5 m, were deployed on the downwind profiler. A standard hi-vol sampler and a hi-vol sampler with a 15 μm size selective inlet (SSI) were also deployed downwind. In addition, two cyclone impactors were operated to measure particle size distribution. A hi-vol sampler, a hi-vol sampler with an SSI, and a cyclone impactor were utilized to characterize the upwind particulate concentrations. Wind speed was monitored with warm wire anemometers. No road width was reported.

A total of 18 paved road tests and 21 unpaved road tests were completed. The test data were assigned an "A" rating. Eleven industrial unpaved road tests were conducted as follows: five unpaved road tests at the stone crushing plant, three unpaved road tests at the sand and gravel processing plant, and three unpaved road tests at the copper smelting plant. For rural unpaved roads, six tests were conducted on roads with a crushed limestone surface in Kansas, four tests were conducted on dirt roads in Missouri, and two tests were conducted on gravel roads in Colorado. Rural road tests only measured emissions from light duty vehicles at speeds from 25 to 40 mph. The industrial road tests were conducted with medium duty vehicles at the stone crushing and copper smelting plants and heavy duty vehicles at the sand and gravel processing facility. Table 4-21 presents summary test data and Table 4-22 presents detailed test information.

4.2.12 Reference 12

Midwest Research Institute, "Iron and Steel Plant Open Source Fugitive Emission Control Evaluation," for U. S. EPA, August 1983.

This test report centered on the measurement of the effectiveness of different control techniques for particulate emissions from open dust sources in the iron and steel industry. The test program was performed at two integrated iron and steel plants, one located in Houston, Texas, and the other in Middletown, Ohio. Water and petroleum resin (Coherex®) were used to reduce emissions from traffic on unpaved roads. Control techniques to reduce emissions from paved roads and coal storage piles were also evaluated. Particle emission sizes of interest in this study were total particulate (TP), IP, and PM-2.5.

The exposure profiling method was used to measure unpaved road emissions at Armco's Middletown Iron and Steel plant. For this study, one downwind profiler with four or five heads located at heights of 1 to 5 m was deployed. Two high volume parallel slot cascade impactors samplers, one at 1m and the other at 3m, measured the downwind particle size distribution. A standard hi-vol sampler and an additional hi-vol sampler fitted with a size selective inlet (SSI) were located downwind at a height 2 m. One standard hi-vol sampler and two hi-vol samplers with SSIs were located upwind for background collections. The road width was not reported.

Nineteen unpaved road tests for controlled and uncontrolled emissions were performed. Testing included 10 runs of heavy-duty traffic (>30 tons) and 9 runs of light-duty traffic (<3 tons). Six heavy duty traffic tests were controlled and four were uncontrolled, whereas, the light-duty traffic had five controlled tests and four uncontrolled tests. The testing methodology was assigned an "A" rating, although a lack of reported moisture data downgraded the report to a "B" rating. Uncontrolled and watered tests were used in the exploratory development described in Section 4.3; however, due to the lack of reported moistures the data were not included in the final emission factor equation. Table 4-23 presents summary test data and Table 4-24 presents detailed test information.

For heavy-duty traffic, a 17 percent solution of Coherex® in water applied at a rate of 0.19 gal/yd^2, provided an average control efficiency of 95.7 percent for TP, 94.5 percent for IP, and 94.1 percent for PM-2.5 over a 48 hr period. Water was applied at a rate of 0.13 gal/yd^2 and, ½ hour after application, was found to decrease emissions by 95 percent for all particles. Control efficiencies 4.4 hours after the water applications were 55.0 percent for TP, 49.6 percent for IP, and 61.1 percent for PM-2.5.

A 17 percent solution of Coherex® in water was the only control applied during testing for the light-duty traffic. The Coherex® solution was applied at a rate of 0.19 gal/yd^2 and, 51 hr after application, provided a control efficiency of 93.7 percent for TP, 91.4 percent for IP, and 93.7 percent for PM-2.5.

4.2.13 Reference 13

Midwest Research Institute, "Extended Evaluation of Unpaved Road Dust Suppressants in the Iron and Steel Industry,"for U. S. EPA, October 1983.

This study centered on the reduction of particulate emissions for various dust suppressants used on unpaved roads in the iron and steel industry. Long-term control effectiveness of the dust suppressants was determined through testing at iron and steel plants located in East Chicago, Indiana and Kansas City, Missouri. Water, an emulsified asphalt, and a petroleum resin were the dust suppressants used. Particle emission sizes of interest in this study were TSP, IP, PM-10, and PM-2.5.

The exposure profiling method was used to measure unpaved road emissions at the Jones and Laughlin's (J&L's) Indiana Harbor Works and Armco's Kansas City Works. For this study, one downwind profiler, with four sampling heads at heights of 1.5 to 6 m, was deployed during all testing. High volume cascade impactors located at heights of 1.5 and 4.5m measured particle sizes. A high volume cascade impactor was also used to characterize the upwind particle distribution. Warm-wire anemometers at two heights monitored wind speed and a wind vane monitored horizontal wind direction. Road width was not reported.

Twenty-nine controlled and uncontrolled unpaved road tests were performed in this study. Three uncontrolled tests and eight controlled tests were conducted at J&L's Indiana Harbor Works; and three uncontrolled tests and 15 controlled tests were completed at Armco's Kansas City Works. All tests have been assigned an "A" rating. Only uncontrolled tests and controlled tests using water were utilized in the emission factor equation development. Table 4-25 presents summary test data and Table 4-26 presents detailed test information.

The three controlled conditions in this study included a 20 percent solution of emulsified asphalt (Petro Tac) applied at 0.7 gal/yd^2, water applied at 0.43 gal/yd^2, and a 20 percent solution of petroleum resin (Coherex®) applied at 0.83 gal/yd^2 followed by a repeat application of 12 percent solution 44 days later.

The control effectiveness was reported as the number of vehicle passes that occurred as the control efficiency decayed to zero. The initial asphalt emulsion application had an estimated lifetime of 91,000 vehicle passes for PM-10, the initial petroleum resin application had an estimated lifetime of 7,700 vehicle passes for PM-10, and the water application had an estimated lifetime of 560 vehicle passes for PM-10. Also, a reapplication of the petroleum resin had an estimated lifetime of 23,000 vehicle passes for PM-10.

4.2.14 Reference 14

Midwest Research Institute, "Improved Emission Factors for Fugitive Dust From Western Surface Coal Mining Sources" for U. S. Environmental Protection Agency, Cincinnati, OH, July 1981.

This study was conducted to develop emission factors for major surface coal mining activities occurring in the western United States. Results are reported of testing conducted in 1979 and 1980 at three surface coal mines located in Wyoming, North Dakota, and New Mexico. Sampling was conducted on the following mining operations: drilling, blasting, coal loading, bulldozing, dragline operations, haul trucks, light- and medium-duty trucks, scrapers, graders, and wind erosion of exposed areas. Particulate sizes measured include, TSP, IP, and PM-2.5.

Exposure profiling was used to measure emissions from line source activities such as vehicle traffic on unpaved roads and from scraping and grading. Comparisons of data from profiling and upwind-downwind methods were made for scrapers and haul roads. A modified exposure profiling methodology was utilized for blasting emission measurements, and a wind tunnel was used to measure wind erosion emissions. Area source emissions such as coal loading were tested with an upwind/downwind methodology.

The exposure profiling method used a downwind profiler with four sampling heads located at heights of 1.5 to 6.0 m. A standard hi-vol sampler (2.5 m), a hi-vol sampler fitted with a cascade impactor (2.5 m), and two dichotomous samplers (1.5 and 4.5 m) were located downwind. Dust fall buckets were placed upwind and downwind at a height of 0.75 m to measure the particle deposition. Upwind concentrations were measured with one dichotomous sampler and one standard hi-vol sampler, both located at a height of 2.5 m. Wind speed was measured with warm wire anemometers downwind at heights of 1.5 and 4.5 m. Road widths were not reported.

A total of 256 tests were performed in the study. Fifty-six of the tests were used in the development of the AP-42 emission factor equation. The source activity distribution for unpaved road tests was as follows: 20 uncontrolled haul road tests, 8 controlled haul road tests, 10 uncontrolled light- and medium-duty vehicle tests, 2 uncontrolled light- and medium-duty vehicle tests, and 15 uncontrolled scraper tests. Table 4-27 presents summary test data and Table 4-28 presents detailed test information.

4.2.15 Reference 15

Midwest Research Institute, "Fugitive Particulate Matter Emissions," for U.S. EPA, April, 1997.

This test report describes the results of field measurement and other data collection activities that were undertaken in late 1995 and early 1996. The study focused on the determination of PM-10 and PM-2.5 components of fugitive dust emissions from representative paved and unpaved roads at four geographic locations in the United States (Kansas City, MO; Reno, NV; Raleigh, NC; and Denver, CO.) Although, an emphasis was placed on the estimation of the PM-2.5 fraction of the emissions from unpaved and paved roads, this study only reports PM-10 emission factors and PM-2.5/PM-10 ratios.

Exposure profiling was employed to measure particulate emissions. As is general practice with profiling methods, the downwind sampling equipment was placed 5 m after the emission source and the upwind sampling equipment was placed 10 m before the source. For the unpaved road PM-10 tests, a high-volume air sampler equipped with a cyclone preseparator was utilized. A high-volume sampler equipped with cyclone preseparators and parallel-slot, five-stage cascade impactors collected particle sizing information. Also, dichotomous samplers were operated for particle sizing measurements. Wind speed was monitored by wind odometers at three heights and wind direction was recorded with a wind instrument.

State-of-the-art equipment was employed for particle sizing at two of the unpaved road locations; however, at the Raleigh, North Carolina location, an Amhurst Aerosizer Particle sizer failed because of a power supply problem. At the Kansas City, Missouri location, MRI personnel operated a DustTrak Aerosol Monitor light scattering instrument.

Thirteen uncontrolled unpaved road tests at three locations were completed as follows: five tests in Kansas City, four tests in Reno, and four tests in Raleigh. Testing was completed using lightweight captive vehicle traffic operated at a speed of 30 mph. This study recommends a PM-2.5/PM-10 particle size adjustment factor of 0.15 for unpaved roads. The test data were assigned an "A" rating and were used as part of the PM-10 validation study discussed in Section 4.3.1 of this report. Table 4-29 presents summary test data and Table 4-30 presents detailed test information.

4.2.16 References 16-19

Illinois State Water Survey--AWMA/APCA Publications, 1988-1989

Approximately 36 other unpaved road tests have been reported in a series of three APCA/AWMA papers. These tests employed a exposure profiling method to characterize emissions from captive traffic on several rural roads near Champaign, Illinois. A conversation[19] with the project manager confirmed that there is no test report that describes the methodology and results for the tests.

Twenty-one tests are reported in Reference 16, with the experimental methodology being described in an earlier APCA paper (Reference 18). The main interest in Reference 16 is the set of emission factors developed through exposure profiling. Sampling made use of three dichotomous samplers located at 1.55, 3.05, and 4.88 m. (Note that the sampling heights are different from those given in the paper [Reference 18] describing the methodology.) The stacked samplers were located at a distance of 20 m from the road. Reference 18 notes that wind speed and direction were continuously monitored, but no other details are available. No dates are given for the tests.

Captive traffic was used to generate emissions from unpaved, limestone roads. Single tests at each of three travel speeds (25, 35, and 45 mph) were conducted in each experiment. A total of 8 experiments (denoted as 7 and 9 through 14) are reported in Reference 16. Although the only two road identification codes are reported, it is not clear whether the tests were conducted at the same location and thus constitute replicate samples.

In each of the 21 cases analyzed, the emission factors were calculated by assuming a linear profile for exposure values. Thus, the maximum exposure 20 m downwind from the road distance is assumed to occur at ground level even though the wind speed (and thus exposure) vanishes at ground level. This leads to a systematic high bias in the emission factors reported.

Surface samples were collected “periodically” from the roads. All tests reported in a single experiment are associated with a single silt value. When samples were not available for the day that emission testing occurred, values are interpolated. Sample collection and analysis methods were not specified.

An additional fifteen tests were conducted in 1988 and are reported in Reference 17. In those tests, a fourth dichotomous sampler was included in the sampling array 20 m from the roadway. Sampling spanned 1.5 to 6.1 m, but individual sampling heights are not reported. Wind speed was monitored on-site at a 1.5 m height. Those measurements were combined with 10-m wind data from an off-site meteorological station to develop a logarithmic profile for calculation purposes.

A total of 4 experiments (15 through 18) are reported in Reference 17. With the exception of experiment 15, all consisted of an individual test at each of 4 captive vehicle speeds: 25, 35, 45 and 55 mph. Experiment 15 examined emissions at speeds of 25, 45 and 55 mph.

The 1988 tests were associated with a great deal of surface sampling. Three different samples were collected before and after every 100 vehicle passes. As opposed to Reference 16, separate silt values are reported with each test in an experiment.

Two sets of surface samples were considered. The first set was generally collected in the same manner as described in AP-42, Appendix C.1. Contrary to AP-42 Appendix C.2, however, these samples were not oven-dried prior to sieving. A second set of samples focused on the tracks and ruts formed by the captive traffic. The paper does not compare the results from the two different sets of samples.

Two roads were tested – one with limestone and the other with glacial gravel. Experiments 16 and 17 were conducted on the limestone road and on consecutive days; these constitute replicate measurements. Experiment 14 was conducted on the limestone road, but it is not know whether at the same location as experiments 16 and 17. Experiment 18 was conducted at the glacial road.

Although specific data reduction methods are not described, it is assumed that a linear profile was used to characterize exposure values. As noted earlier, this would lead to maximum exposure at ground level and to a systematic high bias in the emission factors reported.

Because supporting documentation could not be obtained, the data were not available for the development of an emission factor equation.

4.3 DEVELOPMENT OF CANDIDATE EMISSION FACTOR EQUATION

For unpaved roads, an emission factor equation has been found to be successful in predicting particulate emissions at different sites with varying source parameters. This section describes the development of the emission factor equation that will be proposed for the updated AP-42 Unpaved Road section.

Various road surface and vehicle characteristics are likely to have an impact on the particulate emissions from unpaved roads. Those parameters most likely to influence the particle emissions, while at the same time are able to be measured in a practical manner, are considered for the emission equation development. The possible parameters may be grouped into three categories: (a) measure of source activity (b) properties of the material being disturbed and (c) climatic parameters.

The measure of source activity includes the speed and weight of the vehicles traveling on the unpaved road. This category would also include the number of wheels of the vehicles in contact with the unpaved road. Subparameters that affect the particle emissions might also be considered; however, cost conscience efforts and clarity considerations for potential emission equation users have narrowed in-depth reviews of these subparameters. These subparameters may include the following: the turbulence created by the aerodynamics and clearance of the individual vehicle traveling on the unpaved road; the unique characterisics of the tire such as width, pressure, and tread design; angle of wheels compared to vehicle thrust; and wheel slippage over the unpaved road surface. Also, if extensive detailed traffic data were available for 15,000+ vehicle passes in the current data set, it would be possible to consider the relation of emissions of tangential wheel velocity compared to vehicle speed.

The properties of the material being disturbed includes moisture content and the content of the suspendable fines in the surface material. Although difficult to characterize within the magnitude of the available data, emissions could potentially be affected by interactions between dust particles of different physical characteristics. Conditions of the unpaved road may also be considered such as the characteristics of the road base (e.g., compacted, hardbase, washboard). Difficult to characterize variability in road conditions and resultant complexity of the emission equation were considered as basis for not including the road base characteristics in the emission factor equation.

Climatic characterization is generally reflected by the precipitation-free days per year on which emissions tend to be at a maximum. The radiant energy of the sun may be important when determining the control efficiency of watering, and in effect the average moisture content of the surface material. Direct moisture measurements are appropriate in this case.

The parameters readily measureable and applicable to a general unpaved road equation include surface silt content, surface moisture content, mean vehicle weight, mean vehicle speed, and mean number of wheels. Discussion of the analysis of these parameters continues later in this section.

The development of a revised unpaved road emission factor equation was built upon findings from the reviewed data sets. First, the decision was made to include all tests of vehicles traveling over unpaved surfaces. For example, tests of scrapers in the “travel mode” between cut and fill areas were included. Also, tests of very large off-road haul trucks used in the mining industry were also included in the developmental data set. On the other hand, graders blading an unpaved road were not included because of the low speed and the additional road surface disturbance involved. This decision had the effect of greatly expanding the historical data base. Not only are far more data available, but the data encompass a wider range of vehicle weights and travel speeds.

The decision to composite the data sets was based on findings from Reference 4, which dealt with the western surface coal mining industry. Remarks made in Section 4.2.4 bear mention here as well. Reference 4 found that the "generic" unpaved road emission factor model currently contained in AP-42 (Equation 2-1 in this document) performed at least as well in predicting emissions from both haul trucks and light-duty vehicles as did emission factors developed specifically for the industry under consideration.

Next, the decision was made to add tests of watered roads to tests of uncontrolled roads, because moisture content is also affected by natural mitigation resulting from climatic factors. Chemically controlled unpaved roads were not included because those treatments cause lasting physical changes to the road surface. A review of the measurable physical characteristics (silt content and moisture content) of chemically controlled unpaved roads found no identifiable trends. Reference 8 examined the historical data base and concluded that a general control estimation method based on surface characteristics was not feasible.

The inclusion of both uncontrolled and watered roads was based on findings in the Reference 4 study. That study and a later review included moisture as a potential correction parameter in developing a predictive equation for unpaved roads. It was found that both the old (Reference 14, circa 1980) and new (Reference 4, 1992) haul truck data could be successfully fitted with one equation that applied to both watered and uncontrolled surfaces. The decision was also supported by a similar approach taken in developing the current AP-42 paved road equation. In that case, controlled and uncontrolled tests were combined.

Inclusion of watered surfaces in the data base recognizes a fundamental difference in how the addition of water controls emissions (as opposed to the addition of other types of suppressants). First, the addition of water is a short-term control measure and is similar to the effect of rain. In addition, it causes no permanent change in the road surface characteristics. To an extent, one could argue that a road subject to frequent rain is no different than a road which is routinely watered.

Finally, the decision was made to focus on PM-10 emission tests. Because Equation 2-1 was developed earlier than the 1987 promulgation of the PM-10 NAAQSs, that factor did not focus on the particle size range of current regulatory interest. Combining data sets emphasizes the basic physical process of dust generation by vehicle traffic on unpaved roads. In keeping with that view, it is reasonable to expect that emission factors for different size fraction resemble one another. The approach requires that the models developed for different particle size ranges be “consistent,” in the sense discussed below.

As a first step, the “developmental” data base was prepared from the test reports discussed in the previous section, with the following exceptions:

1. No test data were included from Reference 5. As noted earlier, these data were rated “D.”

2. No data were included from Reference 7, because the unpaved road considered had been previously treated with a chemical dust suppressant. Also, individual tests of chemical dust suppressants in other references were not included.

Finally, some additional preparation of the data base was required. For example, References 12 and 14 did not present PM-10 emission factors; values were developed by log-normal interpolation of the PM-15 and PM-2.5 ratios to total particulate emissions. In addition, References 1, 12, and 13 did not report individual surface moisture contents. However, because silt content is determined after oven drying, the necessary information was readily available for Reference 1, which was being prepared at the same time that the current work was being undertaken. In Reference 13, some individual tests had moisture contents reported and a few additional tests were associated with moisture contents as well. Those tests for which moisture data were reported were included in the development data set. Furthermore, the data from Reference 3 had been corrected for “combustion particulate” content (although upwind concentrations had not). Using information contained in the report, “total” PM-10 emission factors (i.e., without regard to chemical composition) were calculated for inclusion in the developmental data set. (An ASCII data file containing the developmental data set is provided in the file D13502B.ZIP located on EPA’s CHIEF web site under Draft AP-42 Sections.

Model development relied on the stepwise linear regression routine contained in the SYSTAT, Version 4 set of statistical routines. The default level of significance used by SYSTAT for a variable to “enter” the stepwise linear regression was 0.15 (15 percent). In this context, “level of significance” refers to the probability of making a so-called Type I error. The possibility of making this kind of error arises because we are dealing with samples drawn from a parent population. That is to say, under the default setting, samples drawn from two completely independent populations would be found to have a significant relation <u>purely due to chance</u> 15 times out of 100. The 15 percent level of significance was used for exploratory data analysis; refined analysis relied on specifying a 5 or 10 percent significance level.

Standard statistical tests of significance assume normal parent populations. Because unpaved road emission factors and key correction parameters are log-normally distributed, the regression analysis needs to rely on log-transformed data. This results in a multiplicative model, which is the form of the current AP-42 emission factor predictive equation.

Stepwise multiple linear regression was used to develop a predictive emission factor equation from the data set. Five potential correction parameters were included:

1. Surface silt content, s;
2. Surface moisture content, M;
3. Mean vehicle weight, W;
4. Mean vehicle speed, S; and
5. Mean number of wheels, w.

In addition to the emission factor and correction parameter values, the data base also contained codes indicating:

1. Whether the test was of an uncontrolled or a watered surface;
2. The type of road;
    a. publicly accessible unpaved road
    b. unpaved travel surface at an industrial facility
    c. "simulated" unpaved road
3. The predominant type of vehicle traveling the road;
    a. Light or medium-duty vehicles;
    b. Haul trucks;
    c. Scrapers in the travel mode; and
    d. Heavy-duty, over-the-road trucks.

For the initial analyses, the data base was sorted by whether the test represented uncontrolled or watered conditions and by the type of road (industrial vs. public unpaved road). There were two main objectives in this step. The first objective was to determine simply whether the different portions of the data base could be successfully combined. The second objective was to determine whether an emission factor model resulting from the large combined data would be consistent. The term "consistent" refers to (a) whether or not the same basic set of correction parameters could be used to estimate emission levels and (b) whether or not the relationships were similar between different subsets in the data base.

For example, suppose that stepwise regression of one portion (*I*) of the data base (e.g., uncontrolled industrial roads) showed that emissions were highly dependent on variable X but independent of variable Y. If stepwise regression of another portion (*II*) of the data base, on the other hand, indicated that emissions were very dependent upon Y but not on X, then the results for the two portions would not be viewed as consistent. The consistency in the relationships between independent and dependent variables is also important. To continue the example, suppose that regression of portions *I* and *II* both showed that the emission levels depend on variable X. If, however, for portion *I*, emissions depended on the 0.5 power of X while in portion *II*, emissions varied with the second power of X, then the relationships would again be viewed as “inconsistent.”

Given that the individual sets within the data base do not necessarily contain many test results, evaluation of consistency cannot always follow hard and fast rules. For example, one would reasonably expect that the emissions from watered tests would depend on the surface material moisture content. The lack of a discernible relationship between moisture and emissions from the uncontrolled tests in the data base would not necessarily indicate inconsistency. Furthermore, determining how “close” two relationships are, requires considerable judgment as well. For example, both a power of 0.86 and power of 1.1 indicate a roughly linear relationship.

The analysis began by stepwise regression of only the 160 uncontrolled tests in the data base, using the potential correction parameters of silt, weight, speed and number of wheels. Note that moisture content was not included. In this case, mean vehicle weight entered the regression first, and surface silt content on the second step. This first regression was roughly equivalent to repeating how the current AP-42 unpaved road emission factor was derived. Unlike the past, however, the effort focused on PM-10. The resulting emission factor for PM-10 exhibited an almost linear (power of 1) relationship with silt content. Furthermore, emissions were shown to follow a "less-than-linear" relationship with vehicle weight, although the exponent was roughly half of that contained in the current AP-42 equation (Equation 2-1).

Next, uncontrolled and watered tests were considered separately, but this time with moisture content included as a potential correction parameter. For the 137 uncontrolled tests, weight and silt were again the first two variables to enter the regression. The exponents for both these variables were consistent with the values obtained for only the uncontrolled tests. However, two additional variables entered the stepwise regression in this case. Surface moisture content entered on the third step and mean vehicle speed on the fourth.

Inclusion of speed was somewhat tentative, in that its level of significance was just slightly greater than 10 percent. The default significance level for a variable to enter the regression was 15 percent. If the requirement for a variable to enter had been tightened to the 10 percent level of significance, speed would not have entered the relationship.

For the 43 watered tests, only two correction parameters entered the regression--silt and weight. The powers for silt and weight were reasonably consistent with the results obtained when the uncontrolled tests were considered separately. The reasonably consistent relationships for both silt and weight suggested that the two uncontrolled and watered portions of the data base could be successfully combined.[b]

When both uncontrolled and watered tests were considered as one data set, weight and silt again entered first and second, with moisture entering on the third step. Wheels would enter the equation if the level of significance were relaxed to 20 percent; however, for this analysis at the 10 percent level of significance wheels are not included. Speed entered on the fourth iteration. The resulting emission factor equation has the form

---

[b] The relationships for both of these variables are also reasonably consistent with the relationships in the current AP-42 model (Equation 2-1).

$$E = k\, s^{0.85}\, W^{0.50}\, S^{0.32} / M^{0.29} \qquad (4\text{-}3)$$

where k is a constant of proportionality.[c] The R^2-value (0.354) for Equation 4-3 indicates that the model explains approximately 35 percent the variation in emission factors.

An alternative to Equation 4-3 results from tightening the significance requirement, from 10 percent to 5 percent, for a variable to enter the regression. In this case, speed does not enter the equation, and the equation has the form:

$$E = k\, s^{0.82}\, W^{0.46} / M^{0.28} \qquad (4\text{-}4)$$

This equation has a R^2-value of 0.345, which is only slightly less than Equation 4-3.

Equations 4-3 and 4-4 represent the two candidate PM-10 emission factor equations considered in this study. Initially, preference was given to Equation 4-3 because the inclusion of speed was viewed as providing additional predictive accuracy for instances involving very slow or very fast traffic. Equation 4-3 was initially chosen and validation of that model proceeded.

However, in the validation of Equation 4-3, it was found that almost no additional predictive accuracy was achieved and that the equation did not permit actual estimates of the effects of speed reduction. The inclusion of speed was highly dependent on the data set being used. For example, exclusion of only one or two low-speed tests from the data resulted in speed not entering the regression at even the 15 percent level of significance. On the other hand, dropping those tests had no effect on the other terms in the model. Thus, the four-parameter model (Equation 4-3) appeared to be relatively unstable.

Furthermore, past testing studies have found that, when all other road/traffic parameters are held constant, emissions depend on a higher power of mean vehicle speed than the 0.32 value given in Equation 4-3. In Reference 6 and other older studies designed to assess the influence of vehicle speed on PM emissions, powers between 1 and 2 have been found. Note, however, that those studies were able to separately consider different speeds by supplying “captive” traffic during testing. In other words, the testing organization supplied essentially all the vehicular traffic during the field exercise to tightly control source conditions. This is a "parametric approach" that is the only systematic way to isolate the effect of individual source parameter on emission levels. In practical terms, such an approach is restricted to roads that (a) have relatively little "natural" traffic and (b) are traveled by mostly light-duty vehicles.

The captive traffic approach to systematically examine the effect of vehicle speed is in pointed contrast to how most tests in the data base were conducted. Most tests were conducted on roads at which

---

[c] Working versions of the emission factor equation are presented. In this context, the term “working” refers to factors that require that weight be expressed in tons, speed in mph, and silt and moisture contents in percent. Furthermore, the emission factor must be expressed in lb/VMT. In this case, the constant of proportionality has a complicated set of dimensions. The model recommended later in Equation 4-5 has been “normalized” by dividing, for example, weight by a default vehicle weight of 3 tons. In that case, the constant of proportionality has the same dimensions as the emission factor itself and can be readily converted from one set of units to another.

the traffic could not be tightly controlled by the testing organization. Because data from many studies have been assembled and because most tests do not rely on “captive” traffic, it is not possible to isolate the effect of speed on emissions. Without the benefit of captive traffic, it is not surprising that weight and speed are highly intercorrelated in the data set. Furthermore, speed and emissions are not significantly correlated in the developmental data set. In fact, there is a negative (although not significant) correlation between emission factor and speed.

It is crucially important to keep in mind that predictive accuracy is the goal of any emission factor equation. With this in mind, the predicted-to-actual ratios for Equation 4-3 were compared to those for Equation 4-4. The summary statistics follow:

	Equation 4-3 (with speed term)	Equation 4-4 (no speed term)
Minimum	0.104	0.100
Maximum	30.1	27.4
Geometric Mean	1.02	0.986
Geometric Std. Dev.	2.74	2.71

(Note that geometric rather than arithmetic statistics are used here. The reason for this choice is explained in Section 4.5.1). In comparing the two sets of statistics, it is clear that the inclusion of a speed term in Equation 4-3 lends almost no additional accuracy.

In summary, the following emission factor equation is recommended for estimating PM-10 emissions from vehicles traveling over unpaved surfaces:

$$E_{10} = 2.6\ (s/12)^{0.8}\ (W/3)^{0.4}/(M/0.2)^{0.3} \tag{4-5}$$

where:

E_{10} = PM-10 emission factor (lb/VMT)
s = surface material silt content (%)
W = mean vehicle weight (tons)
M = surface material moisture content (%)

Note that the "normalizing factors" of 12 percent silt and 3 tons are the same as for the current AP-42 model. This allows one to compare the leading term of 2.6 lb/VMT in Equation 4-5 to the factor of 2.1 lb/VMT inherent in the current version of the unpaved road predictive model.[d] (The selection of 0.2 percent to normalize the moisture term follows from the specification of a default value. See Section 4.4).

---

[d] That is, the leading value of 5.9 (in Equation 2-1) times the aerodynamic particle size multiplier of 0.36 for PM-10.

To the extent practical, the development of emission factor equations for other the PM size ranges followed that for PM-10. That is to say, the preferred approach was to develop a stepwise regression of the available test data. For PM-30 (used as a surrogate for TSP), stepwise regression of the 65 uncontrolled emission test data led to the following result:

$$E_{30} = k\ s^{0.97}\ W^{0.52} / M^{0.45} \qquad (4\text{-}6)$$

where all variables are the same as before and E_{30} denotes the PM-30 emission factor in lb/vmt. The R^2-value for the above factor is 0.49 and the equation compares well with the intermediate and final results for PM-10. In contrast to PM-10, however, vehicle speed did not enter the stepwise regression for PM-30.

When both uncontrolled and watered PM-30 tests were considered, the same three variables--silt and moisture contents, and mean vehicle weight--again entered the stepwise regression of the 92 test date. With the inclusion of the tests of emissions from watered surfaces, the only noticeable change in exponents was a slight reduction in the power for silt content. Because of the consistency between the watered/ uncontrolled tests and between the PM-10/PM-30 results, the following emission factor equation is recommended for PM-30:

$$E_{30} = 10\ (s/12)^{0.8}\ (W/3)^{0.5} / (M/0.2)^{0.4} \qquad (4\text{-}7)$$

The PM-30 emission factor is clearly consistent with the factor for PM-10 (Equation 4-5). Both factors involve the same three independent variables, each raised to essentially the same power. In contrast to PM-10, vehicle speed did not enter any of the stepwise regressions of PM-30 test data.

Model building efforts for PM-2.5 initially followed the same procedures as for PM-10 and PM-30. That is, stepwise linear regression of 77 uncontrolled PM-2.5 emission test data led resulted in three variables entering the equation

$$E_{30} = k\ s^{0.67}\ W^{0.21} / M^{0.17} \qquad (4\text{-}8)$$

where all variables are the same as before and $E_{2.5}$ denotes the PM-2.5 emission factor in lb/vmt
Note that, again, the same three variables entered the stepwise regression: silt content, mean vehicle weight and moisture content. Although the power to which the silt term is raised is reasonably comparable to the exponents in the PM-10 and PM-30 factors, the two remaining exponents are only half those in the other emission factor equations. More troubling is the fact that a low R^2 value for the equation implies that only 8 percent of the variation in emission levels is explained by the equation. Furthermore, when the watered tests are added to PM-2.5 developmental data set, two more variables--mean vehicle speed and number of wheels--now enter the stepwise regression. The R^2 for the equation is again low at a value of 0.23. In other words, even with five variables, the regression-based PM-2.5 factor appears to be disappointingly poor in terms of predictive ability.

Because of the failure of stepwise regression to produce a suitable PM-2.5 emission factor equation, the significant difference from the PM-30 and PM-10 equations, the potential for the five variable PM-2.5 equation to result in a value exceeding the PM-10 equation under some circumstances, and the low R^2 for the three variable equation that is reasonably comparable to the PM-10 and PM-30 equation, an alternative approach was taken. In this case, a PM-2.5 factor was developed by scaling the PM-10 model (Equation 4-5) by the measured PM-2.5/PM-10 in the available data base:

	Geometric mean ratio of PM-2.5 / PM-10
Uncontrolled (n = 108)	0.140
Watered (n=20)	0.196
Overall (n=128)	0.148

No significant difference was found between the ratios for watered versus uncontrolled conditions, so the overall mean was applied. Furthermore, no significant correlation (at the 5 percent level) was found between PM-2.5/PM-10 ratio and emission factor, silt, moisture, weight, speed, or number of wheels.

In summary, for the three PM size fractions of greatest interest, the following emission factor equation is recommended for inclusion in AP-42:

$$E = k\ (s/12)^{a}\ (W/3)^{b}/(M/0.2)^{c} \qquad (4\text{-}9)$$

where: k, a, b and c are empirical constants given below and

E = size-specific emission factor (lb/vmt)
s = surface material silt content (%)
W = mean vehicle weight (tons)
M = surface material moisture content (%)

The parameters for size-specific emission factors in Equation 4-9 are given below:

Empirical constant	PM-2.5	PM-10	PM-30
k	0.38	2.6	10
a	0.8	0.8	0.8
b	0.4	0.4	0.5
c	0.3	0.3	0.4

Based on the rating system given in Section 3.5, both the PM-10 and PM-30 emission factors would be rated “A” by strictly following the decision rules presented there. However, because the predictive equation was developed to span a very broad range of source conditions and has an R^2 of only 0.34, a lowering of the quality rating is appropriate. The PM-10 and PM-30 emission factors are rated "B." Because the factor is based on scaling the PM-10 factor, the PM-2.5 factor is downgraded 1 letter. Thus the PM-2.5 factor carries a quality rating of "C."

It is important to note that the overall performance of any emission factor improves when it is applied to a number of sources within a specific area. This is an important distinction between fugitive dust sources and the "stack" ("point") emission sources (such as utility boilers) commonly discussed by AP-42. That is to say, an area being inventoried typically contains no more than a handful of the stack-type sources which use a specific emission factor. Furthermore, stack sources are far better defined and steady in terms of operating conditions (feed rate, air flow, etc.). In contrast to a handful of stack sources, an inventoried area may contain dozens of unpaved travel surfaces, each with very different vehicle characteristics that change with hour of the day, seasonally, etc. In that case, the performance of an emission factor in accurately predicting emissions from a single, isolated source should not form a central focus. Instead, one should be most concerned about how well the factor performs in estimating the total (or average) emission from the entire set of sources over time periods of interest.

4.3.1 Validation Studies

A series of validation studies were undertaken to examine the predictive accuracy of the various emission factors recommended in the preceding section. Validation focused on the PM-10 model.

This section discusses the performance of the model primarily in terms of the predicted-to-measured ratio:

$$\frac{\text{emission factor predicted by model}}{\text{measured emission factor}}$$

As a practical matter, because of the log-linear regression used to develop the emission factor models, the log of the predicted-to-measured ratio is identical to the “residual” or error term:

residual = log(predicted) - log(measured) = log(predicted-to-measured)

Throughout this section, summary statistics are presented in terms of geometric mean and standard deviation. This follows directly from the use of log-linear regression. Furthermore, use of the geometric mean is clearly more appropriate to describe ratios than the arithmetic mean for the following reason. Unlike the arithmetic average, the geometric clearly represents the tendency of the ratio. To illustrate this point, consider the following 10 hypothetical ratios:

Case	Predicted-to-measured	Measured-to-Predicted
1	0.678	1.47
2	1.48	0.68
3	2.76	0.36
4	0.885	1.13
5	0.754	1.33
6	0.248	4.03
7	1.87	0.53
8	0.126	7.94
9	1.76	0.57
10	3.15	0.32
Arithmetic mean	1.37	1.84
Geometric mean	0.95	1.05

By using the arithmetic mean of the predicted-to-measured ratio of 1.37, one could argue that the predictions were about 37 percent higher than the measured. This leads to a natural suspicion that the measured values were roughly 37 percent lower than the predictions. However, it is seen that the arithmetic mean of the measured-to-predicted ratio is in fact 1.84 which is greater than 1.37. On the other hand, the geometric mean has the property that it is equal to the inverse of the mean for the inverse ratio.

In addition, because of the log-linear regression, the residuals are log-normally distributed. For this reason, logarithmic plots of the residuals are presented.

The first two PM-10 validations used the data base assembled for developing the model. The first made use of a cross-validation analysis of the PM-10 data set. In this approach, each data point is eliminated one at a time. The regression obtained from the "reduced" data base is used to estimate the missing data value. In this way, a set of "n" quasi-independent observations is obtained from the data set of "n" tests.

The PM-10 cross-validation (CV) shows that the model is fairly accurate for a very broad range of source conditions. Table 4-31 indicates that, although the model may slightly under- or overpredict individual emission factors in some specific subset of the data base, the general agreement is quite good. The CV analysis further found that, for the quasi-independent estimates of the measured emission factors:

1. 52 percent are within a factor of 2;
2. 73 percent are within a factor of 3;
3. 90 percent are within a factor of 5; and
4. 98 percent are within a factor of 10.

Again, recall that, because a facility typically contains numerous roadway segments, each with its own vehicle mix, one is most concerned about how well the factor performs in estimating the total (or average) emission. Thus, even though the above-cited statistics suggest that, for example, there is approximately a 30 percent probability of over- or underestimating emissions by a factor of 3 for an individual roadway segment, there is a substantially lower chance of making the same level of error for emissions from the totality of roadways under consideration at a facility. Computation of an exact probability would depend on: (a) the number of individual segments under consideration and (b) the relative contribution of each segment to the total PM emissions. Note that item (b) is a relatively complicated function of the emission factor, the vehicle traffic and the road segment length .

To illustrate the increased confidence, a series of simple random drawings of 5 tests from the developmental data set was made. Comparing the sum of the measured and the estimated emissions is analogous to a hypothetical situation in which plant contains 5 road segments, each with the same length and same number of vehicle passes. In 1000 repetitions of the random draw of 5 from the developmental data set, the following was found for the sum:

1. 73 percent were within a factor of 2;
2. 92 percent were within a factor of 3; and
3. 99.6 percent were within a factor 5.

In this illustration, one would have only and 8 percent chance of over- or underestimating total emissions by a factor of 3.

Plots of the residuals versus individual PM-10 emission factor, silt, moisture, weight, speed and wheels are presented in Figures 4-1 through 4-6, respectively. In examining the PM-10 residuals (i.e., the error between individual predicted and measured observed emission factors), it was found that Equation 4-9 tends to overpredict the lowest and underpredict the highest measured factors. In other words, the model appears to have a systematic bias at the extremes of the parent data base. This tendency is to be expected of any model developed from regression techniques.

The only other significant relationship found for the residuals in the PM-10 cross-validation involved the tendency of the equation to overpredict emissions for very slow speeds. The equation does not exhibit any bias for mean vehicle speeds 15 mph and higher. Figures 4-7 and 4-8 present separate residual plots for average vehicle speeds below and at 15 mph or higher, respectively. For the 19 tests conducted with an average speed less than 15 mph, Figure 4-7 suggests overprediction by approximately 80 percent. In contrast, at speeds higher than 15 mph (and especially for speeds 45 to 55 mph) the residuals are symetrically distributed about the line of perfect agreement.

The finding that the equation overpredicts for very slow speeds also influences how to account for the emission reduction due to speed control. This overprediction suggests that speed reduction has a near linear effect on emissions. That is to say, for an approximately 50 percent reduction (i.e., from 30 mph to less than 15 mph) in speed, the emission factor is roughly 50 percent lower than expected (i.e., overpredicted by about 80 percent). This is consistent with the linear reduction based on the current AP-42 factor (Equation 2-1). As discussed in Section 4.5, a linear effect for speed reduction is included in the revised AP-42 section.

A second validation of the PM-10 factor reserved approximately 20 to 25 percent of the data base for validation purposes. Test data were randomly selected for inclusion in either the “development” or the “validation” data set. Two separate random selections were performed. The development data set is used to develop the relationship which is used to estimate tests in the validation set. The first development set led to the following predictive equation for PM-10:

$$E = 2.8\ (s/12)^{0.78}\ (W/3)^{0.44}\ /\ (M/0.2)^{0.35} \tag{4-10}$$

and Development Set 2 led to the following equation for PM-10:

$$E = 2.7\ (s/12)^{0.80}\ (W/3)^{0.43}\ /\ (M/0.2)^{0.26} \tag{4-11}$$

Note that both development sets led to equations very similar to that in Equation 4-5. When the two models were used to predict data that had been withheld for validation, the following summary statistics resulted:

Validation set	No. of cases	Ratio of predicted to measured			
		Minimum	Maximum	Geo. mean	Geo. std.dev.
1	n = 41	0.123	29.3	0.926	2.92
2	n = 40	0.125	6.58	1.27	2.63

Unlike the quasi-independent estimates obtained in the cross-validation, the above truly represent independent applications of an emission factor model developed through stepwise regression technique. For that reason, this validation leads to a slight bias in the resulting estimates, underpredicting in the first set by 7 percent and overestimating by roughly 30 percent in the second. Nevertheless, the spread (variation) in the estimates is quite comparable to that found in the cross-validation and the estimates generally agree well with the measured values in the validation data set.

A final PM-10 validation study involved nine emission tests that had not been formally reported when the study began (Reference 15). Table 4-32 shows the results of the comparisons of predicted to measured PM-10 emission factors. Predictions based on both Equation 4-5 and the current AP-42 equation are considered. In general, agreement is quite good for the new unpaved road equation.

Validation of the PM-30 and PM-2.5 emission factors was also undertaken. For the PM-30, a cross-validation similar to that performed for PM-10 led to results very comparable to those found earlier. Figures 4-9 through 4-14 present the residuals from the PM-30 cross-validation. Interestingly, there was no significant relationship between the residuals and speed for the PM-30 equation. In other words, unlike the PM-10 equation, the PM-30 equation does not appear to systematically overpredict at very slow travel speeds.

In the PM-30 cross-validation, the following results were found comparing the predicted to measured values,

1. 50 percent were within a factor of 2;
2. 72 percent were within a factor of 3; and
3. 96 percent were within a factor of 5.

Remarks made earlier in connection with PM-10 bear repeating here. Recall that, in general, one is more interested in how well the factor performs in estimating the total (or average) emission from several roadway segments within a facility. In this way, there is considerably greater accuracy in the total emission estimate than might be inferred from the above statistics. As in the case of PM-10, consider the example of comparing the measured and predicted sums in random draws of five from the data set. In 100 realizations,

1. 83 percent were within a factor of 2;
2. 98 percent were within a factor of 3; and
3. All were within a factor of 5.

Note that the estimate for the total is substantially "tighter" than that for the individual road segment.

Because the result for PM-2.5 in Equation 4-9 was not developed by stepwise regression, a different type of validation was undertaken. In this case, the estimate based on Equation 4-9 was directly compared to the measured emission factor contained in the data. Because PM-2.5 data were not used directly to develop a regression-based model, the comparisons already represent essentially independent applications of Equation 4-9. That is to say, there was no need to eliminate tests on a point-by-point basis and repeatedly use stepwise regression to develop quasi-independent estimates.

In comparing the Equation 4-9 estimates to the measured emission factors in the PM-2.5 data set, it was found that, for individual test results,

1. 44 percent were within a factor of 2;
2. 68 percent were within a factor of 3; and
3. 78 percent were within a factor of 5.

Again, greater accuracy results when the predictive equation is applied to a set of roadway segments to estimate total emissions. As discussed in connection with the PM-10 and PM-30 validations, an illustration is provided by summing the emissions from five randomly selected tests from the data set. In 100 realizations of the random draw of five tests,

1. 62 percent were within a factor of 2;
2. 78 percent were within a factor of 3; and
3. 90 percent were within a factor of 5.

In summary, then, the validation found that Equations 4-5, -7 and -9 provide reasonably accurate estimates of the PM-10, -30, and -2.5 emissions from an individual roadway. As noted throughout this section of the document, one has substantially greater confidence when the predictive models are applied to a set of roadways contained at a specific facility.

4.4 DEVELOPMENT OF DEFAULT VALUES FOR ROAD SURFACE MATERIAL PROPERTIES

As noted earlier, all previous versions of the AP-42 unpaved road emission factor have included the road surface silt content as an input variable. The predictive equations recommended in the last section are no exception. AP-42 Section 13.2 has always stressed the importance of using site-specific input parameters to develop emission estimates. Recognizing that not all users will have access to site-specific information, AP-42 has included methods to allow readers to determine default values appropriate to their situation.[e]

* Table 13.2.2-1 currently in AP-42 contains default silt information for various applications. As part of this update, the table was modified to (a) include updated information on construction sites and log yards and (b) reformat the information for publicly accessible roads. Item (a) was a relatively straightforward process. On the other hand, item (b) required a thorough reexamination, as described below.

In order to develop default information for publicly accessible unpaved roads, a data set of available silt and moisture contents was assembled. The 78 data points were collected either as part of a field emission testing program or as input necessary to prepare emission inventories. Note that several of the

---

[e] The inclusion of the surface moisture content as an input variable is not considered to represent an undue burden on the users of AP-42. In particular, the methods presented in AP-42 Appendix C.2 require oven drying before sieving. In other words, determination of the silt content of a road surface sample requires that the moisture content of the sample also be determined. Thus, users of AP-42 who have already determined site-specific values for road surface silt content should have corresponding moisture content information available as well.

inventory-type samples were aggregated from subsamples collected from different road segments within some portion of the study area.

Data are classified as being from either an “eastern” or a “western” location, based on the common distinction between “pedalfer” and “pedocal” soils. For pedalfer soils common in the eastern U.S., precipitation exceeds evaporation. Conversely, evaporation is greater than precipitation in the West and the soils are termed “pedocal.” The 97th meridian is roughly coincident with the dividing line between pedalfer and pedocal soils.

Also, to the extent practical, data were classified as being from a “gravel” or “dirt” type of unpaved road surface. In this context, “dirt” refers to a road surface constructed from soils in the general vicinity of the site without a crushed aggregate (stone, slag, etc.) being incorporated. Similarly, “gravel” refers to surfaces in which aggregate material has been incorporated, regardless of whether the aggregate is crushed stone or some other material (such as slag or scoria).

Statistical analysis of the data set was undertaken to examine whether significant differences exist between the characteristics of eastern vs. western and gravel vs. dirt roads. Because the available data set had not been developed for this use, i.e., specifically to explore how unpaved road surface characteristics vary because of different road surface materials or different locations in the country, the data set contains unequal subsets of data. The 78 data points are distributed as shown below:

	Location	
Surface type	East	West
Dirt	10	14
Gravel	15	31
Unknown	0	8

The unequal sample sizes make it difficult to efficiently examine differences. First, the choice of statistical tests becomes limited. Generally, the most powerful methods to examine treatment and interaction effects rely on having equal number of observations per cell. On an even more fundamental basis, there is a question whether the available data represent a reasonably representative, random sample from the set of all publicly accessible unpaved roads. That assumption would underlies any statistical test undertaken.

Because of the data limitations, a series of pairwise comparisons such as,

1. Eastern gravel vs. eastern dirt roads;
2. Eastern vs. western roads; and
3. Gravel vs. dirt roads.

were undertaken to determine if there existed significant differences in either moisture or silt content. The small-sample comparison of means test was used with the level of significance set at 10 percent. When appropriate, a one-sided alternative hypothesis was used. For example, one could reasonably expect, on an a priori basis, that on average

1. Gravel roads have lower silt contents than dirt roads; and
2. Moisture contents are lower in the western U.S. than in the East

When there was no a priori reason available, a two-sided alternative hypothesis was selected. For example, there was no reason to suspect that the set of eastern gravel roads would have higher silt contents than gravel roads in the west. In that case, the alternative hypothesis selected was that the mean silt contents for eastern vs. western gravel roads are not equal.

Given the limitations on the available data set, it is not particularly surprising that the pairwise comparisons led to somewhat contradictory findings. For example, although the data set indicated that eastern dirt roads had a higher average moisture content than eastern gravel roads, that result was not duplicated for western roads or for roads overall. Similarly, gravel surfaces were found to have a lower mean silt content than dirt when (a) only eastern roads and (b) all roads were compared. That is, no significant difference was found for silt contents between western gravel and dirt roads. Results from the pairwise comparisons are summarized below. In the table, “S” and “M” indicate that a significant different (10 percent level of significance) in the mean value of the silt and moisture content, respectively, was found in the comparison.

Comparison of gravel vs. dirt			Comparison of East vs. West		
East	S	M	Gravel	--	--
West		--	Dirt	--	M
Overall	S	--	Overall	--	--

In keeping with the findings summarized above, it was decided to provide separate default silt values for gravel and dirt roads, for use throughout the United States (i.e., no distinction between east and west).

	Mean Silt Content
Gravel Roads	6.4 percent
Dirt Roads	11 percent

Specification of an appropriate default moisture content for a dry road proved more problematic. The overall mean moisture content in publicly accessible road data set was found as 1.1 percent. Although this value potentially could have provided the default, it was believed that 1.1 percent did not adequately represent the extremes of the data set. The data base contained moisture contents approximately 0.1 to 0.3 percent for roads even in what are not considered "dry" parts of the nation. For example, four samples collected for an emission inventory of Grants Pass, Oregon, ranged from 0.14 to 0.38 percent in moisture content, with a mean value of 0.24 percent. The four Raleigh, North Carolina ("BJ") tests presented in Table 4-32 are associated with moisture contents between 0.07 and 0.1 percent. (In fact, the Raleigh test series provided the lowest moisture contents in the entire data set. By comparison, moisture contents for the desert [the Arizona, Palm Springs and Reno tests in References 6, 1 and 2, respectively] ranged from 0.17 to 0.48 percent.)

This situation is not surprising since the moisture content of the surface material of an unpaved road is very dynamic. The moisture content is affected by a number of meteorological and physical parameters that vary considerably with time and by location. For urban roads, rain is the primary meteorological event which adds moisture to the road surface. The frequency, duration, and quantity of rain are important aspects which determine the moisture content on any day and the long term average moisture content. The average annual number of rain days in the U.S. ranges from about 20 to over 200 with a variation in annual rainfall from less than 4 inches per year to over 100 inches per year. The primary meteorological parameters that affect the evaporation of moisture from the road surface include solar radiation, temperature, dew point, and wind speed. The Class A pan evaporation is a reasonable indicator of the evaporation potential. The variation in the annual Class A pan evaporation varies from about 25 inches per year to over 120 inches per year. Some physical parameters which affect the moisture content of the surface material include the amount and size distribution of the loose surface material and vehicle traffic on the road. The amount and size distribution of the loose surface material would affect the maximum amount of water that the surface material is capable of holding. Vehicle traffic enhances the evaporation of moisture from the road surface due to the increase in surface air movement. The presence of trees and other natural and man made formations may affect the moisture balance of the road surface material. As a result, the selection of any single default moisture content would introduce significant bias for all but a few locations in the U.S.

In the interest of encouraging AP-42 readers to collect site-specific data, a reasonably conservative (worst case) value of 0.2 percent was selected for the default dry condition moisture content. This moisture content value is higher than approximately 20 percent of all the publicly accessible uncontrolled road data set. It should be noted that this moisture value is not the average moisture content of the road surface material but is the minimum moisture content following an extended period without water additions to the road surface.

Even though the default moisture value may be viewed as conservative, the default should not generally lead to unacceptable emission estimates. This is due to the fact that moisture is raised to such a low power (0.3 and 0.4) in the predictive emission factors. When the 0.2 percent default is substituted for the site-specific moisture content for the 43 publicly accessible road tests in the PM-10 data set, all but four results are within a factor of 2 of the estimate based on the site-specific value. At most, use of a default value of 0.2 resulted in an estimate 2.5 times greater. Furthermore, on average, the increase in estimated emission factor was only 12 percent when the default was substituted for the site-specific moisture content.

4.5 SUMMARY OF CHANGES TO AP-42 SECTION

4.5.1 <u>Section Narrative</u>

The major revisions to AP-42 Section 13.2.2, Unpaved Roads, are as follows:

1. Text surrounding the emission factor equation was revised to reflect the new equation and provide more background information on how the equation was derived. Reference to the PM-15 size fraction has been removed.
2. The discussion on defaults and quality ratings was substantially expanded. In particular, there is a description of the model's performance when used to predict emissions from very slow-moving traffic and a presentation of a default value for moisture content.
3. The extrapolation to annual conditions (incorporating natural mitigation) has been revised to reflect the variables contained in the new equation. Readers who are interested in finer temporal and spatial resolution are directed to the background reports area of the CHIEF web site (http://www.epa.gov/ttn/chief/ap42back.html). An alternative procedure for estimating emissions on a monthly basis is available as a spreadsheet file. Information required to use this procedure includes hourly precipitation, humidity and snow cover data, and monthly Class A pan evaporation data.

It is emphasized that neither the simple assumption underlying the annual estimates or the more complex set of assumptions underlying the use of the alternative procedure have been verified in any rigorous manner.

4. Section 13.2.2.3, "Controls," was re-organized and re-written. The section now begins with an overview of three basic control methods (vehicle restrictions, surface improvement, and surface treatment). Extensive new material was added to address the effect of speed reduction and watering on fugitive dust emissions from unpaved roads. A new method for "prospective" analysis based on the alternative procedure for estimating emissions using hourly precipitation data and Class A pan evaporation data was added. Slight revisions were made to the material presented for chemical unpaved road dust suppressants.

5. The revised Table 13.2.2-1 is as follows [bold indicates additions, strikeouts indicate deletions]:

Table 13.2.2-1. TYPICAL SILT CONTENT VALUES OF SURFACE MATERIAL ON INDUSTRIAL AND RURAL UNPAVED ROADS[a]

Industry	Road Use Or Surface Material	Plant Sites	No. Of Samples	Silt Content (%)	
				Range	Mean
Copper smelting	Plant road	1	3	16 - 19	17
Iron and steel production	Plant road	19	135	0.2 - 19	6.0
Sand and gravel processing	Plant road	1	3	4.1 - 6.0	4.8
	Material storage area	**1**	**1**	**--**	**7.1**
Stone quarrying and processing	Plant road	2	10	2.4 - 16	10
	~~Haul road~~	~~1~~	~~10~~	~~5.0 - 15~~	~~9.6~~
	[Haul road to/from pit	**4**	**20**	**5.0-15**	**8.3]**
Taconite mining and processing	Service road	1	8	2.4 - 7.1	4.3
	Haul road [to/from pit]	1	12	3.9 - 9.7	5.8
Western surface coal mining	**Haul road [to/from pit]**	3	21	2.8 - 18	8.4
	[Plant] ~~Access~~ road	2	2	4.9 - 5.3	5.1
	Scraper route	3	10	7.2 - 25	17
	Haul road (freshly graded)	2	5	18 - 29	24
[Construction sites	**Scraper routes**	**7**	**20**	**0.56-23**	**8.5]**
[Lumber sawmills	**Log yards**	**2**	**2**	**4.8-12**	**8.4]**
~~Rural roads~~	~~Gravel/crushed limestone~~	~~3~~	~~9~~	~~5.0 - 13~~	~~8.9~~
	~~Dirt~~	~~7~~	~~32~~	~~1.6 - 68~~	~~12~~
~~Municipal roads~~	~~Unspecified~~	~~3~~	~~26~~	~~0.4 - 13~~	~~5.7~~
Municipal solid waste landfills	Disposal routes	4	20	2.2 - 21	6.4
[Publicly accessible roads	**Gravel/crushed limestone**	**9**	**46**	**0.10-15**	**6.4**
	Dirt (i.e., local material compacted, bladed, and crowned)	**8**	**24**	**0.83-68**	**11]**

[a] References 1,5-16.

4.5.2 Emission Factors

Analysis of the test data exhibited an emission factor equation appropriate for average conditions. The equation no longer contains speed and mean number of wheels as parameters. The current data base shows a correlation of emissions to the surface moisture content, which was added as a parameter. The annual precipitation is now considered only when the emission factor equation is annualized for a particular source. As with the old equation, the new equation allows for the emission calculations of different particle sizes (PM-2.5, PM-10, and PM-30) with the use of appropriate constants. The old Section 13.2.2 Equation (1) is presented below (striked out) followed by the new Section 13.2.2 Equation (1).

Old Equation (1) ~~$e = k(5.9)\ (s/12)(S/30)(W/3)^{0.7}\ (w/4)^{0.5}(365-p/365)$~~

~~where:~~
~~e = emission factor (lb/vmt)~~
~~k = particle size multiplier (dimensionless)~~
~~s = silt content of road surface material (%)~~
~~S = mean vehicle speed, (miles per hour [mph])~~
~~W = mean vehicle weight, megagrams (Mg) (ton)~~
~~w = mean number of wheels~~
~~p = number of days with at least 0.01 in. of precipitation per year~~

~~Aerodynamic particle size multiplier~~

~~Constant~~	~~PM-2.5~~	~~PM-10~~	~~PM-15~~	~~PM-30~~
~~k (lb/VMT)~~	~~0.095~~	~~0.36~~	~~0.50~~	~~0.80~~

New Equation (1)

$$E = \frac{k(s/12)^a(W/3)^b}{(M/0.2^c)}$$

where k, a, b

and c are empirical constants given below

E = size-specific emission factor (lb/vmt)
s = surface material silt content (%)
W = mean vehicle weight (tons)
M = surface material moisture content (%)

Constants for Equation 1 based on the stated aerodynamic particle size:

Constant	PM-2.5	PM-10	PM-30
k (lb/VMT)	0.38	2.6	10
a	0.8	0.8	0.8
b	0.4	0.4	0.5
c	0.3	0.3	0.4
Quality rating	C	B	B

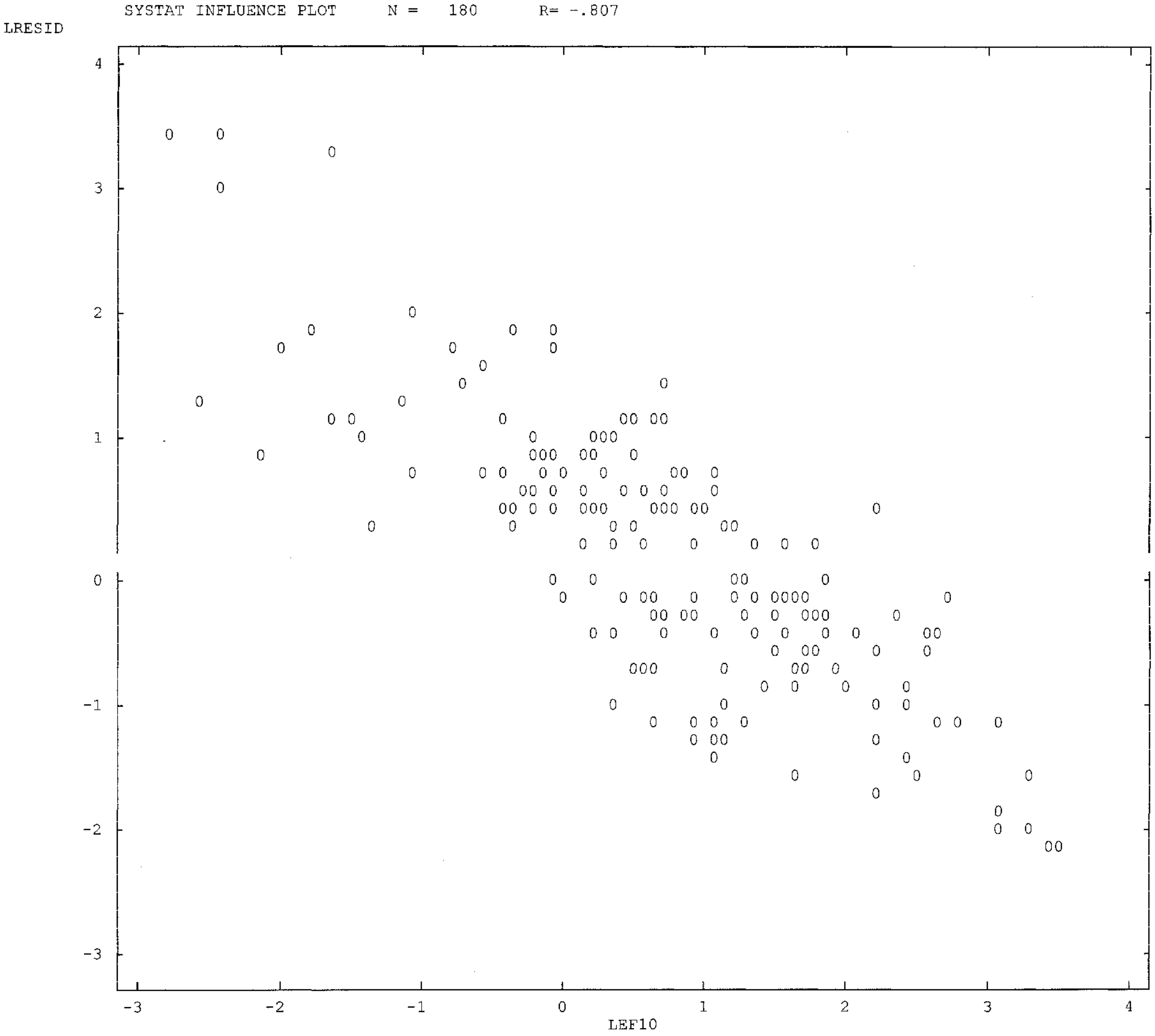


Figure 4-1. PM-10 residuals (log-scale) versus PM-10 emission factor (log-scale).

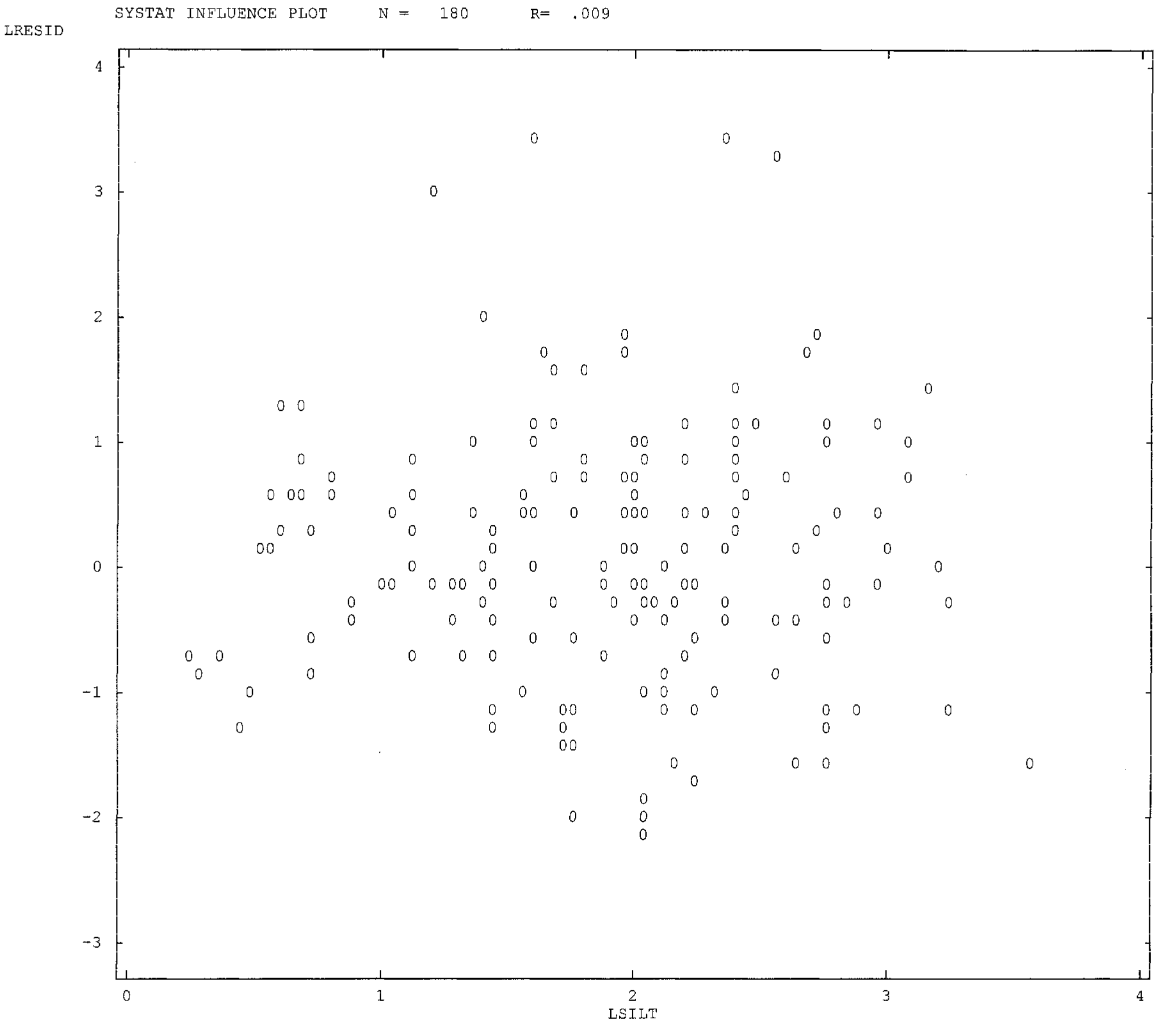


Figure 4-2. PM-10 residuals (log-scale) versus silt content (log-scale).

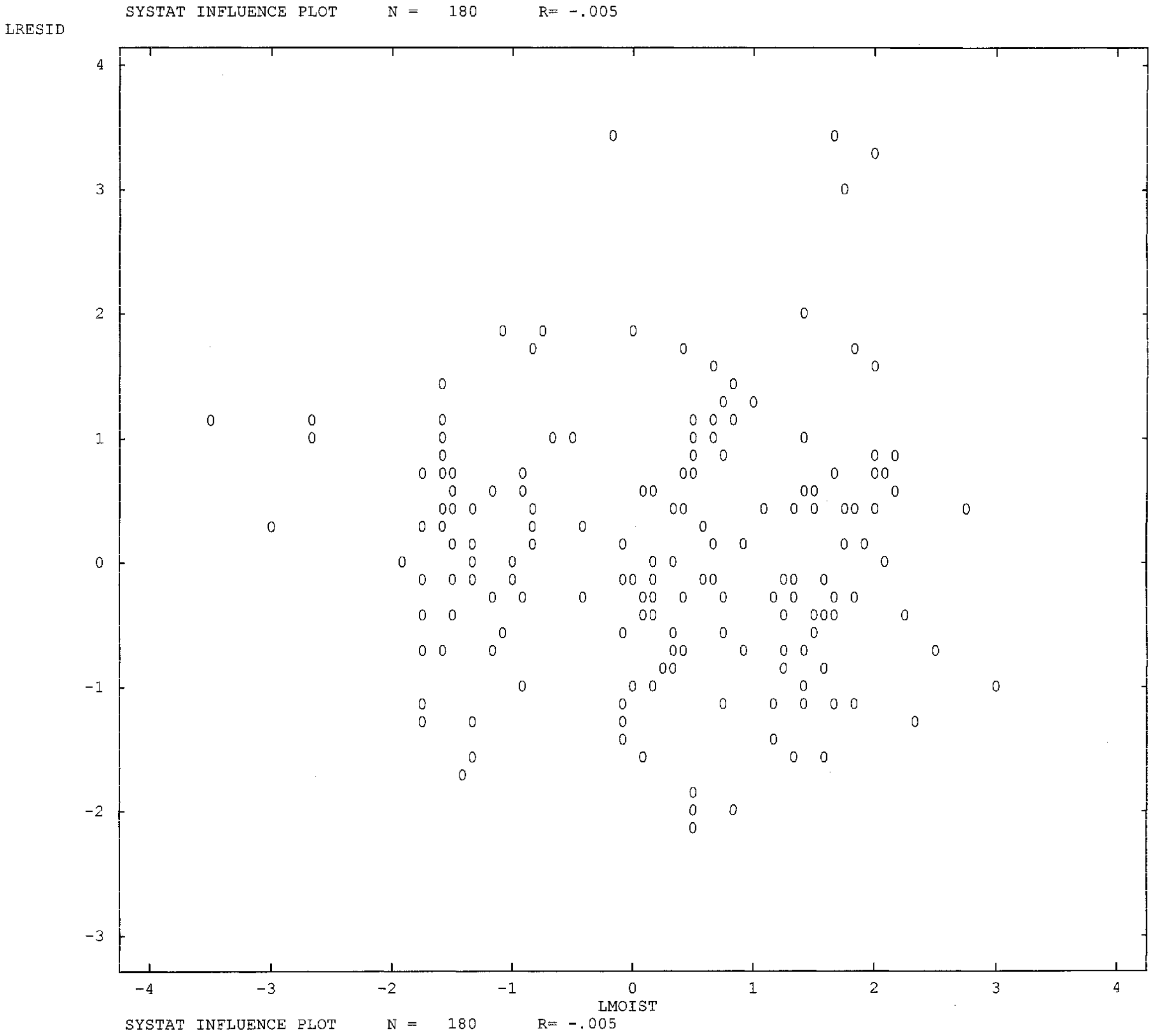


Figure 4-3. PM-10 residuals (log-scale) versus moisture content (log-scale).

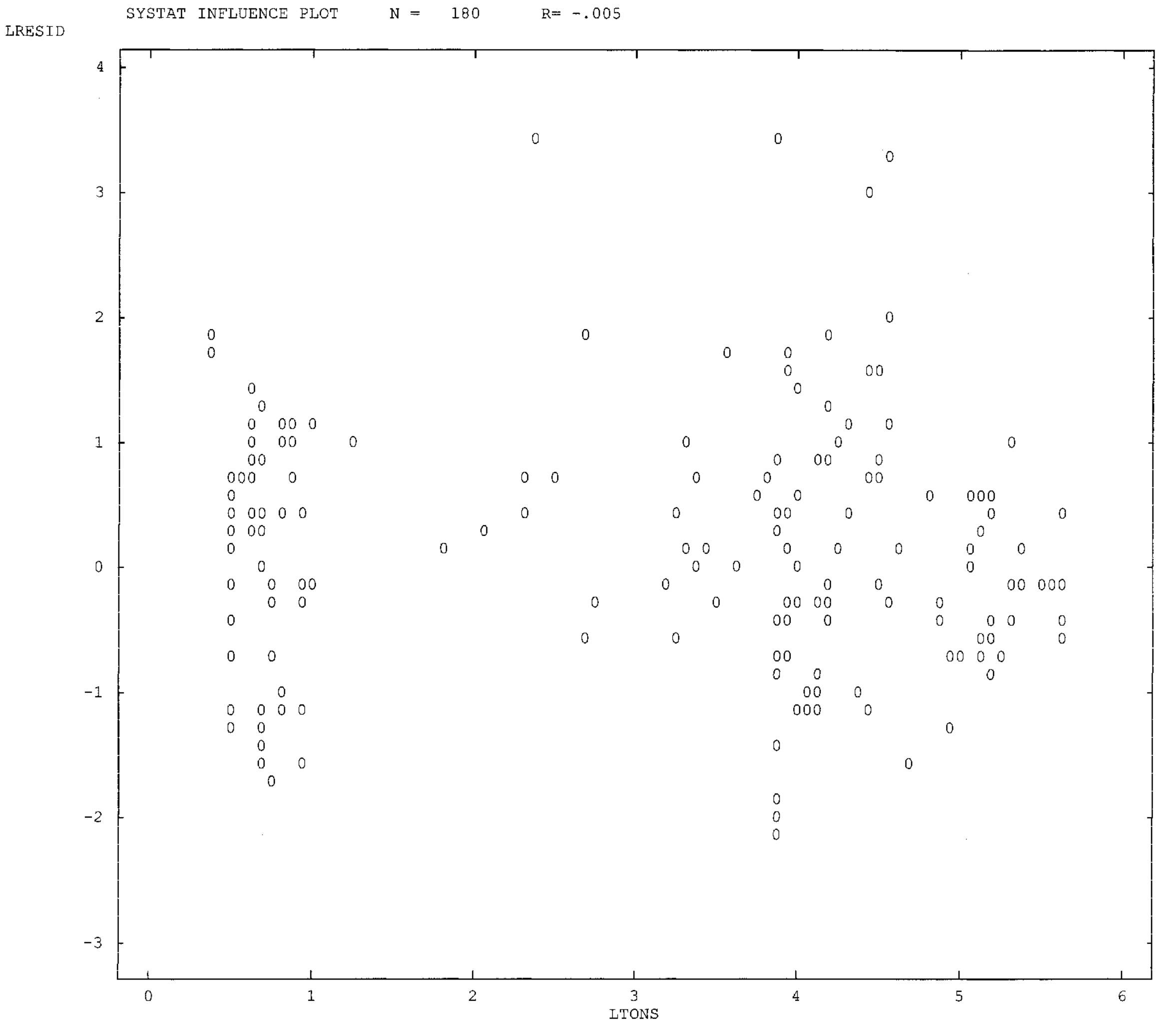


Figure 4-4. PM-10 residuals (log-scale) versus average vehicle weight (log-scale).

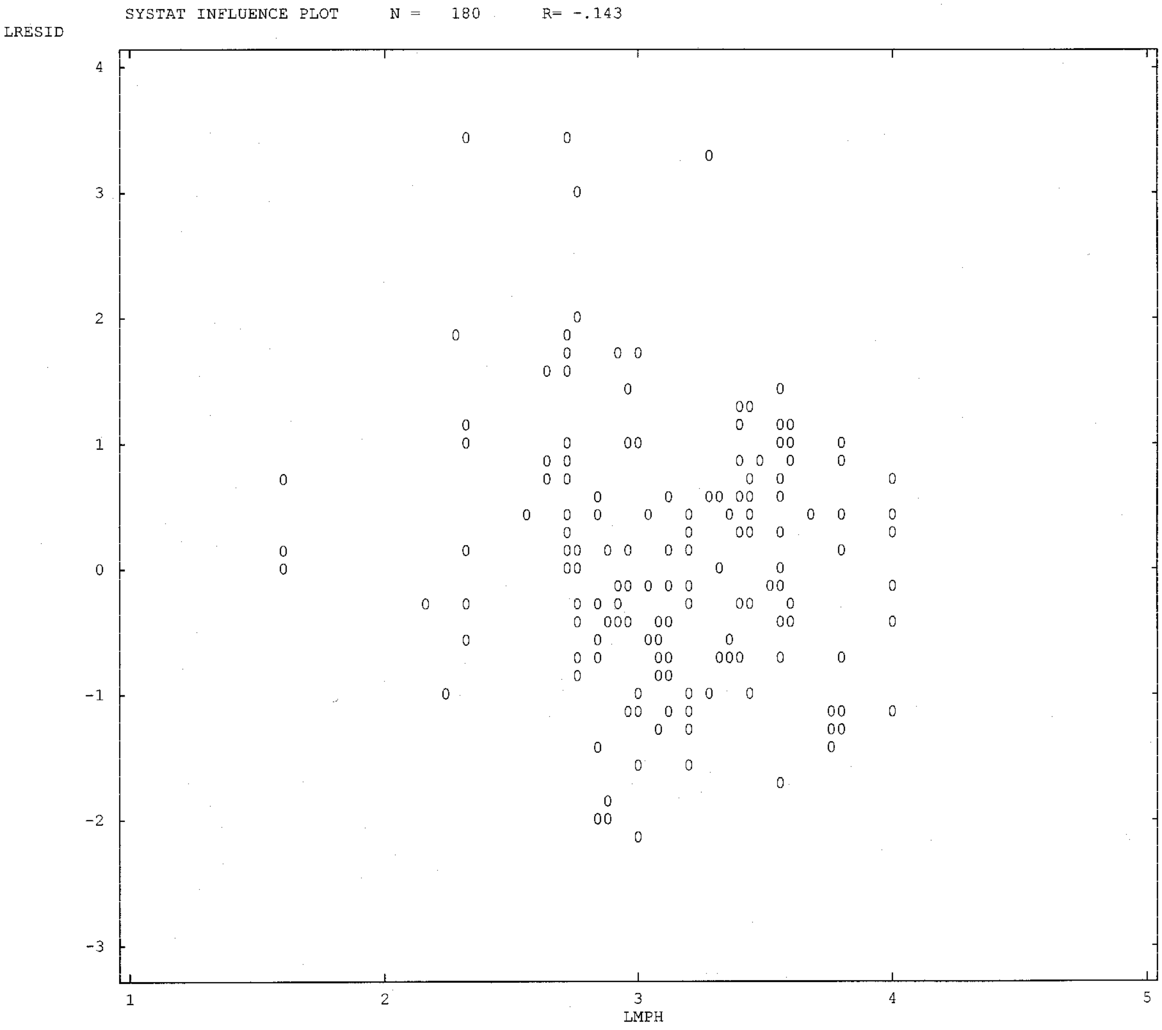


Figure 4-5. PM-10 residuals (log-scale) versus average vehicle speed (log-scale).

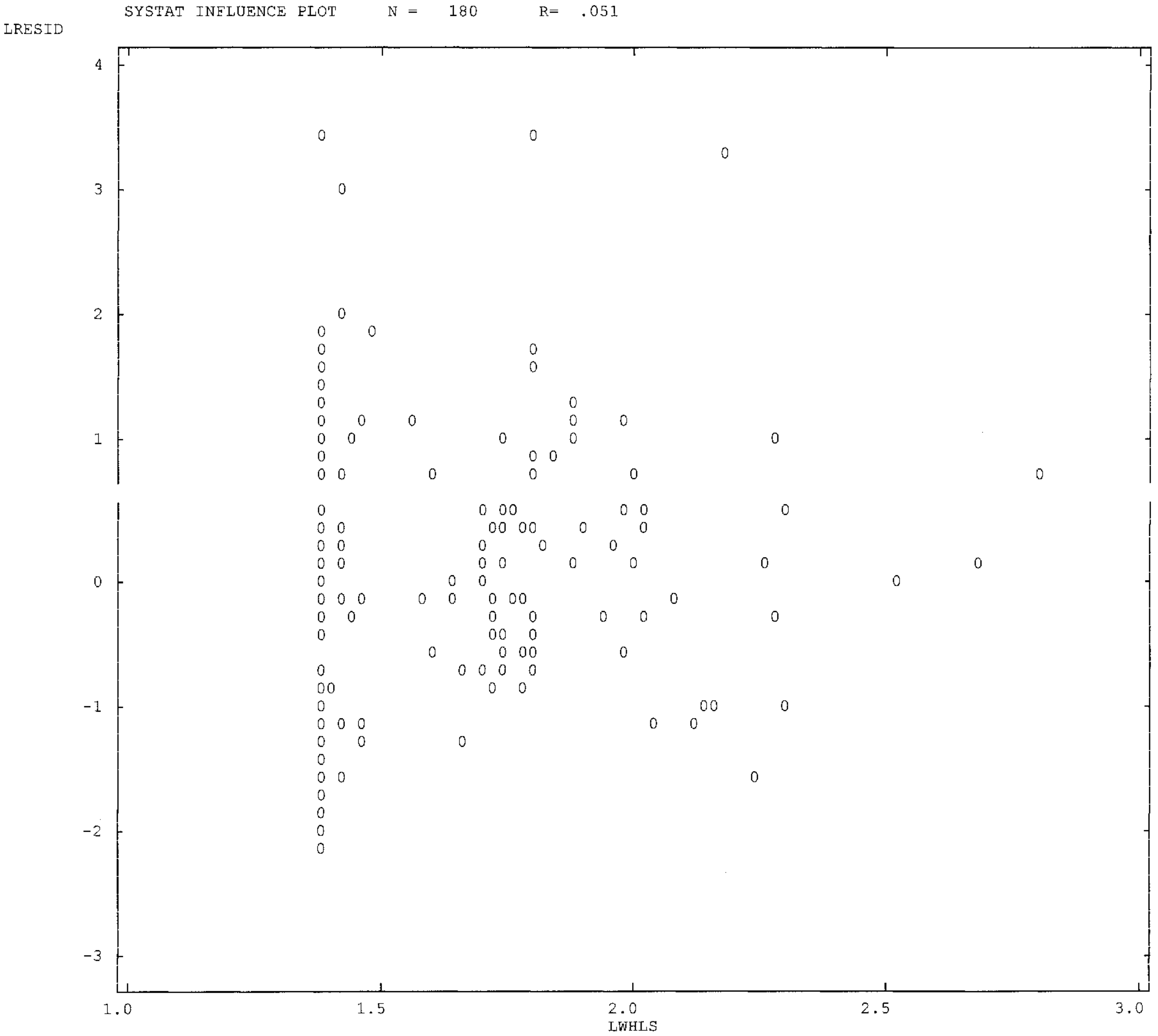


Figure 4-6. PM-10 residuals (log-scale) versus average number of wheels (log-scale).

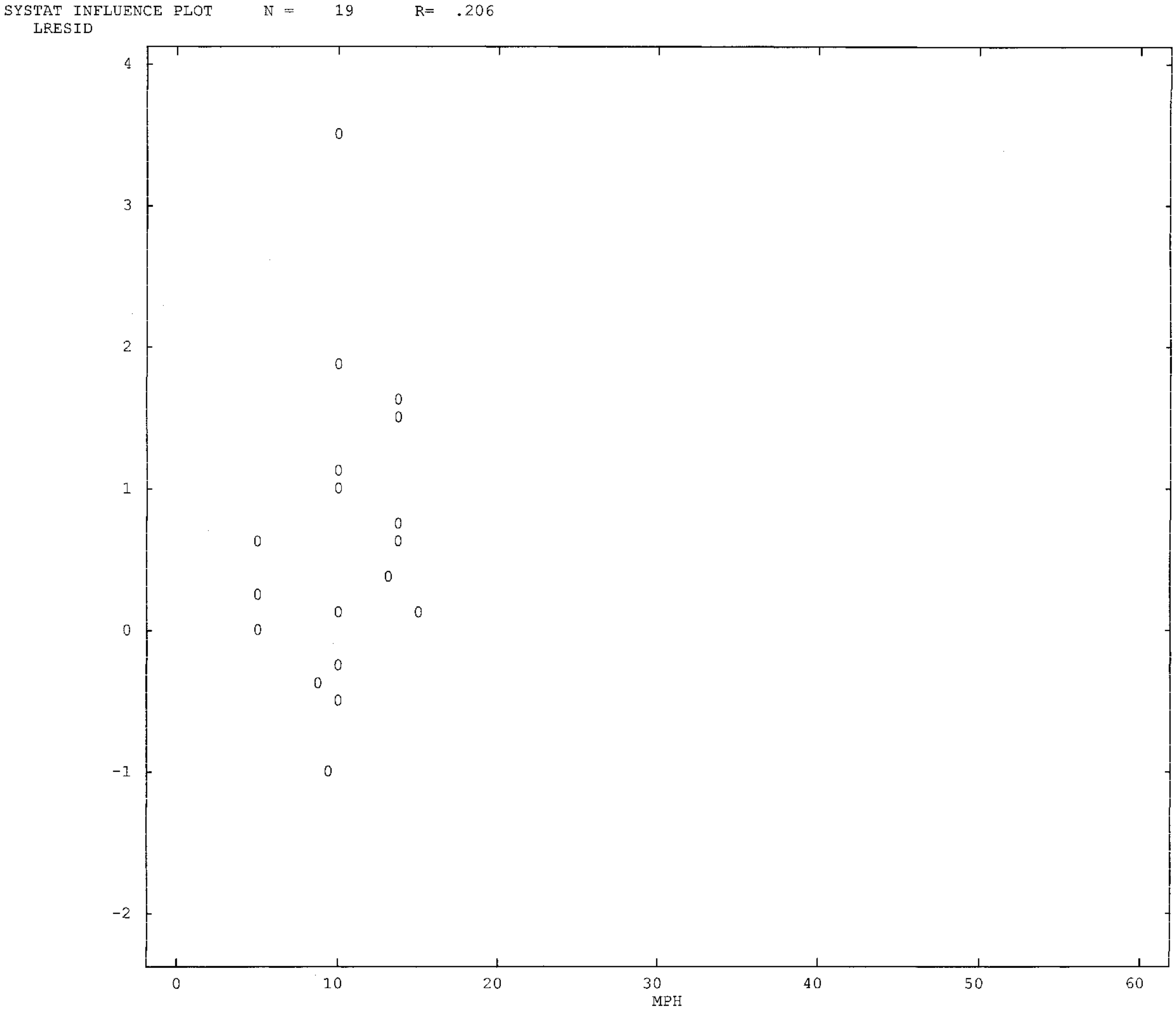


Figure 4-7. PM-10 residuals (log-scale) versus average vehicle speed <15 mph.

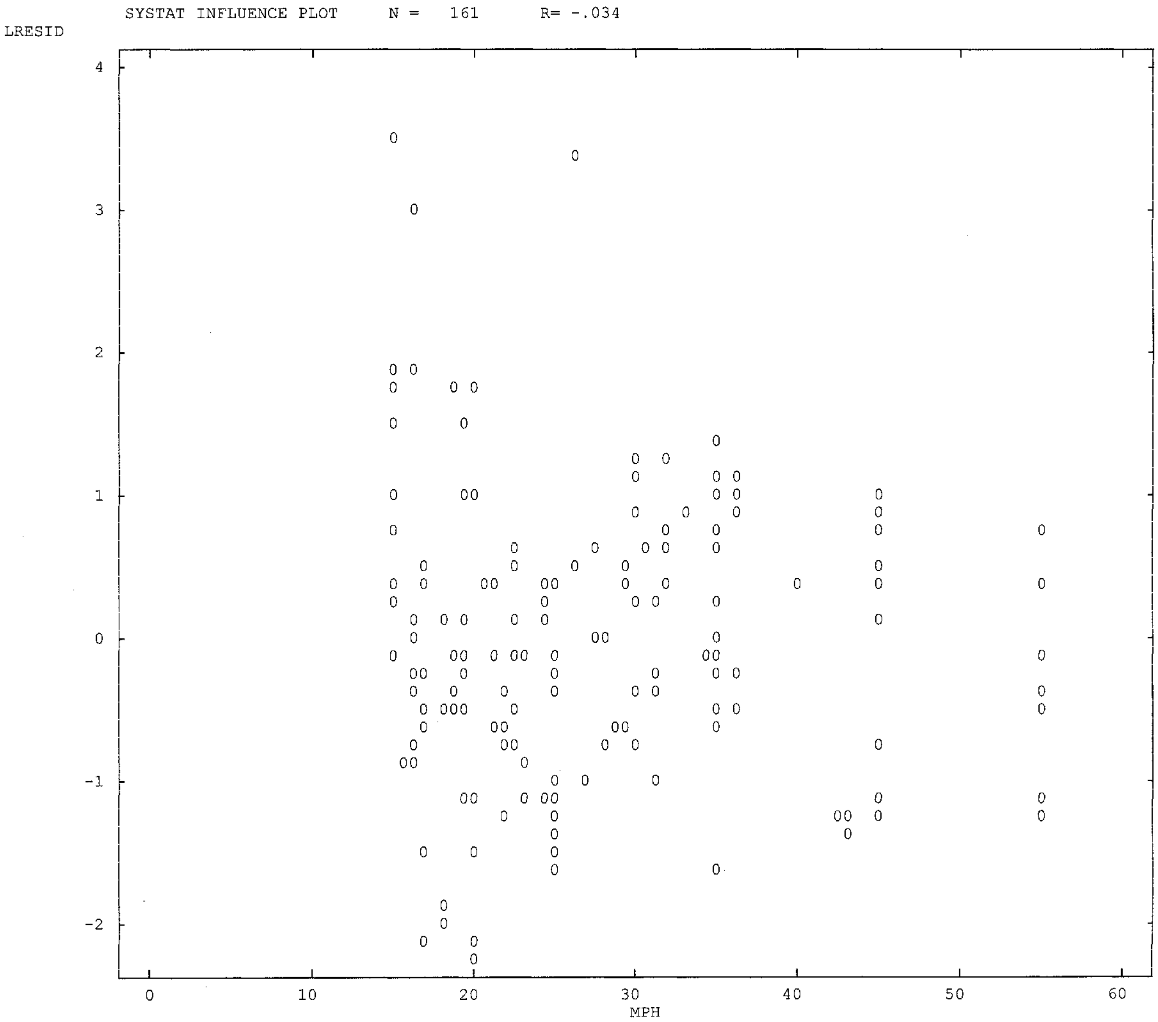


Figure 4-8. PM-10 residuals (log-scale) versus average vehicle speed >15 mph.

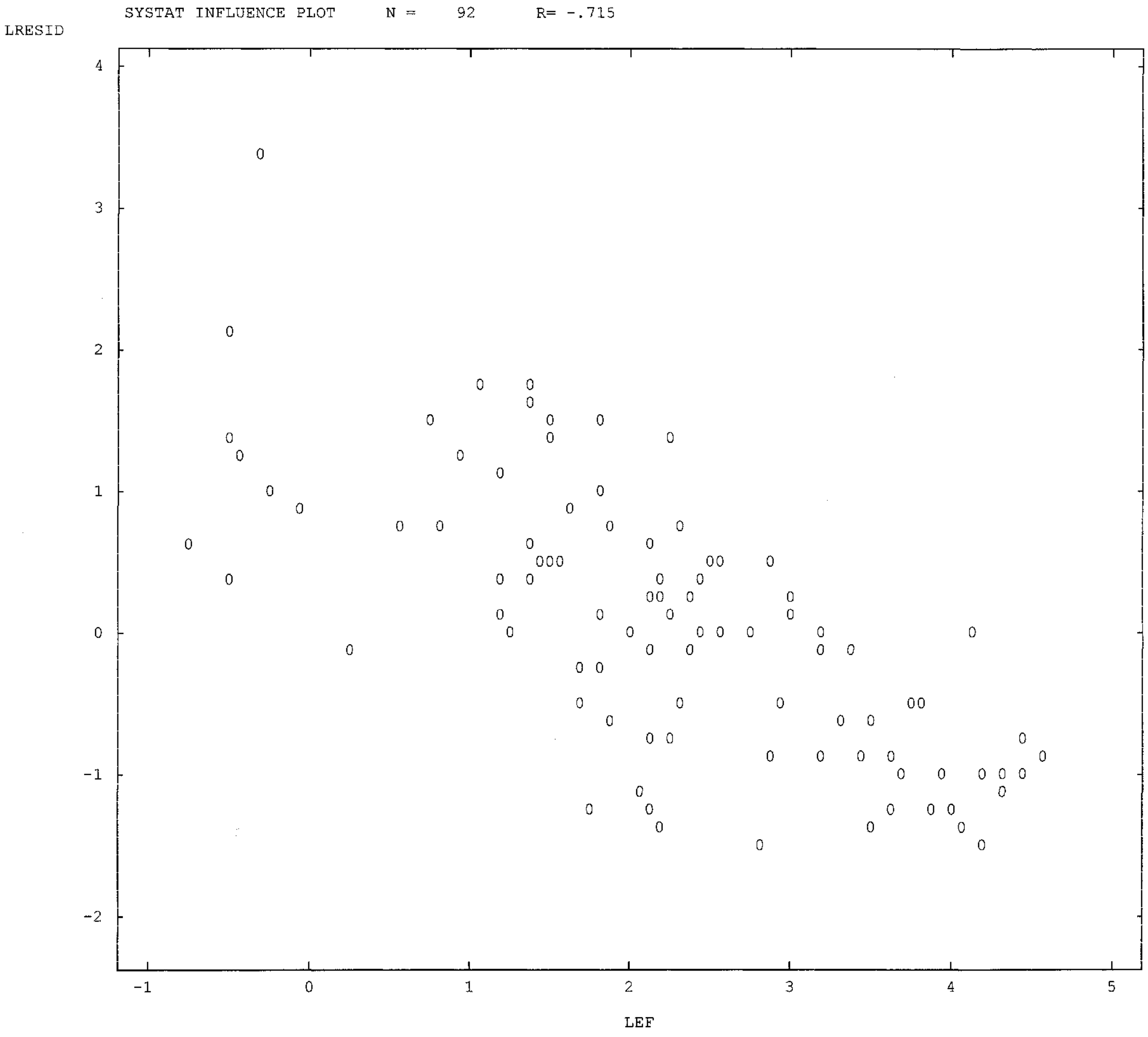


Figure 4-9. PM-30 residuals (log-scale) versus PM-30 emission factor (log-scale).

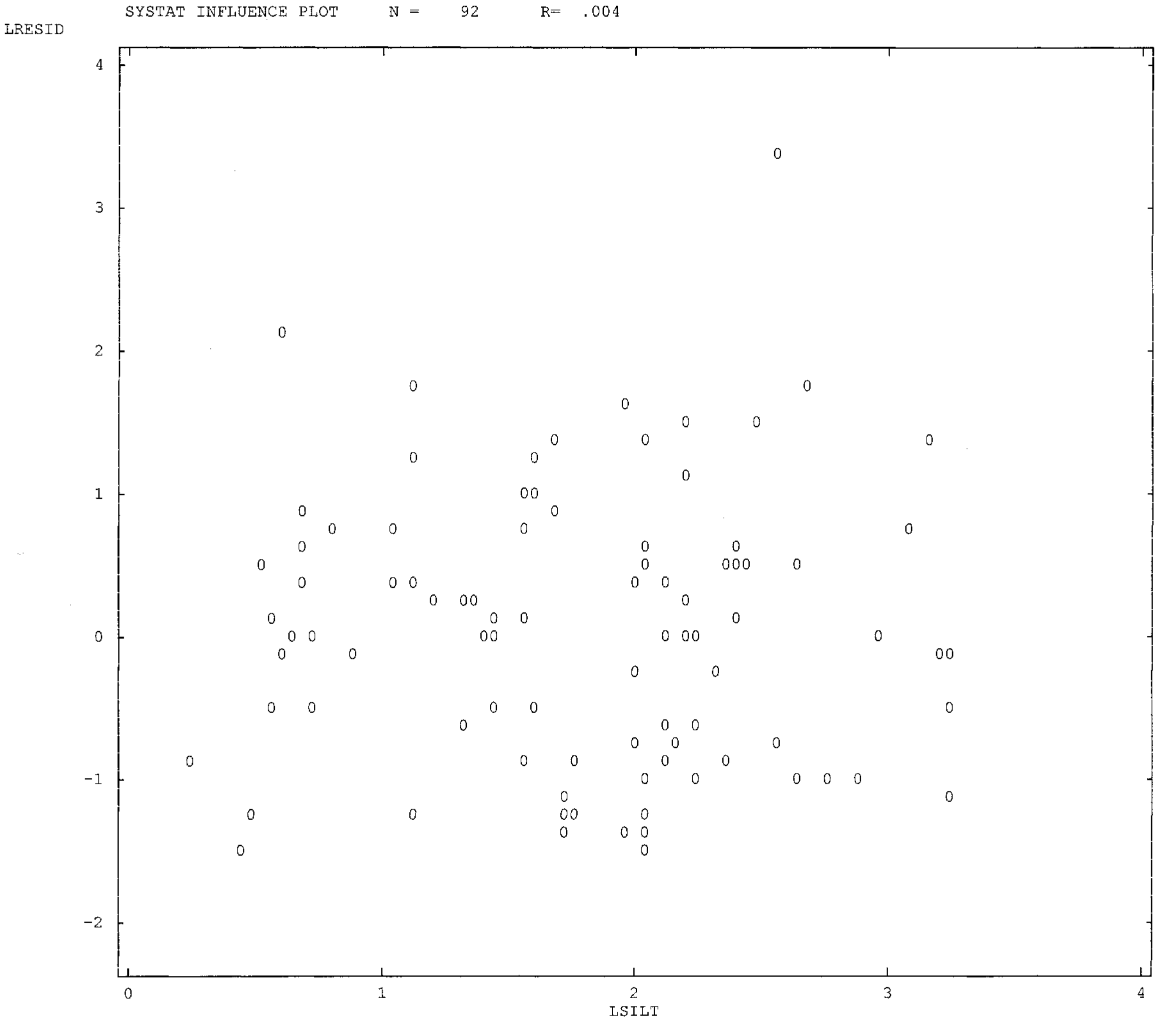


Figure 4-10. PM-30 residuals (log-scale) versus surface silt content (log-scale).

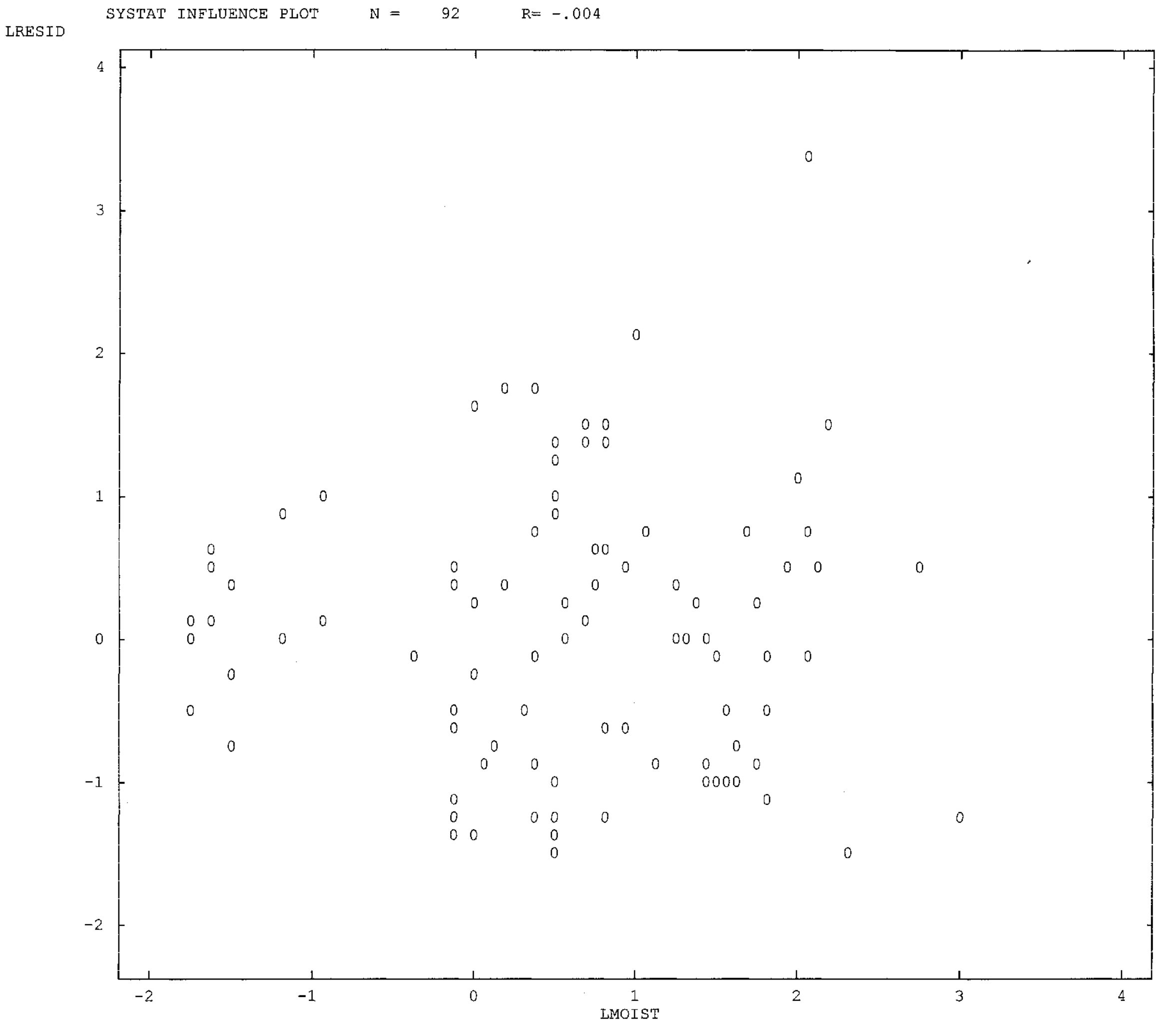


Figure 4-11. PM-30 residuals (log-scale) versus surface moisture content (log-scale).

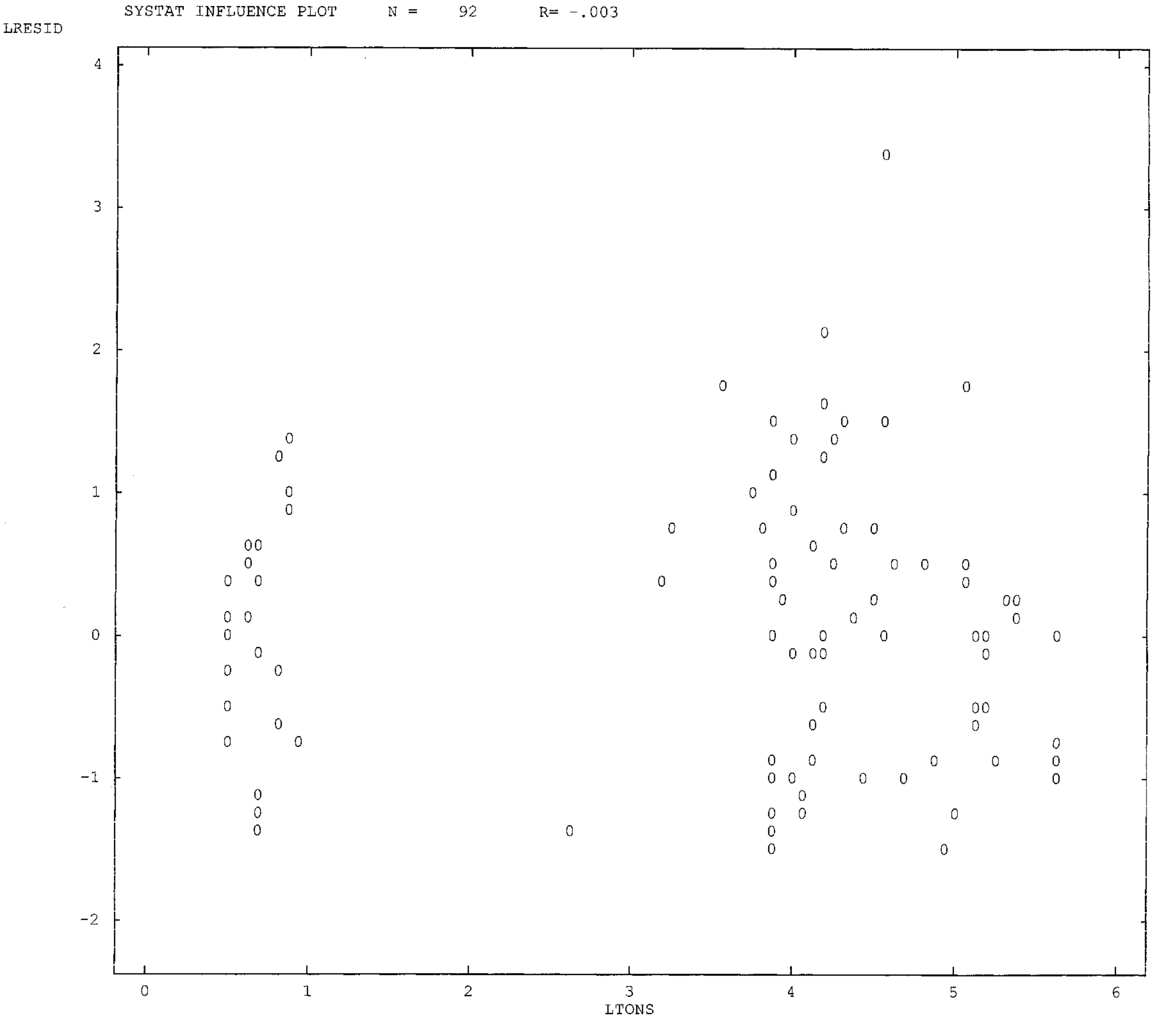


Figure 4-12. PM-30 residuals (log-scale) versus average vehicle weight (log-scale).

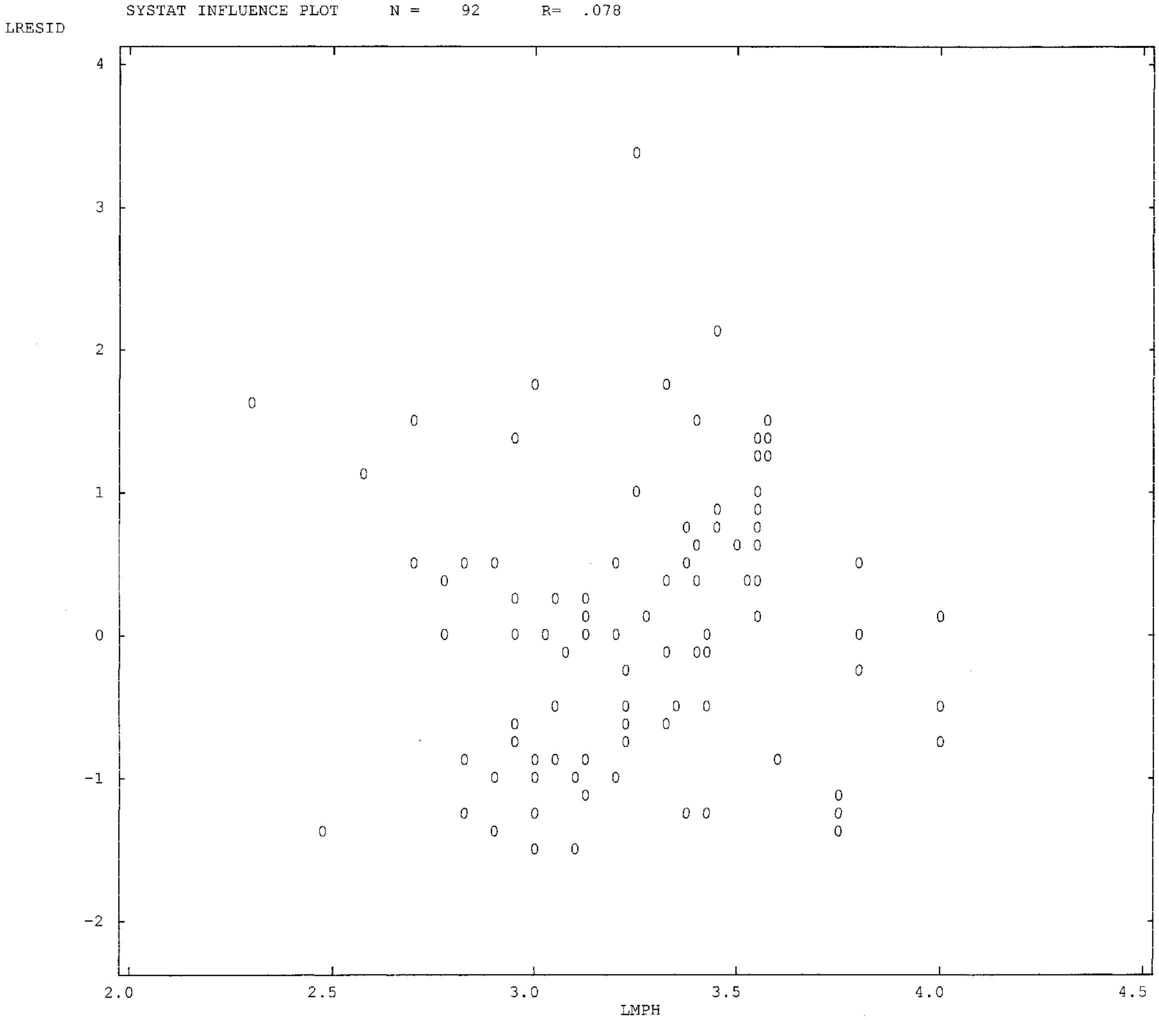


Figure 4-13. PM-10 residuals (log-scale) versus average vehicle speed (log-scale).

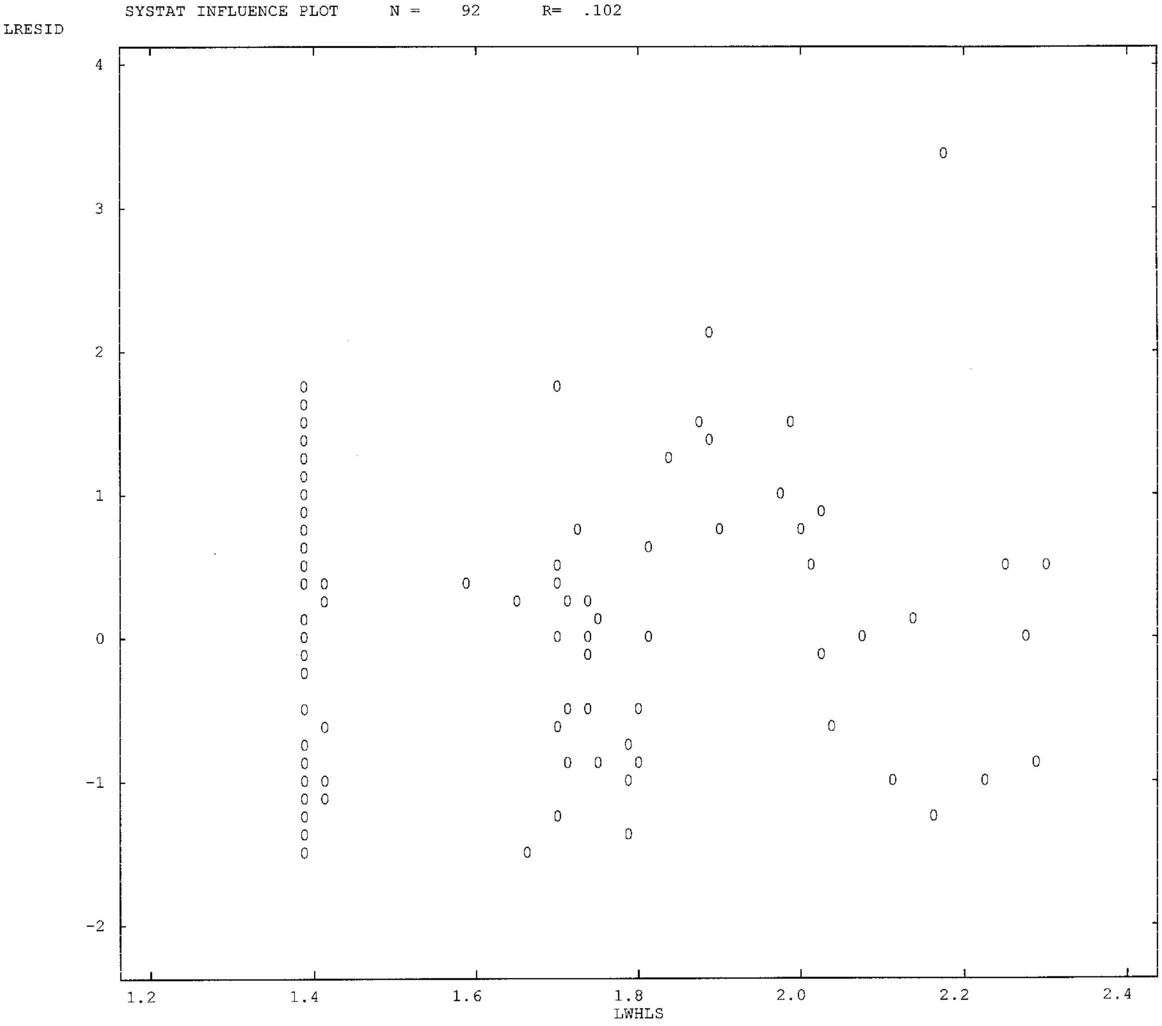


Figure 4-14. PM-10 residuals (log-scale) versus average number of wheels (log-scale).

TABLE 4-1. SUMMARY INFORMATION - REFERENCE 1

Operation	Control method	Test run	State	Test date	No. of tests	PM-10 emission factor, lb/VMT	
						Geom. mean	Range
Unpaved road	None	BK1-BK4	Nevada	5/96	4	0.820	0.309-2.65
Paved road	None	--	Nevada	5/96	3	0.0025	0.0022-0.0028

1 lb/VMT = 281.9 g/VKT

TABLE 4-2. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 1

Unpaved road test runs	PM-10 emission factor, lb/VMT	Duration, min.	Meteorology		Vehicle information			Mean vehicle speed, mph	Silt, %	Moisture %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels			
BK-1	0.375	59	72	6.0	138	1.5	4	15	7.2	0.48
BK-2	0.309	29	70	6.5	150	1.5	4	15	5.2	0.44
BK-3	1.48	47	70	6.6	100	2.0	4	15	5.9	0.45
BK-4	2.65	27	71	6.6	80	2.0	4	15	6.6	0.38

TABLE 4-3. SUMMARY INFORMATION - REFERENCE 2

Operation	Control method	Unpaved road test runs	State	Test date	No. of tests	PM-10 emission factor, lb/VMT	
						Geom. mean	Range
Scraper	None	BA1-BA2	Nevada	6/95	2	8.19	6.05 -11.1
Scraper	None	BA3-BA6	California	6/95	4	0.838	0.550-1.32
Scraper	Watering	BA8-BA9	California	6/95	2	0.174	0.090-0.340
Light duty	None	BA10-BA12	California	7/95	3	7.24	3.33-12.5

TABLE 4-4. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 2

Unpaved road test runs	PM-10 emission factor, lb/VMT	Duration, min	Temp., °F	Vehicle information				Silt, %	Moisture, %
				No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Mean vehicle speed, mph		
BA-1	6.05	43	91	19	54.8	4.2	8.8	7.69	1.16
BA-2	11.1	22	91	12	58.5	4.0	9.5	7.69	1.16
BA-3	1.32	40	74	17	86.5	4.0	14	6.04	7.41
BA-4	0.580	40	74	17	86.5	4.0	14	6.04	7.41
BA-5	1.17	56	74	14	77.0	4.0	14	6.04	7.41
BA-6	0.550	56	74	16	77.0	4.0	14	6.04	7.41
BA-8	0.340	13	70	42	86.7	4.1	16	4.11	4.14
BA-9	0.090	16	70	74	79.6	4.1	16	3.35	5.69
BA-10	3.33	29	105	32	2.8	4.3	25	15.5	0.27
BA-11	9.10	35	105	29	2.0	4.0	25	15.5	0.27
BA-12	12.5	28	105	31	2.0	4.1	25	15.5	0.27

TABLE 4-5. SUMMARY INFORMATION - REFERENCE 3[a]

Operation	Control method	Tests	State	Test date	No. of tests	PM-10 emission factor, lb/VMT		PM-2.5 emission factor, lb/VMT		PM-1 emission factor, lb/VMT	
						Geom. mean	Range	Geom. mean[b]	Range[b]	Geom. mean[b]	Range[b]
Stone quarry Haul truck	Watering	G-DW[b]	North Carolina	8/95	3	0.195	0.006-1.60	0.109	0.027-0.441	0.092	0.063 - 0.136
Stone quarry Haul truck	Watering	S-DW	North Carolina	8/95	3	1.37	0.490-2.99	0.353	0.137-1.32	0.059	0.015 - 0.360

1 lb/VMT = 281.9 g/VKT

[a] Emissions reported are said to include noncombustible particles only. Upwind measurements were not adjusted for noncombustible particles in report calculations.

[b] Negative emissions reported at Garner location are not included in range or geometric mean calculation.

TABLE 4-6. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 3

Unpaved road test runs	PM-10 emission factor, lb/VMT	Duration, min	Meteorology		Vehicle information				Silt, %	Moisture, %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Average vehicle speed, mph		
G-DW-M201A-2	0.0061	356	88	4.66	204	NA[a]	NA[b]	18.55	7.22	5.96
G-DW-M201A-3	1.60	360	85	6.21	245	NA[a]	NA[b]	18.55	6.73	3.65
G-DW-M201A-4	0.76	360	86	6.35	200	NA[a]	NA[b]	18.55	8.23	9.68
S-DW-M201A-1	2.99	240	91	4.99	128	NA[a]	NA[b]	16.87	6.65	3.97
S-DW-M201A-2	0.49	300	90	3.69	250	NA[a]	NA[b]	16.87	9.81	6.44
S-DW-M201A-3	1.74	360	79	6.53	168	NA[a]	NA[b]	16.87	6.48	4.59

[a] Mean vehicle weight not available - Estimated = 52 tons for AP-42 development.

[b] Mean number of wheels not available - Estimated = 6 wheels for AP-42 development.

TABLE 4-7. SUMMARY INFORMATION - REFERENCE 4

Operation	Location	State	Uncontrolled test runs	Test date	No. of tests	Uncontrolled TSP emission factor, lb/VMT		Uncontrolled PM-10 emission factor, lb/VMT		Controlled TSP emission factor, lb/VMT		Controlled PM-10 emission factor, lb/VMT	
						Geom. mean	Range	Geom. mean	Range	Geom. mean	Range	Geom. mean	Range
Haul road Summary	1, 1B, 2 and 4	Wyoming	BB2-16, BB29-34, BB36, BB44-48	9/92-10/92	42	31	0.49-95.1	5.5	0.08-15.6	15	4.64-84.2	2.6	0.83 - 13.0
Coal Haul Road	Site 1	Wyoming	BB2,3,10,11	9/92-10/92	6	42	20.2-95.1	6.1	2.86 -13.6	--	--	--	--
Coal Haul Road	Site 1B	Wyoming	BB6-8, BB12-16, BB45,BB48,	10/92	24	14	0.40 - 20.2	3.6	0.08-6.52	10	4.64-18.0	2.2	0.93 - 4.25
Coal Haul Road	Site 2	Wyoming	BB33,34	10/92	4	46	44.4-47.9	7.3	5.70-9.48	17	10.2-27.3	2.4	0.83 - 6.66
Overburden Haul Road	Site 4	Wyoming	BB29,31,36,44	10/92	8	72	1.27-84.2	13	0.25-15.6	57	38.4-84.2	5.8	2.61 - 13.0
Scrapper	Site 5	Wyoming	BB46,47	10/92	2	--	--	9.5	8.17-11.0	--	--	--	--

1 lb/VMT = 281.9 g/VKT

TABLE 4-8. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 4

					Meteorology			Vehicle				
Site	Run	PM-10 emission factor, lb/VMT	Control measure	Duration, min.	Vehicle passes	°F	Wind speed mph	Mean vehicle weight, ton	Avg. No. of wheels	Mean vehicle speed, mph	Silt, %	Moisture, %
1	BB-2	10.8	None	30	35	61	14.43	131	5.54	36.4	10.7	1.08
1	BB-3	13.6	None	25	35	61	14.43	131	5.54	36.4	10.7	1.08
1B	BB-6	4.67	None	55	40	74	9.68	200	5.80	22.7	3.57	1.19
1B	BB-7	6.51	None	66	45	74	9.60	200	5.73	22.4	3.57	1.19
1B	BB-8	5.20	None	29	18	79	8.68	220	5.56	21.2	3.78	1.01
1	BB-10	3.26	None	88	57	80	18.06	160	5.47	27.5	3.08	1.17
1	BB-11	1.79	None	89	57	80	18.02	160	5.47	27.5	3.08	1.17
1B	BB-12	1.49	None	58	50	73	14.29	155	5.80	22.6	2.24	1.09
1B	BB-13	1.49	None	60	50	73	14.26	155	5.80	22.6	2.24	1.09
1B	BB-14	2.62	None	80	44	59	9.88	92.0	5.18	22.9	3.32	1.77
1B	BB-15	4.37	None	64	41	62	11.39	183	5.66	21.3	2.05	1.39
1B	BB-16	5.18	None	63	51	62	10.01	178	5.57	22.1	2.05	1.39
1B	BB-17	1.63	Watering	79	50	65	12.73	169	5.48	24.6	2.08	1.80
1B	BB-18	4.25	Watering	93	71	65	9.92	184	5.97	23.0	1.34	1.29
1B	BB-19	3.13	Watering	67	47	65	8.15	192	5.74	22.8	1.25	1.45
1B	BB-20	2.69	Watering	53	41	68	7.98	175	5.66	24.3	3.89	1.40
1B	BB-21	1.81	Watering	82	32	78	8.11	218	5.75	22.8	1.76	2.00
1B	BB-22	1.38	Watering	36	32	82	4.54	161	5.50	24.3	1.70	2.50
1B	BB-23	0.940	Watering	52	33	87	7.55	181	5.70	22.6	1.90	4.10
1B	BB-25	1.24	Watering	62	40	60	18.17	207	5.70	19.2	3.82	4.00
1B	BB-26	2.97	Watering	79	63	66	13.51	183	5.65	21.8	2.45	4.40
1B	BB-27	3.86	Watering	72	42	69	12.05	244	5.81	19.5	2.72	1.89
4	BB-29	15.6	None	37	21	65	5.86	283	5.90	18.8	19.2	3.78

TABLE 4-8. (continued)

Site	Run	PM-10 emission factor, lb/VMT	Control measure	Duration, min.	Meteorology			Vehicle			Silt, %	Moisture, %
					Vehicle passes	°F	Wind speed mph	Mean vehicle weight, ton	Avg. No. of wheels	Mean vehicle speed, mph		
4	BB-31	9.34	None	37	22	65	5.18	271	6.09	20.8	19.2	3.78
2	BB-33	5.70	None	92	32	61	13.72	153	5.44	29.2	3.02	1.50
2	BB-34	9.45	None	72	36	63	12.24	170	6.06	28.6	4.88	0.91
2	BB-35	6.65	Watering	87	32	60	8.27	173	5.44	28.0	3.71	2.53
4	BB-36	14.2	None	44	21	69	4.63	286	6.00	19.3	12.9	5.00
1B	BB-38	3.22	Watering	50	43	53	22.71	141	5.26	22.0	1.57	10.3
1B	BB-39	1.70	Watering	45	40	53	22.52	137	5.25	21.8	1.44	12.3
4	BB-40	2.62	Watering	78	40	45	12.24	271	6.05	21.2	4.79	5.70
4	BB-41	5.66	Watering	97	51	45	11.88	267	5.92	22.3	6.48	5.03
4	BB-42	13.0	Watering	70	36	44	11.63	275	5.94	22.0	9.48	4.35
2	BB-43	0.810	Watering	48	25	62	14.11	164	5.52	30.4	1.78	4.65
4	BB-44	0.25	None	105	200	69	9.01	2.00	4.00	30.0	1.82	0.68
5	BB-46	11.0	None	89	32	80	10.13	63.0	4.06	15.5	12.7	4.88
5	BB-47	8.16	None	44	14	80	5.31	65.0	4.00	18.0	14.0	5.11
1B	BB-45	0.0782	None	75	322	53	9.93	2.00	4.00	30.0	1.95	2.10
1B	BB-48	0.120	None	50	381	53	7.71	2.00	4.00	30.0	1.95	2.10

TABLE 4-9. SUMMARY INFORMATION - REFERENCE 5

Operation	Control method	Tests	State	Test date	No. of tests	PM-10 emission factor, lb/VMT	
						Geom. mean	Range
Stone quarry haul truck	Watering	W-201A-1 to W-201A-3	North Carolina	8/95	3	0.112	0.0553-0.217
Stone quarry haul truck	None	D-201A-1 to D-201A-4	North Carolina	8/95	4	1.74	0.528-4.70

1 lb/VMT = 281.9 g/VKT

TABLE 4-10. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 5

Unpaved road test runs	PM-10 emission factor, lb/VMT[a]	Duration, min.	Meteorology		Vehicle information				Silt, %	Moisture, %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton[b]	Mean No. of wheels[c]	Average vehicle speed, mph[b]		
W-201A-1	0.116	330	69	2.7	190	52.5	NA	16.94	5.86	5.59
W-201A-2	0.055	360	63	1.1	192	52.5	NA	16.94	7.35	6.31
W-201A-3	0.217	180	57	1.0	95	52.5	NA	16.94	7.19	5.87
D-201A-1	0.528	70	62	2.3	33	52.5	NA	16.94	8.54	2.22
D-201A-2	1.57	120	72	1.6	72	52.5	NA	16.94	7.34	1.19
D-201A-3	2.34	90	73	1.3	57	52.5	NA	16.94	9.25	1.31
D-201A-4	4.70	120	62	2.1	78	52.5	NA	16.94	11.03	0.83

[a] Emission Factors are average of left hood and right hood concentrations.

[b] Mean vehicle weight and average vehicle speed were a representative sample applied to entire testing period.

[c] Mean number of wheels not reported, estimated mean from truck description = 6.

TABLE 4-11. SUMMARY INFORMATION - REFERENCE 6

Operation	Control method	Test run	State	Test date	TSP emission factor, lb/VMT			PM-10 emission factor, lb/VMT		
					No. of tests	Geom. mean	Range	No. of tests	Geom. mean	Range
35 mph rural road	None	AZ	Arizona	5/90	3	3.40	3.19 - 3.86	9	0.735	0.497 - 1.43
45 mph rural road	None	AZ	Arizona	5/90	3	4.59	3.56 - 5.94	9	1.26	0.777 - 2.97
55 mph rural road	None	AZ	Arizona	5/90	3	6.73	5.35 - 9.24	9	1.70	0.969 - 2.88

1 lb/VMT = 281.9 g/VKT

TABLE 4-12. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 6

Unpaved road test runs[a]	PM-10 emission factor, lb/VMT	Duration, min.	Avg. wind, mph	Vehicle information				Silt, %	Moisture, %
				No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Mean vehicle speed, mph		
AZ-01	0.780	21	4.9	53	1.9	4.0	45	11	0.2
AZ-02	--[b]	21	4.9	53	1.9	4.0	45	11	0.2
AZ-03	0.920	22	6.0	55	1.9	4.0	45	11	0.2
AZ-04	0.880	22	6.0	55	1.9	4.0	45	11	0.2
AZ-05	1.35	71	4.2	62	1.9	4.1	55	11	0.2
AZ-06	1.46	71	4.2	62	1.9	4.1	55	11	0.2
AZ-07	0.970	31	4.8	54	1.9	4.0	55	11	0.2
AZ-08	--[b]	31	4.8	54	1.9	4.0	55	11	0.2
AZ-09	0.500	97	5.9	172	1.9	4.0	35	11	0.2
AZ-10	--[b]	97	5.9	172	1.9	4.0	35	11	0.2
AZ-11	0.670	96	3.9	178	1.9	4.0	35	11	0.2
AZ-12	0.630	96	3.9	178	1.9	4.0	35	11	0.2
AZ-21	0.810	42	8.2	98	1.6	4.0	45	7.4	0.22
AZ-22	0.920	42	8.2	98	1.6	4.0	45	7.4	0.22
AZ-23	1.16	47	5.0	50	1.6	4.0	45	7.4	0.22
AZ-24	--[b]	47	5.0	50	1.6	4.0	45	7.4	0.22
AZ-25	1.55	27	5.4	51	1.6	4.0	55	7.4	0.22
AZ-26	--[b]	27	5.4	51	1.6	4.0	55	7.4	0.22
AZ-27	2.01	39	7.4	77	1.6	4.0	55	7.4	0.22
AZ-28	2.01	39	7.4	77	1.6	4.0	55	7.4	0.22
AZ-29	0.730	50	7.0	153	1.6	4.0	35	7.4	0.22
AZ-31	0.630	82	4.0	105	1.6	4.1	35	7.4	0.22
AZ-32	--[b]	82	4.0	105	1.6	4.1	35	7.4	0.22
AZ-33	0.650	46	6.4	134	1.8	4.0	35	7.4	0.22
AZ-41	1.03	96	3.8	155	1.6	4.1	35	4.3	0.17
AZ-42	0.680	96	3.8	155	1.6	4.1	35	4.3	0.17
AZ-43	1.43	76	3.7	107	1.6	4.0	35	4.3	0.17
AZ-44	--[b]	76	3.7	107	1.6	4.0	35	4.3	0.17
AZ-45	1.28	48	3.9	72	1.6	4.0	55	4.3	0.17

TABLE 4-12. (continued)

Unpaved road test runs[a]	PM-10 emission factor, lb/VMT	Duration, min.	Avg. wind, mph	Vehicle information				Silt, %	Moisture, %
				No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Mean vehicle speed, mph		
AZ-46	--[b]	48	3.9	72	1.6	4.0	55	4.3	0.17
AZ-47	2.88	97	3.0	35	1.6	4.0	55	4.3	0.17
AZ-48	2.62	97	3.0	35	1.6	4.0	55	4.3	0.17
AZ-49	2.97	72	5.2	36	1.6	4.3	45	4.3	0.17
AZ-50	2.57	72	5.2	36	1.6	4.3	45	4.3	0.17
AZ-51	1.91	115	5.0	45	1.6	4.0	45	4.3	0.17
AZ-52	--[b]	115	5.0	45	1.6	4.0	45	4.3	0.17

[a] Test runs include simultaneously collected samples (ex. AZ-01 and AZ-02). Tests AZ-1 through 12, AZ-21 through -33, and AZ-41 through -52 conducted in Pinal, Pima, and Yuma Counties, respectively.

[b] TSP emission factor.

TABLE 4-13. SUMMARY INFORMATION - REFERENCE 7

Operation	Location	State	Test dates	No. of tests	Controlled TSP emission factor, lb/VMT		Controlled PM-10 emission factor, lb/VMT	
					Geom. mean	Range	Geom. mean	Range
Vehicle traffic	AU-X (Unpaved road)	PA	11/89	2	0.61	0.39-0.96	0.16	0.14-0.18
Vehicle traffic	Paved road	PA	11/89	6	0.033	0.012-0.12	0.0095	0.0009-0.036
Vehicle traffic	Paved road	PA	11/89	4	0.078	0.033-0.30	0.022	0.0071-0.036

1 lb/VMT = 281.9 g/VKT.

TABLE 4-14. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 7

Unpaved road - test runs	PM-10 emission factor, lb/VMT	Control method	Duration, min.	Meteorology		Vehicle information			Silt content, %
				Temp., °F	Wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean vehicle speed, mph	
AU-X-1	0.14	Chemical suppressant	168	62	8.7	110	3.9	25	3.3
AU-X-2	0.18	Chemical suppressant	71	60	6.5	101	2.1	26	4.1

TABLE 4-15. SUMMARY INFORMATION - REFERENCE 8

Operation	Control method	Test runs	State	Test date	No. of tests	TSP emission factor, lb/VMT		IP emission factor, lb/VMT		PM-10 emission factor, lb/VMT		PM-2.5 emission factor, lb/VMT	
						Geom. mean	Range	Geom. mean	Range	Geom. mean	Range	Geom. mean	Range
Heavy-duty traffic	None (U)	AP	Indiana	5/85 & 8/85	4	10.3	2.20 - 37.6	1.21	0.064 - 7.91	2.55	0.575 - 6.42	0.408	0.156 - 0.791
Heavy-duty traffic	Calcium chloride (C)	AP	Indiana	5/85 & 8/85	1	1.26	1.26	--	--	--	--	--	--
Heavy-duty traffic	Petro Tac (P)	AP	Indiana	5/85 & 8/85	5	2.59	0.645-7.70	0.305	0.076-1.46	0.193	0.048-1.08	0.066	0.019-0.369
Heavy-duty traffic	Coherex (X)	AP	Indiana	5/85 & 8/85	5	4.68	0.653-21.3	0.776	0.108-4.26	0.564	0.078-3.20	0.079	0.011-0.766
Heavy-duty traffic	None (U)	AQ	Missouri	9/85, 10/85, & 11/86	2	6.67	5.68-7.84	1.47	1.25-1.72	1.00	0.851-1.18	0.180	0.153-0.212
Heavy-duty traffic	Calcium chloride (C)	AQ	Missouri	9/85, 10/85, & 11/86	6	2.09	0.211-17.5	0.279	0.032-3.87	0.144	0.008-2.98	0.418	0.102-0.922
Heavy-duty traffic	Generic (G)	AQ	Missouri	9/85, 10/85, & 11/86	11	3.05	1.27-14.5	0.728	0.397-2.46	0.546	0.279-2.03	0.118	0.029-0.724
Heavy-duty traffic	Petro Tac (P)	AQ	Missouri	9/85, 10/85, & 11/86	5	4.84	2.57-11.9	0.781	0.387-2.26	0.572	0.283-1.78	0.134	0.064-0.582
Heavy-duty traffic	Soil Sement (S)	AQ	Missouri	9/85, 10/85, & 11/86	11	1.63	0.200-6.78	0.265	0.050-1.08	0.176	0.014-0.816	0.053	0.009-0.148
Heavy-duty traffic	Coherex (X)	AQ	Missouri	9/85, 10/85, & 11/86	9	2.14	0.208-10.5	0.282	0.034-1.42	0.182	0.017-1.11	0.104	0.013-0.334

1 lb/VMT = 281.9 g/VKT.

TABLE 4-16. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 8

Unpaved road test runs	PM-10 emission factor, lb/VMT	Duration, min.	Meteorology		Vehicle information				Silt, %	Moisture, %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Avg. vehicle speed, mph[a]		
AP2-P	0.0479	128	70	11	68	27	12.3	15	1.9	0.46
AP2-X	--	128	70	7.6	68	27	12.3	15	<0.05	0.50
AP2-C	--	128	70	4.2	65	28	11.8	15	2.7	1.2
AP2-U	6.42	127	70	4.2	8	33	7.0	15	8.1	0.64
AP3-P	0.124	119	70	11	50	29	7.08	15	2.6	0.36
AP3-X	0.0780	119	70	8.5	50	29	7.08	15	<0.05	1.4
AP3-C	--	119	70	8.5	50	29	7.08	15	4.3	1.4
AP3-U	4.47	119	70	6.2	10	37	5.2	15	8.3	1.1
AP5-P	1.08	84	73	2.6	34	28	13.9	15	6.1	0.12
AP5-X	3.20	82	73	3.9	34	28	13.9	15	11	0.14
AP6-P	0.178	59	75	2.0	51	26	17.4	15	6.8	0.13
AP6-X	1.38	56	75	3.7	51	26	17.4	15	10	0.08
AP6-U	--	46	75	3.7	51	26	17.4	15	7.3	0.10
AP7-P	0.231	104	72	0.92	87	26	13.5	15	11	--
AP7-X	0.293	109	72	1.6	90	26	13.4	15	12	--
AP7-U	0.575	87	72	1.6	85	25	13.4	15	6.0	--
AQ1-U	0.851	64	82	8.4	50	10	6.0	15	7.0	1.5
AQ1-G	0.887	66	82	8.4	50	10	6.0	15	7.6	1.5
AQ1-S	0.201	75	82	8.4	50	10	6.0	15	0.6	0.94
AQ1-X	0.809	75	82	8.4	50	10	6.0	15	15	1.2
AQ2-U	1.18	69	82	8.7	68	9.8	5.9	15	7.0	1.5
AQ2-G	1.04	82	82	8.7	68	9.8	5.9	15	7.6	1.5
AQ2-S	0.158	85	82	8.7	68	9.8	5.9	15	0.6	0.94
AQ2-X	0.504	82	82	8.7	68	9.8	5.9	15	15	1.2
AQ3-P	0.401	105	75	11	76	9.7	5.9	15	3.1	1.8
AQ3-G	0.329	52	75	9.0	19	9.3	5.8	15	6.8	1.5

TABLE 4-16. (continued)

Unpaved road test runs	PM-10 emission factor, lb/VMT	Duration, min.	Meteorology		Vehicle information				Silt, %	Moisture, %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Avg. vehicle speed, mph[a]		
AQ3-S	0.135	50	75	9.0	19	9.6	5.9	15	1.5	1.1
AQ3-X	0.103	47	75	9.0	19	9.6	5.9	15	12	1.6
AQ4-G	2.03	22	75	11	50	24	6.0	15	6.8	1.5
AQ4-S	0.440	28	75	10	50	24	6.0	15	1.5	1.1
AQ4-X	0.585	22	75	12	50	24	6.0	15	12	1.6
AQ4-C	0.451	33	75	13	50	24	6.0	15	--	--
AQ5-P	1.78	21	63	5.9	34	24	5.9	15	5.0	1.1
AQ5-G	0.497	20	63	5.9	34	24	5.9	15	10	1.3
AQ5-S	0.816	29	63	5.9	34	24	5.9	15	4.4	0.99
AQ5-C	2.98	20	63	5.9	34	24	5.9	15	12	1.4
AQ6-P	0.568	18	75	5.0	44	24	6.0	15	5.0	1.1
AQ6-G	0.812	28	75	5.0	36	24	6.0	15	10	1.3
AQ6-S	0.646	23	75	5.0	36	24	6.0	15	4.4	0.99
AQ6-C	2.43	23	75	5.0	36	24	6.0	15	12	1.4
AQ7-P	0.283	30	64	6.5	50	24	6.0	15	3.6	1.2
AQ7-G	0.390	25	64	6.5	48	24	6.0	15	7.0	1.2
AQ7-S	0.284	28	64	6.5	50	24	6.0	15	2.9	0.95
AQ7-X	0.929	28	64	6.5	50	24	6.0	15	6.7	--
AQ8-P	0.536	22	70	5.0	36	24	6.0	15	3.6	1.2
AQ8-G	0.401	16	70	5.0	34	24	6.0	15	7.0	1.2
AQ8-S	0.422	17	70	5.0	34	24	6.0	15	2.9	0.95
AQ8-X	1.11	17	70	5.0	34	24	6.0	15	6.7	--
AQ9-G	0.282	110	64	6.5	125	10	6.0	15	.76	0.95
AQ9-S	0.0145	110	64	6.5	125	10	6.0	15	1.2	0.77
AQ9-X	0.0200	62	64	6.5	79	10	6.0	15	1.1	0.78
AQ9-C	0.0084	267	64	6.5	125	10	6.0	15	1.6	2.1

TABLE 4-16. (continued)

Unpaved road test runs	PM-10 emission factor, lb/VMT	Duration, min.	Meteorology		Vehicle information				Silt, %	Moisture, %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Avg. vehicle speed, mph[a]		
AQ10-G	0.279	138	61	6.6	200	7.6	5.3	15	2.9	1.3
AQ10-S	0.0340	134	61	6.6	200	7.6	5.3	15	--	--
AQ10-X	0.0168	129	61	6.6	200	7.6	5.3	15	--	--
AQ10-C	0.0204	133	61	6.6	200	7.6	5.3	15	--	--
AQ11-G	0.422	127	55	8.7	250	6.5	5.0	15	2.9	1.3
AQ11-S	0.0848	127	55	8.7	250	6.5	5.0	15	--	--
AQ11-X	0.0255	130	55	8.7	250	6.5	5.0	15	--	--
AQ11-C	0.0161	130	55	8.7	250	6.5	5.0	15	--	--

[a] Tests at AQ were conducted with captive traffic and vehicles were operated at 15 mph. For test runs, control methods were desacribed with the following codes: C = calcium chloride, G = Generic, P = Petro Tac, U = uncontrolled, S = Soil Sement, X = Coherex.

TABLE 4-17. SUMMARY INFORMATION - REFERENCE 9

Operation	Test runs	State	Test date	No. of tests	TSP emission factor, lb/VMT		IP emission factor, lb/VMT		PM-10 emission factor, lb/VMT		PM-2.5 emission factor, lb/VMT	
					Geom. mean	Range	Geom. mean	Range	Geom. mean	Range	Geom. mean	Range
Uncontrolled tests - Scraper Travel	AN24-AN25	Michigan	8/85	4	51	41 - 64	34	28 - 43	26	22 - 33	7.7	6.3 - 10
Controlled Tests - Scraper Travel	AN21-AN23	Michigan	8/85	7	10	2.1 - 37	9.2	1.5 - 27	5.3	1.2 - 21	1.6	.47 - 7.2

1 lb/VMT = 281.9 g/VKT

TABLE 4-18. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 9

Unpaved road test runs	PM-10 emission factor, lb/VMT	Control method	Duration, min.	Meteorology		Vehicle information				Silt, %	Moisture, %
				Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Avg. No. of wheels	Mean vehicle speed, mph		
AN21U	1.90	Watering	46	84	3.8	75	49	4	13	8.9	7.3
AN21X	1.20	Watering	57	84	3.7	59	49	4	15	8.9	8.7
AN21Y	6.70	Watering	81	84	3.9	99	49	4	16	8.9	3.5
AN22U	21.0	Watering	56	81	4.1	49	49	4	17	5.9	2.3
AN22Y	11.0	Watering	61	79	3.7	45	49	4	17	5.9	3.1
AN23U	7.30	Watering	35	77	3.1	40	49	4	16	8.4	3.6
AN23Y	4.80	Watering	15	72	2.1	20	49	4	16	8.4	3.4
AN24U	27.0	None	23	82	7.1	20	49	4	18	7.7	1.7
AN24Y	22.0	None	23	82	7.1	20	49	4	18	7.7	1.7
AN25U	33.0	None	12	83	6.8	10	49	4	20	7.7	1.7
AN25Y	30.0	None	12	83	6.8	10	49	4	20	7.7	1.7

AN21U = Site “AN” test no. 21 at station “U.”

TABLE 4-19. SUMMARY INFORMATION - REFERENCE 10

						TP emission factor, lb/VMT		TSP emission factor, lb/VMT		IP emission factor, lb/VMT		PM-10 emission factor, lb/VMT		PM-2.5 emission factor, lb/VMT	
Operation	Control method	Test run	State	Test date	No. of tests	Geom. Mean	Range	Geom. Mean	Range	Geom. Mean	Range	Geom. Mean	Range	Geom. Mean	Range
Heavy-duty traffic	None	AL 1, 3, 4, 7, 8, 9, 12	Indiana	6/84	6	10.4	7.16 - 15.9	4.66	3.69 - 7.13	3.20	2.65 - 4.82	2.46	2.02 - 3.75	0.781	0.618 - 1.23
Light/ Medium duty traffic	None	AL 2, 6, 10, 11	Indiana	6/84	4	4.61	2.54 - 6.88	2.13	1.75 - 2.88	1.39	1.12 - 2.02	1.09	0.860 - 1.58	0.377	0.274 - 0.524

1 lb/VMT = 281.9 g/VKT

TABLE 4-20. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 10

			Meteorology		Vehicle information				
Unpaved road test runs	PM-10 emission factor, lb/VMT	Duration, min	Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Mean vehicle speed, mph	Silt, %
AL-1	7.16	40	64	6.2	40	22	12	19	11.1
AL-2	3.05	55	64	6.3	31	7.7	5.2	20	11.1
AL-3	7.90	24	80	7.6	41	28	14	19	10.6
AL-4	13.3	24	80	9.2	41	27	13	20	10.6
AL-6	4.04	20	80	9.0	42	7.1	4.7	20	10.6
AL-7	9.36	29	73	5.4	42	28	14	17	11
AL-8	8.12	31	73	4.8	40	33	16	18	11
AL-9	3.65	44	59	11	67	31	15	25	6.9
AL-10	3.27	37	59	12	50	9.0	5.6	20	6.9
AL-11	5.60	30	59	14	50	11	6.3	20	6.9
AL-12	7.80	25	60	6.0	39	32	15	16	10.3

TABLE 4-21. SUMMARY INFORMATION - REFERENCE 11

			TP emission factor, lb/VMT		IP emission factor, lb/VMT		PM-10 emission factor, lb/VMT		PM-2.5 emission factor, lb/VMT	
Operation	Type	Control method	Geom. mean	Range	Geom. mean	Range	Geom. mean	Range	Geom. mean	Range
Rural roads	Crushed Limestone - Light duty	None	21.9	17.9-27.0	3.84	3.17-4.99	2.17	1.75-3.09	0.334	0.300-0.407
Rural roads	Dirt - Light duty	None	28.6	11.1-42.1	3.42	2.83-4.18	1.60	0.951-1.99	0.293	0.090-0.507
Rural roads	Gravel - Light duty	None	6.70	5.43-7.96	1.25	1.10-1.39	0.835	0.713-0.957	0.366	0.251-0.481
Copper smelter	Medium duty vehicle	None	8.99	7.62-10.0	2.57	2.21-2.97	1.67	1.46-1.91	0.317	0.283-0.370
Stone crushing	Medium duty vehicle	None	25.0	9.36-35.2	7.1	3.20-9.67	--	2.15-5.83	4.17	2.15-5.83
Sand and gravel	Heavy duty vehicle	None	11.1	8.28-15.3	3.92	3.35-4.44	2.73	2.34-3.26	0.742	0.620-0.982

1 lb/VMT = 281.9 g/VKT

TABLE 4-22. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 11

Run No.	PM-10 emission factor, lb/VMT	Industrial category	Type of traffic	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean No. wheels	Mean vehicle speed, mph	Silt content, %	Moisture content, %
U-1	9.13	Rural roads crushed limestone	Light duty	8.28	125	1.9	4.0	35	9.5	0.25
U-2	3.09	Rural roads crushed limestone	Light duty	7.61	105	1.9	4.0	35	9.1	0.3
U-3	1.75	Rural roads crushed limestone	Light duty	2.46	101	1.9	4.0	35	7.7	0.27
U-4	1.87	Rural roads crushed limestone	Light duty	7.16	102	1.9	4.0	25	8.6	0.4
U-5	1.97	Rural roads crushed limestone	Light duty	11.6	107	2.3	4.0	25	9.2	0.37
U-6	--	Rural roads crushed limestone	Light duty	13.2	51	1.9	4.0	30	--	--
AB-1	12.1	Rural roads dirt	Light duty	13.2	94	2.3	4.0	25	35.1	3.9
AB-2	0.950	Rural roads dirt	Light duty	6.49	50	2.3	4.0	25	16.7	4.5
AB-3	1.99	Rural roads dirt	Light duty	8.50	50	2.3	4.0	25	16.8	3.2
AB-4	1.86	Rural roads dirt	Light duty	11.2	50	2.3	4.0	25	5.8	3.1
AE-1	0.710	Rural roads gravel	Light duty	9.62	46	2.1	4.0	40	5.0	0.26
AE-2	0.960	Rural roads gravel	Light duty	11.2	22	1.8	4.0	35	5.0	0.26
AA-1	2.15	Stone crushing	Med. duty	4.70	55	11	5.0	15	13.7	0.4
AA-2	0.940	Stone crushing	Med. duty	2.46	24	13	4.4	15	15.3	0.34
AA-3	0.090	Stone crushing	Med. duty	4.92	34	10	4.0	10	10.5	0.84
AA-4	4.52	Stone crushing	Med. duty	8.05	56	14	5.6	10	15.6	2.1
AA-5	5.83	Stone crushing	Med. duty	9.40	56	13	5.0	10	15.6	2.1
AC-1	1.63	Copper smelting	Light duty	4.25	51	2.2	4.8	10	19.1	0.07
AC-2	1.46	Copper smelting	Light duty	5.37	49	2.1	4.0	10	15.9	0.07
AC-3	1.91	Copper smelting	Light duty	6.93	51	2.4	4.3	10	16	0.03

TABLE 4-23. SUMMARY INFORMATION - REFERENCE 12

Operation	Control method	Location	State	Test date	No. of tests	TP emission factor, lb/VMT		IP emission factor, lb/VMT		PM-2.5 emission factor, lb/VMT	
						Geom. mean	Range	Geom. mean	Range	Geom. mean	Range
Heavy-duty traffic	None	E	Ohio	11/80	3	132	129 - 133	30.5	25.9 - 33.5	8.35	7.74 - 8.84
Heavy-duty traffic	Coherex	C	Ohio	11/80	4	5.04	3.35 - 8.17	1.48	1.18 - 2.04	0.439	0.274 - 0.594
Heavy-duty traffic	Watering	E	Ohio	11/80	3	28.9	8.27 - 99.3	4.94	0.992 - 25.8	1.07	0.219 - 5.46
Light-duty traffic	None	B	Ohio	7/80	4	11.7	9.98 - 14.2	2.69	1.05 - 4.25	0.731	0.245 - 1.27
Light-duty traffic	Coherex	B	Ohio	10/80	5	0.636	0.089 - 1.23	0.226	0.061 - 0.384	0.0628	0.0318 - 0.0945

1 lb/VMT = 281.9 g/VKT

TABLE 4-24. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 12

Site	Unpaved road test runs	PM-10 emission factor, lb/VMT[a]	Type	Control	Duration, min.	Meteorology		Vehicle information				Silt, %
						Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Avg. No. of wheels	Mean vehicle speed, mph	
E	F-68	25.1	Heavy-duty	None	17	50	7.4	21	22	5.9	20	14
E	F-69	20.6	Heavy-duty	None	13	50	7.9	14	53	10	20	--
E	F-70	25.3	Heavy-duty	None	13	50	8.2	10	53	10	20	16
E	F-65	0.70	Heavy-duty	Watering	57	60	6.4	64	53	10	20	4.5
E	F-66	3.53	Heavy-duty	Watering	20	60	5.5	41	54	9.0	25	--
E	F-67	19.4	Heavy-duty	Watering	17	55	9.5	30	54	9.8	25	5.1
C	F-59	--	Heavy-duty	Coherex	125	50	9.3	61	19	9.3	16	5.4
C	F-60	--	Heavy-duty	Coherex	123	50	8.2	84	46	9.2	22	5.4
C	F-63	--	Heavy-duty	Coherex	107	50	5.2	118	54	7.7	18	2.5
C	F-64	--	Heavy-duty	Coherex	121	50	6.5	136	54	7.8	15	--
B	F-28	0.750	Light-duty	None	45	78	1.6	101	3	4	15	--
B	F-29	3.34	Light-duty	None	34	79	6.2	50	3	4	15	--
B	F-30	2.40	Light-duty	None	17	79	6.2	50	3	4	15	--
B	F-31	3.10	Light-duty	None	40	80	3.5	33	3	4	15	--
B	F-40	--	Light-duty	Coherex	133	50	4.0	300	3	4	25	0.015
B	F-41	--	Light-duty	Coherex	100	50	5.1	255	3	4	25	0.075
B	F-42	--	Light-duty	Coherex	128	50	7.0	294	3	4	25	0.99
B	F-43	--	Light-duty	Coherex	120	50	8.5	300	3	4	25	--
B	F-44	--	Light-duty	Coherex	55	50	9.1	200	3	4	25	1.8

[a] PM-10 emission factor calculated from logarithmic interpolation of PM-15 and PM-2.5 data.

TABLE 4-25. SUMMARY INFORMATION - REFERENCE 13

Operation	Control method	Test run	State	Test date	No. of tests	TSP emission factor, lb/VMT		IP emission factor, lb/VMT		PM-10 emission factor, lb/VMT		PM-2.5 emission factor, lb/VMT	
						Geom. Mean	Range	Geom. Mean	Range	Geom. Mean	Range	Geom. Mean	Range
Heavy-duty traffic	None	AG1-3	Indiana	6/82	3	18.1	12.0-23.4	3.80	1.38 - 7.47	3.05	1.34 - 5.55	0.384	0.117-0.994
Heavy-duty traffic	Petro Tac	AG4-11	Indiana	6/82	8	3.39	0.963-8.88	0.366	0.015-2.24	0.282	0.035-1.54	0.080[a]	0.0154 to 0.259
Heavy-duty traffic	None	AJ1-3	Missouri	9/82	3	16.4	13.8 - 21.4	3.79	2.94 - 5.15	2.86	2.14 - 4.17	0.694	0.498 - 0.915
Heavy-duty traffic	Watering	AJ4-6	Missouri	9/82	3	1.77	0.255-5.81	0.340	0.086-0.781	0.242	0.051-0.563	0.191	0.122-0.272
Heavy-duty traffic	Coherex	AJ7-18	Missouri	9/82	12	2.79	0.384-16.6	0.42	0.047-3.57	0.233	0.006-2.23	0.076[a]	0.0049 to 0.449

1 lb/VMT = 281.9 g/VKT

[a] Only included test runs with reported measurements.

TABLE 4-26. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 13

Unpaved road test runs	PM-10 emission factor, lb/VMT	Duration, min.	Meteorology		Vehicle information				Silt, %	Moisture %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Mean vehicle speed, mph		
AG-1	1.34	31	71	4.2	27	27	9.8	15	7.5	0.59
AG-2	5.55	106	69	7.4	30	25	7.3	17	5.8	0.33
AG-3	3.82	99	70	5.8	22	28	6.6	16	7.2	0.27
AG-4	0.097	107	52	2.7	79	23	9.2	15	0.28	--
AG-5	0.248	128	69	4.8	120	32	10	14	0.29	--
AG-6	0.035	166	87	6.6	160	30	13	15	5.0	--
AG-7	0.136	202	71	2.2	84	34	10	16	4.9	--
AG-8	0.610	100	70	3.2	93	31	9.1	14	5.3	--
AG-9	1.54	75	69	6.3	31	28	6.1	13	8.2	--
AG-10	1.11	76	65	3.4	49	31	8.1	13	8.5	--
AG-11	0.335	62	74	2.6	62	26	5.8	14	13	--
AJ-1	4.17	48	77	3.3	45	54	6.0	15	6.3	--
AJ-2	2.62	46	76	2.0	47	52	6.0	15	7.4	--
AJ-3	2.14	50	80	4.2	50	50	7.1	15	7.7	--
AJ-4	0.060	79	90	6.1	86	48	6.1	15	4.9	5.1
AJ-5	0.560	67	85	5.6	71	50	6.0	15	5.3	2.0
AJ-6	0.493	46	78	4.4	49	48	5.9	15	--	--
AJ-7	0.490	90	66	3.6	68	49	5.9	15	1.9	--
AJ-8	0.022	89	70	5.8	120	34	7.2	15	5.5	--
AJ-9	1.05	126	69	5.3	120	50	6.4	15	7.1	--
AJ-10	1.49	50	62	2.8	44	29	6.0	20	6.1	--
AJ-11	0.904	65	65	3.1	61	27	6.0	19	4.3	--
AJ-12	2.23	68	61	7.7	60	44	6.0	21	5.7	--
AJ-13	0.006	190	57	8.2	150	38	6.0	18	ND	--
AJ-14	0.183	240	42	12	250	56	6.0	22	0.034	--
AJ-15	0.313	131	49	8.8	107	54	6.0	17	1.6	--
AJ-16	0.098	140	55	4.9	140	32	6.0	23	2.1	--
AJ-17	0.066	125	65	7.9	120	34	6.0	20	1.5	--
AJ-18	0.373	119	43	5.0	115	31	6.0	22	1.7	--

TABLE 4-27. SUMMARY INFORMATION - REFERENCE 14

Operation	Control method	Test Run	State	Test date	No. of tests	TSP emission factor, lb/VMT		IP emission factor, lb/VMT		PM-2.5 emission factor, lb/VMT	
						Geom. mean	Range	Geom. mean	Range	Geom. mean	Range
Haul Truck	None	J9-J12,J20,J21, K1,K7,K9-K12, K26,L1,L3,L4, P1-3, P5	North Dakota, Wyoming, New Mexico	1979-80	20[a]	10.8	0.70 - 73	5.54	0.32 - 42	0.23	0.02 - 2.88
Haul Truck	Watering	K6,K8,K13,P4,P6-P9	Wyoming, New Mexico	1979-80	8[a]	2.97	0.60 - 8.4	1.51	0.40 - 4.1	0.09	0.05 - 0.16
Light/Medium Duty Truck	None	J13,J18,J19,K2, K3,K4,K5,P11,P12,P13	North Dakota, Wyoming, New Mexico	1979-80	10	2.94	0.60 - 9.0	1.79	0.33 - 6.6	0.119	0.03 - 1.5
Light/Medium Duty Truck	CaCl2	J7,J8	North Dakota	1979-80	2[b]	0.35	ND-0.35	0.34	ND-0.34	0.09	ND-0.09

1 lb/VMT = 281.9 g/VKT

[a] Haul Truck uncontrolled tests listed in report text = 19 and watered tests = 9, however data tables list 20 uncontrolled and 8 watered tests.

[b] Test Run J7 was reported as a nondetect (ND). Geometric Mean was calculated using only the detected test.

TABLE 4-28. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 14

Unpaved road test run	PM-10 emission factor lb/VMT[a]	Duration, min.	Meteorology		Vehicle information				Silt, %	Moisture, %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, tons	Mean No. of wheels	Mean vehicle speed, mph		
J-6	--	67	76.1	0.9	39	--	--	--	7.9	5.4
J-9	4.6	51	82.94	4.8	41	65	8	19.3	9.4	3.4
J-10	14.1	52	87.8	4.4	45	60	7.7	19.3	9.4	2.2
J-11	9.4	48	86.9	4.2	40	60	9.9	20	8.2	4.2
J-12	4.9	49	80.06	0.8	19	99	9.5	15	14.2	6.8
J-20	2.9	49	73.4	2.5	23	125	10	16.8	11.6	8.5
J-21	3.1	26	77	1.6	14	110	9.3	15	--	--
K-1	1.6	86	58.28	6.2	65	63	6.1	32.9	7.7	2.2
K-6	0.6	177	64.04	3.4	84	89	7.4	34.8	2.2	7.9
K-7	1.6	53	74.3	2.6	57	24	4.9	34.2	2.8	0.9
K-8	0.8	105	50.54	5.7	43	65	6.3	36	3.1	1.7
K-9	2	89	53.6	5	63	74	6.7	29.2	4.7	1.5
K-10	1.5	65	51.08	5	40	69	6.6	36	7.7	2
K-11	1.5	64	54.5	5.2	50	73	6.5	30	8.9	2
K-12	2	58	59.9	5.4	43	95	7.3	36	11.8	2.3
K-13	0.3	73	39.2	3.7	78	64	6.6	31.7	1.8	2.7
L-1	0.2	92	33.26	1.9	57	95	8.8	26.1	13	7.7
L-3	27.7	47	55.76	6.5	26	107	9.3	20	13.8	4.9
L-4	20.9	48	56.48	6.1	32	86	8.3	20	18	5.1
P-1	11.3	57	95	3.8	15	79	8.5	26.7	4.7	0.4
P-2	2	95	80.6	1.8	10	42	7.2	26.1	4.7	0.4
P-3	6.3	89	80.6	3.8	18	94	9.7	31.1	4.1	0.3
P-4	1.2	135	80.6	3.7	48	55	7.6	31.7	2	0.3
P-5	3.4	108	89.6	2.8	38	47	7.1	31.1	3.1	0
P-6	0.7	112	84.2	2.2	48	25	5.6	31.7	2.8	2.9
P-7	2.3	95	84.2	2.5	35	61	7.6	31.1	2.4	1.5

TABLE 4-28. (continued)

Unpaved road test run	PM-10 emission factor lb/VMT[a]	Duration, min.	Meteorology		Vehicle information				Silt, %	Moisture, %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, tons	Mean No. of wheels	Mean vehicle speed, mph		
P-8	1.2	103	84.2	3	49	47	7.5	29.2	7.7	15.3
P-9	1.4	142	80.6	3.7	48	58	8.7	31.1	1.6	20.1
J-1	2.48	87	73.94	2.8	63	50	4.1	19.3	8.9	5.7
J-2	2.09	34	77	1.4	33	53	4	19.3	23.4	2.3
J-3	16.3	51	84.92	1.3	35	54	4.1	24.2	15.8	4.1
J-4	0.963	52	68	1.1	30	36	4	20	14.6	1.5
J-5	5.8	60	85.1	1.4	14	70	4	18	10.6	0.9
K-15	4.54	13	41	3.9	6	46	4	28		
K-16	10.3	41	47.84	2.6	10	64	4	30	25.2	6
K-17	20.9	18	53.6	4	31	57	4.1	23	25.2	6
K-18	10.7	37	55.58	2.6	30	66	4	25	25.2	6
K-22	2.92	110	41	3	20	45	4	31.7	21.6	5.4
K-23	6.61	43	42.98	4.6	20	54	4	28	24.6	7.8
L-5	115	14	38.3	8.6	20	53	4	21.1	21	
L-6	51.3	22	39.56	9.4	15	50	4	20	21	
P-15	--	43	89.6	1.6	4	42	4	16.2	7.2	1
P-18	0.714	33	80.6	3.9	18	64	4	10	7.2	1
J-7	--	59	82.94	1.1	104	7	4.2	25	3	3.6
J-8	0.27	68	86	1.6	160	3	4	25	3	3.6
J-13	3.22	26	77.9	2.9	59	2.2	4	25	10.1	1
J-18	5.32	21	79.7	3.7	34	2.6	4	25	8.8	1.1
J-19	3.69	31	80.24	3.6	70	2.3	4.1	25	8.2	0.9
K-2	0.195	55	46.94	5.5	150	2.3	4	35	4.9	1.6
K-3	0.242	58	53.78	4.8	150	2.4	4	35	4.9	1.6
K-4	0.225	67	61.16	3.1	150	2.4	4	35	5.3	1.7
K-5	0.351	68	68.72	4.3	150	2.4	4	35.9	5.3	1.7

TABLE 4-28. (continued)

Unpaved road test run	PM-10 emission factor lb/VMT[a]	Duration, min.	Meteorology		Vehicle information				Silt, %	Moisture, %
			Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, tons	Mean No. of wheels	Mean vehicle speed, mph		
P-11	2.56	73	95	5.8	100	2	4	42.5	5.5	0.9
P-12	2.94	60	95	5.2	125	2	4	43.1	5.5	0.9
P-13	2.52	55	84.2	4.2	100	2	4	43.1	5.5	0.9

[a] PM-10 emission factors were calculated from the PM-15 and PM-2.5 data using logarithmic interpolation.

TABLE 4-29. SUMMARY INFORMATION - REFERENCE 15

Operation	Control method	Tests	State	Test date	No. of Tests	PM-10 (<10 μm) Emission Factor (lb/VMT)*	
						Geom. Mean	Range
Lightweight vehicle	None	BG	Missouri	11/95 to 12/95	5	0.352	0.0884-1.12
Lightweight vehicle	None	BJ	North Carolina	4/96	4	1.15	0.851-1.31
Lightweight vehicle	None	BK	Nevada	5/96	4	0.819	0.309-2.63

1 lb/VMT = 281.9 g/VKT

* Study reports a PM-2.5/PM-10 ratio of 0.15

TABLE 4-30. DETAILED INFORMATION FOR UNPAVED ROAD TESTS - REFERENCE 15

			Meteorology		Vehicle information					
Unpaved road test runs	PM-10 emission factor, lb/VMT	Duration, min	Temp., °F	Avg. wind, mph	No. of vehicle passes	Mean vehicle weight, ton	Mean No. of wheels	Average vehicle speed, mph	Silt. %	Moisture, %
BG-1	0.503	85	60	4.2	110	2	4	30	7.2	0.93
BG-2	0.925	125	60	11.6	330	2	4	30	6.22	0.65
BG-3	1.12	84	65	12.2	300	2	4	30	6.07	0.54
BG-4	0.118	102	57	6.0	306	2	4	30	7.56	1.38
BG-5	0.0884	88	62	4.0	320	2	4	30	7.97	1.12
BJ-1	1.24	92	84	10.2	257	2	4	30	4.01	0.1
BJ-2	1.28	115	84	10.5	261	2	4	30	2.9	0.1
BJ-3	0.851	115	84	14.6	247	2	4	30	4.26	0.07
BJ-4	1.31	82	84	16.4	251	2	4	30	3.70	0.09
BK-1	0.372	59	72	5.0	138	2	4	30	7.2	0.48
BK-2	0.309	29	70	5.6	150	2	4	30	5.24	0.44
BK-3	1.49	47	70	6.5	100	2	4	30	5.88	0.45
BK-4	2.63	27	71	6.5	80	2	4	30	6.55	0.38

TABLE 4-31. RESULTS OF CROSS-VALIDATION

Type of vehicle/road	Uncontrolled/ watered	No. of cases	Ratio of quasi-independent estimate to measured emission factor	
			Geo. mean	Geo. std. dev.
Haul trucks	U	39	0.98	2.44
	W	34	1.10	2.49
	Overall	73	1.03	2.45
Light-medium duty/traffic on industrial roads	U	29	1.09	2.85
Light-medium duty/traffic on public roads	U	43	0.97	2.36
	Overall	72	1.02	2.54
Heavy duty/traffic on industrial roads	U	3	1.28	1.39
Scrapers in travel mode	U	23	0.82	3.62
	W	9	1.00	5.13
	Overall	32	0.87	3.93

TABLE 4-32. PREDICTED VS. MEASURED RATIOS FOR NEW UNPAVED ROAD EQUATION USING REFERENCE 15 TEST DATA

Run	Silt, %	Moisture, %	Weight, tons	Speed, mph	No. of wheels	Measured PM-10 emission factor, lb/VMT	Ratio of Predicted to measured	
							Equation 4-5	Current AP-42
BJ-1	4.01	0.10	2	30	4	1.23	0.88	0.43
BJ-2	2.90	0.10	2	30	4	1.29	0.65	0.30
BJ-3	4.26	0.07	2	30	4	0.840	1.51	0.67
BJ-4	3.70	0.09	2	30	4	1.32	0.80	0.37
BG-1	7.20	0.93	2	30	4	0.503	0.95	1.89
BG-2	6.22	0.65	2	30	4	0.925	0.95	0.89
BG-3	6.07	0.54	2	30	4	1.12	0.81	0.71
BG-4[a]	7.56	1.4	2	30	4	0.118	6.95	8.44
BG-5[a]	7.97	1.1	2	30	4	0.088	10.3	11.9

[a] These tests were conducted during misty conditions.

REFERENCES FOR SECTION 4

1. Muleski, G., Midwest Research Institute, *Letter Report of Field Tests, MRI Project No. 4470, "Road Sampling,"* for Washoe County District Health Department, Reno, Nevada, August 1996.

2. *Improvement of Specific Emission Factors (BACM Project 1)*, South Coast AQMD, South Coast AQMD Contract No. 95040, March 1996.

3. *PM-10, PM2.5, PM-1 Emission Factors for Haul Roads at Two Stone Crushing Plants*, National Stone Association, Washington, D.C., November 1995.

4. *Surface Coal Mine Emission Factor Study*, U. S. Environmental Protection Agency, EPA Contract No. 68-D2-0165, Assignment I-06, Research Triangle Park, NC, January 1994.

5. *PM-10 Emission Factors for a Haul Road at a Granite Stone Crushing Plant*, National Stone Association, Washington, D.C., December 1994.

6. *Unpaved Road Emission Impact*, Arizona Department of Environmental Quality, Phoenix, AZ, March 1991.

7. *Roadway Emissions Field Tests at US Steel's Fairless Works*, U.S. Steel Corporation, Fairless Hills, PA, USX Purchase Order No. 146-0001191-068, May 1990.

8. *Evaluation of the effectiveness of Chemical Dust Suppressants on Unpaved Roads*, funded by LTV Steel Company, Inc., prepared for U. S. Environmental Protection Agency, Office of Research and Development, Washington, D.C., EPA No. 600/2-87-102, November 1987.

9. *Fugitive Emission Measurement of Coal Yard Traffic at a Power Plant*, Midwest Research Institute for Confidential Client, December 1985.

10. *Critical Review of Open Source Particulate Emission Measurements - Part II - Field Comparison*, Southern Research Institute, Birmingham, AL, August, 1984.

11. *Size Specific Particulate Emission Factors for Uncontrolled Industrial and Rural Roads*, U. S. Environmental Protection Agency, Research Triangle Park, NC, EPA Contract No. 68-02-3158, Assignment 12, January 1983.

12. *Iron and Steel Plant Open Source Fugitive Emission Control Evaluation*, U. S. Environmental Protection Agency, Research Triangle Park, NC, EPA Contract No. 68-02-3177, Assignment 4, August 1983.

13. *Extended Evaluation of Unpaved Road Dust Suppressants in the Iron and Steel Industry*, U. S. Environmental Protection Agency, Research Triangle Park, NC, EPA Contract No. 68-02-3177, Assignment 14, October 1983.

14. *Improved Emission Factors for Fugitive Dust from Western Surface Coal Mining Sources*, U. S. Environmental Protection Agency, Research Triangle Park, NC, EPA Contract No. 68-03-2924, Assignment 1, July 1981.

15. *Fugitive Particulate Matter Emissions Final Draft Report*, U. S. Environmental Protection Agency, Research Triangle Park, NC, EPA Contrct No. 68-D2-0159, Assignment 4-06, January 1997.

16. A. L. Williams, G. J. Stensland, and D. F. Gatz, *Development of a PM10 Emission Factor from Unpaved Roads*, APCA Publication 88-71B.4, Presented at the 81st Annual Meeting of APCA, Dallas, TX, June 19-24, 1988.

17. A. L. Williams and G. J. Stensland, *Uncertainties in Emission Factor Estimates of Dust from Unpaved Roads*, AWMA Publication 89-24.6, Presented at the 82nd Annual Meeting & Exhibition, Anaheim, CA, June 25-30, 1989.

18. W. R. Barnard, G. J. Stensland, and D. F. Gatz, *Development of Emission Factors for Area and Line Source Fugitive Dust Emissions: Implications of the New PM-10 Regulations*, Transactions of PM-10 Implementation of Standards, ed. by C. V. Mathai and D. H. Stonefield, APCA publication TR-13, p 326, 1988.

19. Telephone communication between G. Stensland, Illinois State Water Survey, Champaign, Illinois, and G. Muleski, Midwest Research Institute, Kansas City, Missouri, July 11, 1997.

5. PROPOSED AP-42 SECTION

Summaries of comments on the proposed AP-42, Section 13.2.2 Unpaved Roads, and responses to these comments are presented on the following pages. The final AP-42 section is available as a seperate file.

IDAHO Department of Environmental Quality
Memorandum dated December 31, 1997 from Val Bohdan of Idaho DEQ to Ron Myers of EPA (attached)

3) The backup studies cited in this draft appear to have no representation from the cement/ concrete industry—a significant number of which exist in the State of Idaho. By contrast, much data backup originated as studies of the coal and steel industries—none existing in Idaho. This raises the question of eventual appropriateness of the proposed emissions formulas in terms of country regional fit.	MRI agrees that wider representation of different industries would be extremely beneficial in developing a truly generic equation applicable to all situations. Nevertheless, one must use the data available to develop emission factors. Unfortunately only limited data are available for cement/concrete industries. Please see also the response to the Portland Cement Association. Additionally, text has been added to the background document to more fully describe the approach taken here to capture the essential features of the emission process with a few readily obtained variables.
4) The issue of control efficiency factoring which can be afforded by vehicular speed reduction is very confusing and needs to be resolved more clearly. Logically, speed reduction, especially on the lower range, needs to be incorporated as an inducement for emissions reduction.	The linear reduction in emissions due to decrease in vehicle speed was not clearly expressed in the draft AP-42 section. This will be corrected in the final version.
5) We would like to suggest the use of clear statements in the writing of the whole Section 13.2.2. Instead of "should be," the direction needs to be "do this" or "use this" in order to give some assurance to the eventual user of this section.	Suggested wording changes will be considered in conjunction with suggestions made by other reviewers.
6) Notwithstanding the derivation process for the formulas, it seems logical that the formulas should be mathematically simplified for the eventual user. Use of negative exponentials can intimidate those not acquainted with higher math and thus should be avoided simply by placing the exponent as a positive number in the denominator. Moreover, combining of numerical constants should be carried out as far as possible, again to assist the eventual ease for the user.	These suggestions need to be considered in conjunction with comments made by other reviewing organizations.
7) Concerning the default moisture content value of 0.5%: For Southern Idaho, much of which is considered "high desert" area, the 0.5% default value is probably correct. We glean this value from the 1996-1997 "Pocatello Road Dust Study" of moisture content which was performed, however, on an unpaved MgCl treated local road. The lower end of this study indicated the moisture content value of 0.6%.	Note that the default value of 0.2% will be incorporated at the "normalizing" factor for moisture. This value was selected based upon the available moisture content data available from uncontrolled publicly accessable unpaved roads. The 20th percentile moisture content value was selected to represent a typical minimum value exclusve of natural mitigation. See also response to Minnesota Pollution Control Agency comment.

Specific Comments:

Comments pertaining to the Section 13.2.2 Draft

(a) Page 13.2.2-3: the first equation should be simplified to become $E = (k/7.03)\ (s)^{0.8}\ (W/3)^{b}\ (1/M^{c})$ (1) Notice that "a" factor has been replaced by 0.8. This is proper since the value for "a" is the same for all the particulate sizes considered in this equation. Also notice that the	Wording/organization suggestions will be considered in conjunction with other comments and suggestions received. To avoid the use of a negative exponent, one could also write Equation 1 in the draft section as $E = (k/7.03)\ (s)^{0.8}\ (W/3)^{b}\ /\ (M/1)^{c}$ (1)

value of superscript “c” is positive. Thus, Table 13.2.2-2 supporting Equation 1 needs also to be changed: eliminate row "a” (since the constant remains the same for all particulate sizes), and change the minus sign (-) for “c” factor to a plus sign (or better yet, no sign in front of it at all).	In response to the Minnesota Pollution Control Agency comments and evaluation of the moisture data from publicly accesable roads, the normalizing factor for moisture will be changed to 0.2%. See also the comments from the North Carolina DNR.
(b) Page 13.2.2-4: At the bottom of this page, the formula should be changed to read S/15 not (15-S/15) if you intend the factor to drop linearly from 15 to zero vehicular speed “S”. It needs to be stated more clearly that the emissions factor remains constant at speeds above 15 mph.	As noted above, the expression in the draft section was in error and will be corrected.
In Table 13.2.2-3, (Range of Source Conditions for Equation 1) on this page, we recommend that column headings also contain the appropriate letter symbols (s, W, S, and M—in that order) from Equation 1. This will aid all users, especially the infrequent users.	MRI agrees that change might be useful to infrequent readers of AP-42 and the change will be made in the final version.
(c) Page 13.2.2-5; The equation on this page should also be simplified to become $E = (k/7.03)\,(s)^{0.8}\,(W/3)^{b}\,(1/M_{dry}^{c})\,[(365-p)/365] \qquad (2)$ The issues identified in Paragraph “a” (just above) also apply to this equation. Moreover, your use of the term M/1 appears overly simplistic and should be shortened to just M.	The "1" serves to non-dimensionalize the M term. The normalization allows one to more readily convert the emission factor expression from one set of units to another. This includes units for both the dependent (i.e., emission factor) and the independent variables. Please see the footnote "'c" in connection with Equation 4-1 of the background document.
Page 13.2.2-6; Insert the word “directly” at the sign of * in the third sentence from the bottom, which reads: “Although vehicle speed does not appear * as a parameter, it is obvious…”	This change will be made in the final versions of both the background document and the AP-42 section.
(d)Page 13.2.2-8; The second paragraph (control efficiency afforded by speed reduction) is very confusing and should be either clarified or deleted. The use of a power factor for vehicular speed “S” is very misleading and counters earlier statements. However, the power factor $S^{3/2}$ may best represent the emissions factor relationship for speeds below 15 MPH. If that is the case, then it should be so stated. A simple graph may be the best way to explain and clarify this point.	MRI agrees that the paragraph as presented can be confusing. The discussion about speed being raised to a power between 1 and 2 refers to tests conducted of captive traffic and will be removed and/or revised in order to improve clarity. At present, however, there is no good technical basis for the use of a 3/2 power relationship.

Attachment to Review and Comments on the Draft AP-42 Section 13.2.2, Unpaved Roads From the Idaho Division of Environmental Quality (IDEQ)

The following are the comments/suggestions compiled by the Technical Services Bureau, Air and Hazardous Waste Section, Idaho DEQ, in response to the invitation to comment on the Draft AP-42 Section 13.2.2. The cover letter addresses the AP-42 draft section whereas the following comments are more broad-based and address the background document and the overall methodology for the study.

General Comments:

In making such sweeping changes to a set of equations which govern the emission estimation process from a major source category for the next decade(s), more testing and studies are warranted. The much touted ease of use is achieved by sacrificing the fine dependencies afforded by specific governing parameters, such as number of wheels and speed. The moisture term is a definite improvement but can be already enhanced in its application and by reference from other studies already performed. It is strongly recommended that this equation be implemented in a test-mode for one or two years before finalizing it. This would allow more time to analyze and study the effects of these proposed changes.	MRI agrees that more tests -- especially for the PM-2.5 size fraction -- would be extremely beneficial.
1. What were the basic guidelines used to select studies used in the background document? The IDEQ is aware of two other studies, performed in Idaho with guidance from the Midwest Research Institute (MRI) that meets established screening criteria, which could have been used as background information for developing this emission factor. As those studies were conducted in Idaho, they would have provided some regional representation, a more extensive database, and made the factors more robust and applicable to regions like Idaho.	The two studies mentioned in the comment were directed to paved roads. The first was a surface sampling program and no emission test data were collected. The second study involved a yearlong road surface sample collection together with a one-time paved road emission testing program (April 1997). Only one unpaved surface was sampled and no unpaved road emission testing was performed. The background document under review considered only test reports with unpaved road emission test data.
2. The studies chosen have no representation from the cement/concrete industry. Are the differences accounted by the silt content adequate to characterize emission factor dependence on significant parameters? The cement/concrete industry constitutes a significant number of sources in Idaho.	Clearly, one must rely on the available historical emission test data in order to develop the candidate emission factor expressions. MRI agrees that additional testing in many industries and parts of the country would be very beneficial.
3. The document seems to primarily focus on PM-10. Is there a similar study planned for PM-2.5 to decipher the relationships between significant parameters that contribute to fine particle emissions? This is especially relevant in light of the fact that geologically derived material and agricultural impacts contribute to regional contributions of fine particles from studies in the west. This is also an issue of focus since the promulgation of the new PM-2.5 standards in mid-1997.	Once again, one must rely on the historical data available and most data referenced PM-10. MRI agrees that more testing focused on PM-2.5 is very much needed to improve the estimation methods for all fugitive emission sources.
4 . There appears to be a preference to test unpaved roads in iron and steel industries in the east and coal industry in the west. Are these thought to be major contributors of emissions from this source category? Is there any test that was reviewed from unpaved roads in agricultural rural areas? IDEQ feels that such information is key to have in the database as most western states have agriculturally-dependent areas from which emissions have to be quantified, as accurately as possible, if any sort of control scenario is desired to be achieved.	The Arizona DEQ study considered three unpaved roads in rural portions of that state, and two sites were within the immediate vicinity of active agricultural lands. As noted above, although one must rely on the historical data base, collection of additional emission test data from many different situations would be very beneficial in later updates to this section of AP-42.

5.	The IDEQ is aware of several studies to characterize emissions from paved and unpaved roads by the Washington State University in Pullman from 1994 to 1997 using tracers (The Measurement of Roadway PM-10 Emission Rates using Tracer Techniques, Washington State Department of Transportation, Technical Report # WAR 397.1). This study had important findings related to road emissions compared to relative humidity. There seems to be no mention of the same.	This report was issued to the Washington State DOT in March 1996 and the federal DOT forwarded it to EPA in November 1996. As a result, the test report was not available when the AP-42 update project began during the late summer of 1996. (It should be noted that there is no discernible trend in Table 4 of the WSU study between the 3 sets of paired unpaved road emission factors and relative humidity.)
6.	The Columbia Plateau PM-10 study reports a number of wind erosion studies, and techniques to address them. Specifically, the soil erosion factor, and the surface roughness factor, are mentioned as key parameters for wind erosion. Would this also not be a major factor in emissions from unpaved roads? (See related comment beginning of next section).	The emission factor developed and recommended for inclusion in AP-42 deals with traffic-generated PM, which is an ongoing emission source for active roads rather than the occasional wind erosion of the surface. Because traffic causes emissions even in the absence of wind, it is not intuitive that the parameters presented in the comment are applicable to the emission factor under consideration. See also the response to first comment under "Specific Comments," below.
7.	As there seem to be key omissions in the literature search conducted, to compile the database for the study, IDEQ is skeptical as to the comprehensiveness and soundness of the proposed equation to adequately provide an accurate emission factor for every region in the country.	Please see responses to comments 1 and 5.
8.	IDEQ is also concerned that the use of this forum is to review and provide comment is instituted at a stage later than at which key directional changes to the study can be implemented. What procedures are followed at each phase of the study to ensure participation and encourage input from state and local agencies, to make the study more robust and applicable to all regions? This process would also foster confidence in the final product.	

Specific Comments:

<u>Chapter 2, Background Document</u>:

1.	Is it not intuitive that over time, over a given surface area, that the suspendable particulate loading would decrease (by advection, carry-out, etc.), provided new material is not significantly added to the road surface (relates to erosion factors)? Is there, then, any decay factor, or parameter (added or planned) to be added to the equation as a correction for this effect? The effect of not having this correction would be an assumption that constant surface loading is available for re-suspension over an infinite amount of time resulting in gross overestimates–as compared to realistic measurements.	No, it does not seem intuitive that an actively used unpaved road will lose its dust emitting potential over time. Instead, the surface is continually ground by passing vehicles. Although there is only a limited amount of data available, emission tests conducted on the same uncontrolled road (References 8 and 13 in the background document) from one year to the next do not provide evidence of diminished emission potential (due to traffic over the roadway) .
•	How is the effect of relative humidity in the friction layer of the planetary boundary layer on characteristics of suspended particles accounted for? Although	The draft section does not include a direct treatment of relative humidity (RH). During the 1980s, attention was directed to use of a relative humidity term in road predictive emission factor equations. In one version of the unpaved model, RH was raised to a

there may be no measurable precipitation on the ground surface, high relative humidity associated with high pressure events and associated interventions may result in decreased circulation events in the surface friction layer closest to the ground and cause suppression of dust, as in a fog with some precipitable water content.	positive power of about 4, whereas in another version the same organization found RH dependence at a power of -0.2. Furthermore, the WSU unpaved road results are inconclusive with respect to the relationship between unpaved road emissions and RH. Recall that the emission factor presented in the draft section references dry conditions. Clearly, misty conditions should result in lower observed emissions; nevertheless, there are insufficient data to determine the mathematical relationship. EPA has drafted additional guidance to better account for the effects of precipitation within the AP-42 section.
Chapter 3, Background Document:	
• In the last paragraph of page 3-7 the comments suggest, that tests from various sources have been combined to derive the new equation. This approach suggests that a large amount of testing was conducted to come up with gross average. As explained elsewhere in the document, a mathematical fit needs not always imply a reality fit. A log-normal distribution conveniently encompasses a wide range. This approach is good as screening criteria but not for further refined purposes as is applied from the AP-42 for permitting, PSD, and SIP purposes. For refined purposes, an industry-by-industry equation should be considered. Although the final equation may or may not differ much, the approach makes the study more robust and increases user confidence as the database would be broad. At the very least, a comparative study should be undertaken to establish the applicability and usefulness of industry specific equations.	As noted above, the development of an emission factor makes use of the data available. Under the ideal situation, one could have sufficient information to develop industry-specific factors for use in different regions of the country. MRI would welcome the opportunity to work with a broader data base that spans many more industries; however, these types of tests simply are not available. To the best of our knowledge, the only industry-specific unpaved road emission factors recommended in AP-42 pertain to western surface coal mining. As a result of this update of the unpaved road section, the emission factors in the western surface coal mining AP-42 section for haul trucks and for light duty trucks are being replaced with the equations developed during this effort. As part of Section 234 of the 1990 CAAA, a thorough comparison of the generic (i.e., Chapter 13) unpaved road expression with the industry-specific equations was undertaken. The background document summarizes the findings that, when applied to independent data (i.e., not used in the development of the models), the generic expression performed as well or better than the industry-specific factors.
Chapter 4, Background Document:	
• It is interesting to note that tests continue to be accepted as approved even as the emission factor values spread over 2-3 orders of magnitude without further investigation as to this extensive spread. The final calculations of emissions and the discretion, as to which order of magnitude to choose, is left to the field operator or engineer in the absence of any further supporting documentation on application of such ranges of values. In a practical regulatory sense this scenario leaves emissions from certain categories in"grey areas."**[underline added; see response]**	The intent of the comment is unclear to MRI. The 2 to 3 orders of magnitude spread in the overall data base is directly attributable to the wide range of underlying source conditions (e.g., vehicle weight, road surface texture, etc.). Should the comment refer to individual test reports, that type of spread might result if one were to compare controlled and uncontrolled test results. (In particular, the intent of the last 2 sentences (underlined) is especially unclear to MRI.) On the other hand, when one considers roads under comparable source conditions, there is considerably less spread.
• Please correct the table columns in Table 4-8.	Wind speed will be placed under the "meteorology" heading instead of "vehicle."
• The comment on page 4-20 that Equation 2-1 performed as well in estimating emissions as did factors for specific sources in the coal industry could also mean that the specific industry factors were somehow biased. It does not necessarily mean the general Equation 2-1 is adequate and correct. It seems a fundamentally gross over-generalization to then lump all the tests, in all studies reviewed, to	Please see response to Chapter 3 comment (above).

come up with one large data set for the emission factor development. Is this the only specific industry factor test that provided the impetus to lump all the test data?	
• It is not clear whether reference 12 was used in the final equation development as it did not have moisture content or PM-10 factors listed. What is the exact meaning of “data was used in the expanded data analysis, they were not included in equation development”?	MRI agrees that, as written, the background document is confusing on this point. That portion of the document will be rewritten to clearly explain that although Reference 12 was not used in development of the final emission factor equation, its data were used in those analysis that did not directly reference moisture content as a potential correction parameter (as in the second full paragraph on page 4-24 of the background document).
• If as mentioned in page 4-26 the effect of speed could not be isolated due to unavailability of speed segregated data … (s)uch data should probably be obtained to study the effects of speed on emission factors. This leads to the conclusion that if a model does not simulate reality to some extent then, perhaps, the fundamental assumptions that went into creating the model are flawed, and are unable to be verified. It could lead to serious errors if the equation is used in this manner. The speed correction factor seems like an extreme ad hoc measure to solve this problem.	MRI agrees that collection of additional test data can only strengthen the validity of estimation methods. Nevertheless, as pointed out several times, one is forced to work with the data sets that are available.
• Different size fractions may have different influences and effects, as related to the determined significant parameters, in that multiplication of PM-10 emission factors by appropriate size fraction would only be applicable as a rule-of-thumb calculation.	MRI agrees that there can be substantially different mechanisms involved in the reentrainment of particle sizes other than PM10. The reduced quality ratings for "scaled" emission factor equations reflect that concern. (See also responses to comments made by the Minnesota and North Carolina state agencies.)
• It is interesting to note that a high measure of reliability is established using equation 4-5, as established by Table 4-32 without inclusion of speed in the equation! It is also particularly worrisome that the emissions increase with decreasing speed. **[underline added; see response]** This table also demonstrates the effect of high humidity (misty conditions) on the suppression of emissions.	Because all tests in Table 4-32 were conducted with a travel speed of 30 mph, it is unclear what is meant by the underlined portion of the comment.
The attached graph demonstrates the effect that speed multiplier will have on the emission factor. The emission increases linearly with decreasing speed from 15 mph to 0 mph, and also causes an anomaly of having emissions from a stationary vehicle with a ‘B’ rating! The text implies the need for an inverse effect. So, the multiplier has to be inversed, as mentioned in the cover letter.	As noted elsewhere, this term will be corrected in the final version.
• What is the rationale for using 12, 3, and 1 as the norms’ for silt content, mean vehicle weight, and moisture content, respectively?	The reference silt and weight values are the same as those used to normalize the old unpaved road factor. The moisture content of 1% was selected because it corresponds approximately to the geometric mean value for uncontrolled tests in the data set. However, MRI expects to revise the final equation with a normalizing value of 0.2% which is the same as the default value. This change should help ensure that water addition is not "double counted." (See also the response to a Minnesota Pollution Control Agency comment.)

Chapter 5, Proposed AP-42 Section:

• It is possible for the end-user of the equation to obtain daily precipitation totals and relative humidity readings from the National Weather Service (NWS), Local Climatological Data (LCDs). It should be made feasible to incorporate short-term relative humidity and precipitation data into daily or hourly estimates for emissions. Annual data can then be very accurately totaled from this equation. This approach is preferred to the national precipitation data map provided.	As mentioned elsewhere, EPA has indicated its plans to include additional discussion in the final version of the AP-42 section on how to incorporate more finely resolved precipitation data in emission estimates for public roads. Two methods are provided to accomodate local climatological information. One method provides a very simplistic but directionally correct method that has been used for many years to accomodate long term differences in the average moisture content of the road surface material. Another method accomodates more variables that are believed to result in changes in the road surface moisture content. This additional method requires hourly data on the quantity of precipitation, humidity and snow cover as well as monthly data on the evaporation potential (Class A pan evaporation and average traffic volume).
• The number of samples in determining silt content values in the table should be at least 10 or more to provide an adequate level of confidence in the data.	MRI agrees that more confidence should be placed on values based on more samples, but believes that it is important to provide the sparse industry-specific information that is available. State agencies should encourage site specific collection and analysis of road surface material to better characterize the silt and moisture content of roads. If state agencies have more surface material data, they are encouraged to forward that information to EPA for inclusion in Table.13.2.2-1

MINNESOTA POLLUTION CONTROL AGENCY

Letter dated October 29, 1997 from Michael J. Sandusky of Minnesota Pollution Control Agency to Ronald E. Myers of EPA. (attached)

Table 1 summarizes the findings of the MPCA staff in a thorough review on statistical analysis of the emission data provided by the EPA. **(see table in attached comments for footnotes, etc.)**

Table 1. Empirical Constants from Statistical Analysis of Uncontrolled Particulate Emission Factors

	PM-2.5		PM-10		PM-15		PM-30	
Constant	Draft	MPCA	Draft	MPCA	Draft	MPCA	Draft	MPCA
k, lb/VMT	0.24	3.57	1.6	1.72	2.4	3.41	5.3	6.08
a	0.8	0.67	0.8	0.77	0.8	0.72	0.8	0.97
b	0.4	0.24	0.4	0.43	0.4	0.29	0.5	0.52
c	-0.3	-0.55	-0.3	-0.24	-0.3	-0.06	-0.4	-0.45
Cases	?	77	180	141	?	77	92	65
R-squared	?	0.125	0.345	0.384	?	0.255	?	0.512
Adj. R-sq	?	0.089	?	0.371	?	0.224	?	0.488
Q. Rating	B	?	A	?	B	?	A	?
Regression	?	Forced	Stepwise	Stepwise	?	Forced	Stepwise	Stepwise

The fitting constants' quality ratings, the potential dual role of road surface moisture content, the annual adjustment for precipitation, and the disappearance of vehicle speed are major concerns to the MPCA. We believe, however, that the PM10 emission factor equation (lb/VMT) with the fitting constants is acceptable from the statistical standpoint.

Quality Rating Scheme

Emission Factor Documentation for AP-42 Section 13.2.2 (Draft Report) describes in Section 3.3 emission data and emission factor quality rating scheme used for unpaved roads source category. It states, "(t)he uncontrolled emission factor quality rating scheme used for this source category represents a refinement of the rating system developed by EPA for AP-42 emission factor. The scheme entails the rating of test data quality followed by the rating of the emission factor(s) developed from the test data…."

The quality control and quality assurance efforts in the development of emission factors for this source category are important. However, we believe that the final quality rating, as seen in Table 1 for PM-10, should also be more related to the goodness of fit of the regression model. In plain words, we think the ratings of A and B in Table 1, should be lower, e.g., C and D.

To further explain our concern with factor ratings, let's look at another rating and the

The MPCA re-evaluated the different emission factors presented in Equation 1 and Table 13.2.1 of the draft AP-42 section. Several items should be noted:

1. The expressions for PM-30 do not agree because MPCA regressed only the 65 uncontrolled emission tests whereas the expression recommended for inclusion in AP-42 is based on both the 65 uncontrolled as well as the 27 watered tests. Note, however, that the two expressions in MPCA's Table 1 are essentially identical in terms of the "fitting constants." Thus, had only uncontrolled tests be considered in the development, the resulting PM-30 expression would not be substantively different from the recommended equation.

2. Similarly, the MPCA's PM-10 expression also is based on some subset of the total data sets used by MRI. Although it could not be confirmed from the information presented, it appears that the MPCA expression is again based on the uncontrolled test data. As was the case with the PM-30 factors, the MPCA's results indicate that no substantive difference in the form of the PM-10 would be expected if MRI had considered only uncontrolled tests in the AP-42 update.

3. The differences between the MPCA and MRI expressions for PM-2.5 and PM-15 stem the fact that MPCA developed their expression from a regression analysis while the background document describes how the draft versions were scaled against the PM-10 expression. Page 4-28 of the background document discusses MRI's stepwise regressions of PM-15 and -2.5 data and the decision to scale emission factors against the result for PM-10.

MRI agrees that the quality ratings should be dropped one letter when the emission factor is applied to a specific test road. The background document and draft AP-42 section will be revised to reflect this decision. (See also the response to comments from the North Carolina DNR.) The revisions will also discuss how the overall performance of the emission factor improves when it is applied to a number of roads within a specific area. This is an important distinction between fugitive dust sources and the type of combustion emission source mentioned in the comment. That is to say,

assumptions we make about it. An emission factor rating of A is given to the SO_2 emission factor for No. 6 oil fired, normal firing utility boilers in the current AP-42 Table 1.3-1. People in the regulatory and regulated communities are very confident in using such an emission factor. Now, when an emission factor rating of A is given to the uncontrolled PM-10 emission fitting constants, it has some profound implications. First, it implies that the predicted uncontrolled PM-=10 emission for unpaved roads from the regression model is the best (true), however, it also implies it is directly comparable to that of the SO_2 emission factor for No. 6 oil fired, normal firing utility boilers in the current AP-42 Table 1.3-1 (not true). People using these factors, who tend to take a number out of a table without carefully reading the context, will assume these factors are of equally high quality. Second, when people realize that less than 40 percent of the total variance in the emission data is explained by the regression model (see PM-10 column in Table 1) and rating A still is given to the regression model, they are going to seriously doubt the reliability of all the emission factors from AP-42—stack emissions and fugitive emissions.	a facility being inventoried typically contains no more than a handful of the stack-type source mentioned. Furthermore, the stack sources are far better defined and steady in terms of operating conditions. On the other hand, a facility may contain dozens of unpaved travel surfaces, each with very different vehicle characteristics that change with hour of the day, seasonally, etc. In that case, the performance of an emission factor in accurately predicting emissions from a single source is not necessarily the central issue. Instead, one is interested in how well the factor performs in estimating the total (or average) emission from the entire set of sources over time periods of interest. It should be noted that for many sources of particulate matter, the performance of AP-42 emission factors applied to individual source is not significantly different than the predictive capability of the unpaved road equation. The emission factor ratings are more a function of the number of emission tests supporting the emission factor than on the inherent variability of the emissions from the source being characterized.
We believe that people can be satisfied with the notion that, because of inherent variability, fugitive emission factors can never achieve the same level of quality rating. Therefore, we would urge you to lower the factor ratings associated with the proposed AP-42 for unpaved roads.	MRI agrees. Please also see the response to the first "General Observation" made in the North Carolina comments

Road Surface Material Moisture Content

The efficiency of water application to control particulate emissions is not analyzed statistically in this study, although equation (3) is presented in the Draft AP-42 for estimating control efficiency for water applications. Input parameters for this equation include water application parameters and pan evaporation rate, all of which to a great extent determine road surface material moisture content.	EPA has drafted additional guidance to better account for the effects of precipitation within the AP-42 section. This material -- which provides a means of using the hourly precipitation values that are readily available -- will be included in the final versions of both the background document and the AP-42 section.
There is a potential for double-counting the road surface material moisture content and watering control efficiency. If road surface material moisture content resulted from a control technology application, the road surface material moisture content before the application should be used to establish the regression equation with fitting constants shown in Table 1. We would like confirmation from the EPA that this was done correctly.	As noted in response to one of the Idaho DEQ's comments, the normalizing factor for moisture will be changed to 0.2% (i.e., the default value) and the definition of M_{dry} in Equation 2 will be expanded to ensure that this references uncontrolled conditions.
The inclusion of road surface material moisture content makes sense in reflecting the reality, if data collection to establish the equation in Table 1 was done correctly. However, users of the equation still may double count the moisture contribution by using post-application moisture value in the equation to predict uncontrolled emissions and adding control efficiency due to water application to get the “controlled” fugitive emissions. Of course, we realize that each regulatory agency just needs to guard against dual use of moisture.	The moisture contents for the 137 "uncontrolled" tests in the development data set all reference dry conditions (i.e., without any artificial watering or rainfall for a minimum of 24 hours). For the "watered" tests, the moisture content reported represents a time-averaged value of moisture <u>during the test period</u>. Thus, the appropriate value to substitute (for inventorying purposes) in Equation 1 would be the average moisture content during the watering cycle. If Equation 2 were used, then the appropriate value for M_{dry} would be the uncontrolled moisture content.
Table 2 presents moisture content data associated with PM-10 emissions, uncontrolled, watered, and the combined data set. There is a significant overlap between the	Note that Table 2 in the MPCA comments averages over a variety of different industries, road surface types, etc. More meaningful comparisons would result by

uncontrolled data and the watered data, suggesting the difficulty in preventing dual usage of moisture from happening.

Table 2. Road Surface Material Moisture Content for PM10 Emission Data

Description	Uncontrolled	Watered	
Combined Data Set			
Number of valid observations	145	37	182
Missing observations	27	4	31
Mean	1.611	4.751	2.249
Standard deviation	2.049	4.099	2.879
Skewness	1.786	2.17	2.621
Range	8.5	19.8	20.1
Minimum	0	0.3	0
Maximum	8.5	20.1	20.1

Annual Adjustments for Precipitation

Section 2.4 of the Draft Report (page 2-4) indicates the control efficiency of watering depends upon (a) the application rate of the water, (b) the time between applications, (c) traffic volume during the period, and (d) the meteorological conditions during the period. This suggests the annual simplifying assumption (365-p)/365, which reflects only first term, is an over simplification on the effects of natural precipitation, which is equation (2) in the draft AP-42 Section 13.2.2.

In our experience with mining operations, 0.01 inches of precipitation in a 24-hour period cannot achieve 100 percent control of particulate emissions from unpaved roads. A multi-tier approach would be better such as minimal control for 0.01 inches, moderate control for 0.10 inches, near-maximum control for 0.50 inches, and maximum control for 1.00 inches or more. This could be done by developing four maps similar to Figure 13.2.2-1 using current monthly climatological data such as that in the enclosed Climatological Data, Minnesota, February 1997.

Vehicle Speed

Section 4.3 of the Draft Report (page 4-27) states, “it is obvious to any one who has driven on an unpaved road that vehicle speed affects emissions, with faster vehicles generating more dust than slower ones. For this reason, it was decided to incorporate the findings of the captive traffic studies into the AP-42, independent of the emission factor equation.” Unfortunately, the corresponding section of the draft AP-42 Section 13.2.2 (page 13.2.2-8) is unclear on how this should be calculated.

The MPCA staff did confirm the apparent difficulty with vehicle speed in our statistical analysis of the data file, unpaved.dat (July 31, 1997). We are unable at this point of time to propose any better way of dealing with this variable in a statistically acceptable manner. As for the emission factor adjustment for vehicle speed reduction

matching uncontrolled and watered tests from in Tables 4-5 through 4-28 in the background document. However, MRI shares MPCA's concern that the effect of moisture might be "double-counted " and, as noted in a previous response, will expand the discussion of Equation 2 in Section 13.2.2 to ensure that M_{dry} clearly references uncontrolled conditions.

As noted elsewhere in the comment log, EPA plans to incorporate additional guidance in the use of more finely time resolved precipitation data.

Material drafted by EPA includes use of both current hourly rainfall totals as well as antecedent precipitation.

This portion of the AP-42 will be revised to more clearly define the linear decrease in emissions with a decrease in travel speed. As noted elsewhere in the comment response log, the linear reduction in emissions was mistakenly expressed in the draft AP-42 section and will be corrected in the final version.

The 50 mph value was used solely for illustration purposes. The numerical example will be expanded to more fully describe the estimation process.

in the draft AP-42 Section 13.2.2, we strongly suggest that some examples be provided to clarify how this adjustment should be calculated for regulatory purposes. The text on page 13.2.2-8 alludes to a 30 percent reduction in emissions for a vehicle speed reduction from 50 mph to 35 mph; however, it is unclear why 50 mph is the appropriate reference vehicle speed when (1) the proposed emission factor equation lacks any reference vehicle speed, and (2) the SYSTAT regressions indicate vehicle speed adds little to the R^2-values.

NATIONAL STONE ASSOCIATION
Techncial Comments Concerning Sections 4.2.3 and 4.2.5 of the Report Entitled, "Emission Factor Documentation for AP-42, Section 13.2.2 Unpaved Roads (Draft)"
(attached)

3. COMMENTS CONCERNING SECTION 4.2.3

3.1 Adequacy of the Testing Methodology

The first sentence of paragraph 2 of Section 4.2.3 makes an implied statement that the methodology was not adequate. *"The study used an upwind-downwind profiling technique that varied from the more commonly used exposure profiling method."*	As a basis for this response, recall that emission source testing requires one to first isolate and then quantify the PM contribution from the source. This is spelled out more completely in the following responses.
A similar statement was included in the fourth paragraph of Section 4.2.3. This statement goes on to declare that a large rock well created unrepresentative testing conditions. *"At the Garner test location, a large rock wall that stood immediately behind the downwind sampling site may have interrupted natural wind flows and/or created a local recirculation event. The potential wind obstruction and the variation in methodology from common exposure profiling methods accounted for a "B" rating of the test data at the Garner quarry. The Lemon Springs test was assigned an "A" rating."* It is apparent that MRI has assigned a "B" rating to this test report due to the presence of the "large rock wall" and due to the testing methodology. NSA objects to these statements and to the "B" rating.	Issues of pit trapping notwithstanding, the source testing procedure chosen by NSA and its contractors would require them, at a minimum, to a) determine what portion of the downwind particulate is due to the source and what is due to "background" b) ensure that the source contribution is not sampled more than once c) demonstrate that the entire plume is accounted for in a calculation scheme to determine net mass passing through the measurement plane d) relate the net mass passage to some meaningful measure of source activity to obtain an emission factor
The clearly expressed intent of the NSA sponsored studies was to evaluate fugitive particulate emissions from quarry haul roads. A major fraction of a quarry haul road at stone crushing plants is in the quarry pit that varies in depth from 50 feet to more than 300 feet.	
One of the testing locations selected for this test program was a portion of the haul road at the Garner, NC quarry of Martin Marietta. As shown in the photographs included with the test report, this location was approximately 100 feet below the top of the quarry and next to a "large rock wall." The Garner site is highly representative of quarry haul roads in the stone crushing industry. The other test location selected for this test program was at the top of the Lemon Springs, NC quarry of Martin Marietta. This site is representative of the portion of the quarry haul road outside of the quarry pit. NSA believes that the selection of these two sites was technically correct and justifiable.	The tested road may indeed be representative of roads at stone crushing plants, but the test site must allow one to isolate the source contribution in order to characterize emissions. These are separate issues.

There is, in fact, air recirculation due to the close proximity of the face of the quarry wall to the downwind side of the quarry haul road. This is the natural wind flow condition that exists in a deep quarry pit, and it must be taken into account during emission factor testing. This recirculation condition makes the emission profiling technique referred to by MRI difficult to apply for the following reasons. • The haul road and its "shoulder" are not sufficiently wide for the fifteen meter upwind and five meter downwind spacing of the monitoring instruments.	Given the recirculation, any number of things can occur that prevent one from isolating and quantifying the source contribution. For example, the upwind samplers may be impacted by the plume, resulting in too high a background concentration being subtracted out and biasing the calculated emissions low. On the other hand, if the plume circulates in the general vicinity of the samplers, the downwind samplers may repeatedly collect PM from the same vehicle pass, thus biasing the results high. The best one could hope for would be that the recirculation equally impacts both the upwind and downwind samplers to the same extent. Even in that case, however, it is problematic as to how one would attribute the net mass to a suitable measure of source activity if the PM from one vehicle pass is sampled repeatedly.
• The downwind particulate matter concentration does not necessarily approach ambient levels at the 21 foot elevation. Accordingly, there is no clear limit to the concentration profile integration.	At the upper boundary of the plume, the concentration should approach not necessarily an "ambient" level, but the background concentration. Also, if there is "no clear limit," then substantial plume mass would pass over the top sampler. The calculation scheme based on a fixed height (of 28.5 ft) may or may not account for the additional emissions. (See also the comment below on meaning of "ambient.")
Due to the proper selection of the test sites at the Garner and Lemon Springs quarries, the emission factor data are highly representative of stone crushing plant haul roads. The "B" rating is entirely inappropriate for the Garner tests. Exclusive use of the "commonly used emission profiling technique" outside of the quarry, where there was sufficient room for the monitoring towers would have clearly been non-representative of quarry pit haul roads.	The "representativeness" is based on grade, physical setting and other geometrical/location criteria . Nevertheless, for testing purposes, the basic issue of source isolation must be addressed independently.
3.2 Adherence to the Test Program Protocol	
NSA and its contractor, Air Control Techniques, P.C., fully adhered to the test protocol. The first version of this protocol was submitted by NSA to EPA on May 8, 1995. Based on EPA comments, the protocol was revised and resubmitted by NSA on July 20, 1995. Both of these versions included the following statement.	
"Due to the short distances between the downwind side of the haul road and the edge of the quarry cliff, the ambient PM-10 monitors may be influenced by PM-10 emissions from the quarry itself or PM-10 particles formed due to the turbulent eddies that exist at the edge of the cliff."	How are PM-10 particles formed due to the eddies? In the quoted section, does "ambient " refer to background samplers? If so, how would particles formed downwind (i.e., due to eddies) influence the background sampler? Does the protocol address how to deal with these influences?
This comment was included in a section of the protocol explaining why the *"commonly used emission profiling technique"* was not applicable. NSA believes that this statement also clearly indicates our intent to test in the quarry pit itself, not just on the upper portion of the quarry haul road. During an extended negotiation in the three month period prior to the beginning of these tests in late August 1995, EPA personnel, at no time, indicated that the proposed test location in the quarry pit or the testing methodology described in the July 20, 1995 version of the protocol was inadequate. The tests were conducted under the belief that EPA personnel had every opportunity to review the testing approach and that all EPA concerns had been fully satisfied. Accordingly, NSA is surprised that MRI has taken the position on behalf of EPA that	MRI functions as an independent contractor and certainly does not purport to speak directly for EPA. MRI's comments on the test method and the sites chosen are based on a review of the test report and results presented therein. (Note that the test report does not include the protocol in the list of references and -- to the best of MRI's knowledge -- the protocol is not mentioned in the test report.) MRI neither received nor was ever asked to review a copy of the test protocol. Had we reviewed the protocol, at a minimum, questions would have arisen about effects mentioned in the quotation.

the Garner tests should be rated “B” due to the test location and the test methodology. NSA have done everything in our power to work in a fully cooperative manner with EPA. Furthermore, we have conducted these tests in complete adherence to the test protocols. The rating of “B” for the Garner test is completely inappropriate.

3.3 Water Application Rates

The second sentence of paragraph 3 of Section 4.3.2 of the MRI report states the following:

> *“Specific water application rates were not reported, although the watering is said to have occurred approximately every 2.5 to 3 hours.”*

Appendix D of the emission test report for Garner and Lemon Springs (pages 100 through 124) specifically lists the exact time that every haul truck, water truck, pickup truck, tractor, car, and van passed the sampling assembly. This MRI comment seems to imply that Air Control Techniques omitted an important variable and was careless in test documentation. This is not correct.

The term "rate" is used to refer not only to the time between watering but also to the amount (volume) of water applied per unit area. The statement that rates were not reported is simply a remark based on the completeness of the report.

NSA and Air Control Techniques, P.C. have fully reviewed the May 8, 1995 and July 20, 1995 test protocols submitted to EPA prior to the tests. It is clear in these protocols that we did not intend to record the water application rates. Furthermore, it was not our intent to analyze the data in any manner that might involve EPA’s wet suppression efficiency equation. To our knowledge, this is the only equation that uses the water application rates as an independent variable. Accordingly, we are surprised that MRI has taken the position that we failed to include these data. This MRI criticism is even more surprising considering that MRI and EPA have not included water application rate data in the revised haul road equations. If the water application rate data had been present, it is clear that it would have been ignored by MRI and EPA. This MRI criticism is clearly unnecessary.

Had MRI reviewed the protocol, another item that would have been raised is measurement of "rates" (in both the time and volume senses).

NSA would like to emphasize that we adhered fully to the revised test protocol that we submitted to EPA more than a month before the tests began. At no time during the pretest negotiations did EPA personnel request these data. NSA requests that MRI’s criticism regarding the water application rate data be removed from their document.

MRI will revise the background document to clearly state that the volume of water applied per unit road area was not reported.

4. COMMENTS CONCERING SECTION 4.2.5

4.1 The Use of Colocated Push-Pull Hoods

Paragraph five of Section 4.2.5 states the following:

> “The ‘push-pull’ method used for this study is not considered an accepted methodology for measuring open source particulate emissions.”

Paragraph 4 of Section 4.2.5 states the following:

"The low sampling height at relatively low wind conditions used for this test program potentially allows the particulate plume to pass over the sampling device without capture."	
After reviewing the Entropy emission test report (Reference 5), NSA and Air Control Techniques, P.C. believe that the emission factor calculation procedures have not been clearly described, and we understand how MRI could have misinterpreted these results. Actually, the "push-pull" method described in the Entropy emission test report is a straight-forward adaptation of the upwind-downwind concentration monitoring often used for measurement of fugitive dust emissions. Entropy did not calculate the emissions based solely on the quantity of air captured by the hoods. It was also not necessary for the hoods to capture 100% of the haul road emissions in order to facilitate an accurate measurement of the downwind concentration. It is clear from the sample emission factor calculation shown on page 12 of the Entropy report that the average wind velocity (not the hood capture velocity) through the entire testing zone was used to calculate the emission factor. Accordingly, this test used a conventional upwind/downwind concentration measurement technique.	As applied since at least 1972, the "conventional" upwind/downwind (UW/DW) technique utilizes atmospheric dispersion models along with measured net concentrations at a single height to back-calculate an emission rate. In conventional UW/DW sampling, the plume is intended to pass over the sampling device and so complete capture is not an issue. Terms such as "capturing the fugitive emissions" and "capture hoods" are used throughout the Entropy report. On the other hand, we could find no reference to any dispersion [diffusion] model that would be a core feature of "conventional" UW/DW. The calculation scheme described on pages 11 and 12 of the test report relies on the "area of the sampling array." The scheme described here is very reminiscent of the roof monitor and quasi-stack measurement approaches to fugitive emissions. There is no resemblance to "conventional" UW/DW method.
Entropy used the hoods simply to gather a sufficient gas stream sample to measure the downwind concentration. As shown in Figure 2-3 of the Entropy report, the hoods were located approximately 1 meter from the side of the haul road. This is considerably closer than the 5 meter position used in MRI tests. Accordingly, there is considerably less vertical dispersion from the point of dust release next to the haul road surface to the monitoring site in the Entropy tests as compared to MRI tests. Due to the extremely close position of the Entropy hoods, a representative sample of the downwind concentration was obtained. **(underline added; see response)**	The intent of the underlined portion of the comment and the meaning of "representative sample" are unclear to MRI. If the intention is to demonstrate reasonably complete capture, the comment immediately preceding this one is contradictory by stating 100% capture was not necessary. On the other hand, if vertical dispersion is "considerably less," how would that situation affect emission factors back-calculated in a conventional UW/DW method?
NSA and Air Control Techniques, P.C. do not believe that significant quantities of dust escaped over the top of the hoods. Almost all of the particulate matter is emitted close to the road surface. This belief is consistent with the particulate matter emission mechanism described in draft Section 13.2.2.1 of AP-42, *"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 hoods used at Knightdale extended up to ten feet above the road surface, and smoke tracer tests confirmed that during truck passage, the large majority of the emissions remained at less than the 10 foot elevation and were sampled by the hoods. It should also be noted that hoods were located immediately adjacent to a 60 foot cliff that was part of the quarry pit wall. The 60 foot cliff less than 4 meters from the edge of the haul road also precluded the use of an emission profiling tower located 5 meters from the haul road.	Although "tests utilizing smoke" are mentioned on page 4 of the test report, there is no discussion of how or what type of tests were conducted. Where was smoke released -- at the height of the rolling wheels, top of truck, or at the surface? Was the smoke mixed with the dust plume as the particles are dispersed in the wake of the vehicle? What is meant by "immediately adjacent?" The cliff is not evident to MRI in Figure 2-3? What is the orientation of the 60 ft cliff with respect to the hoods? In any event, does the presence of the cliff aid in the capture or is recirculation likely?
It should also be noted that the fans on the upwind side of the haul road were used to enhance particle capture and reduced vertical dispersion of the plumes from the wakes of the haul road trucks. These fans increased the average wind speed across the road surface and drove the particulate toward the hoods.	

4.2 Adherence to the Emission Test Protocol

The “push-pull” upwind-downwind concentration test procedure used at the Knightdale quarry was first proposed in a series of meetings attended by EPA personnel and NSA personnel in the fall of 1993. It was described in an emission testing protocol dated December 3, 1993 and submitted to the Emission Measurement Branch by NSA. EPA personnel did not raise any objections to this test procedure over the ten month period preceding the test program. The only comments received was a telephone call from Dr. Chatten Cowherd or MRI on the first day of testing. NSA and Air Control Techniques believe that more than an adequate opportunity was provided to EPA and MRI to review the test procedure and raise any issues necessary. It was clearly unreasonable to delay the comments for over ten months and then raise issues after the equipment was set-up and testing was underway. It is also unreasonable to declare that the testing procedure is not an accepted methodology.

As mentioned earlier, MRI functions as an independent contractor. MRI's comments on the test method and the sites chosen are based solely on review of the test report and results presented therein. The phone call mentioned in the comment was placed at the request of EPA, who asked MRI to provide a "courtesy" review of the overall approach on short (i.e., <24 hr) notice. To the best of our knowledge, MRI never received a full copy of the protocol. In any event, MRI was never asked to provide formal written comments.

4.3 Co-located Hoods

Paragraph 4 of Section 4.2.5 states the following:

> *“The co-located hoods showed an order of magnitude difference between the left and right hoods in the concentrations sampled in three out of seven tests.”*

It is important to note that the side-by-side hoods were not used in a co-located manner. The emissions data from the two sets of hoods were combined. This is entirely different than the procedures used for co-located ambient monitors. The term “co-located” was not used in the Entropy report.

MRI used the term "co-located" to indicate that the two set of hoods were in very close proximity and Entropy never employed the term in their report. The point being made in the background document was that the test data indicate a non-uniformly emitting source. The importance of a uniformly emitting source would be even more important for a conventional upwind/downwind sampling approach because of the need to apply a dispersion model to the source.

The term “order of magnitude” means a factor of 10. A review of the left and right hood concentrations at Knightdale indicates that MRI is exaggerating with respect to these differences. The data shown in the table [below have been taken from Entropy Table 3-3. One of the tests (Uncontrolled Run 4) was factor of seven different, and two of the tests (Controlled Runs 1 and 2) were approximately a factor of five different.

The data are taken from Entropy Tables 3-4 and 3-5 rather than 3-3. MRI used "order of magnitude" in the sense of "how many places left of the decimal point." Admittedly, this may be less than technically precise and more of "colloquial" use of the term. In any case, factors of 5 to 7 are still surprising high and indicative of a non-uniformly emitting source.

Test Left/Right	Left Hood Concentration grains/DSCF	Right Hood Concentration grains/DSCF	Difference
Controlled Run 1	1.05 E-04	2.06 E-05	5.1
Controlled Run 2	1.35 E-04	2.83 E-05	4.7
Controlled Run 3	2.99 E-04	1.85 E-04	1.6
Uncontrolled Run 1	5.94 E-04	2.83 E-04	2.1
Uncontrolled Run 2	1.29 E-03	1.37 E-03	0.94
Uncontrolled Run 3	2.18 E-03	2.53 E-03	0.86
Uncontrolled Run 4	7.38 E-04	5.18 E-03	0.14

NSA and Air Control Techniques, P.C. have reviewed the Entropy data and believe that the difference is caused primarily by the location of the left hood relative to an intersection of two haul roads and the quarry pit haul road near the test site. It was sometimes necessary for haul road trucks to stop and idle while another vehicle passed

This emphasizes the importance of being able to isolate the source under consideration from the influence of other nearby (upwind) PM sources. Would idling emissions be collected by the upwind samplers? Were diesel emissions from the vehicles passing the array sampled or did these emissions pass above the 10 ft high array at a distance of through the intersection. The stopping point for vehicles exiting the pit and approaching the primary crushers was close to the left hood. Air Control Techniques, P.C. believes that the high concentrations observed in the left hoods during the first two runs were due to the capture of these idling emissions.

NSA and Air Control Techniques can not find any indications of the possible cause for the difference in the Left and Right Hood during Uncontrolled Run 4. However, we do not believe that Uncontrolled Run 4 should be treated as an outlier and discarded. Also, it should be noted that more than a factor of seven variability was described in many of the references used by MRI in developing the proposed unpaved road equation. The following examples illustrate the extent of differences in these other tests.

Variability of Particulate Emission Factor Data

(MRI Conducted Emission Factor Tests)

MRI Reference	Run #	Lbs/VMT	Difference	Silt, %	Moisture, %
2	BA-9	0.09		3.35	5.69
	BA-3	1.32	14.6	3.04	7.41
4	BB-47	78.2		14.0	5.11
	BB-46	8.14	9.6	12.7	4.88
8	AQ7-G	0.39		7	1.2
	AQ6-C	2.43	6.23	12	1.4

All three studies were conducted by MRI, and all three sets of runs were conducted at similar moisture and silt levels as indicated in the table above. MRI chose not to discuss the factor of 6 to 14 variability in their test runs but was highly critical of the factor of five to seven variability in the Entropy data. In fact, variability is a common problem in the large majority of fugitive emission testing projects.

4.4 Recirculation Air Flow

The fourth paragraph of Section 4.3.5 states the following.

> *"Strong evidence of recirculation of emissions to the upwind sampler is provided by the fact that the upwind concentrations increased by roughly an order of magnitude from the controlled to the uncontrolled tests."*

There is no technical basis for the criticism. The upwind concentrations increased *"…roughly an order of magnitude…"* because the upwind ambient air sampler had to be located close to a portion of the unpaved quarry haul road (see Figure 1). During the uncontrolled tests, this section of the road was not watered.

1m away from the road? Are there additional PM or source activity components not included in the emission factors reported? If additional PM emissions were sampled and not subtracted out as background, then one would expect (all other things being equal) that the factors would be biased high. However, controlled runs 1 and 2 have the two <u>lowest</u> factors reported of the 3 controlled tests considered at Knightdale.

MRI's original remark had nothing to do with the emission factors reported. Even so, we cannot let this comment pass without noting that in NSA's table :

- Runs BA-9 and BA-3 should not be compared because, although both are tests of scrapers in transit,
    1. the two tests were conducted at different sites;
    2. more importantly, one was a test of <u>controlled</u> emissions while the other was a test of <u>uncontrolled</u> emissions.
- Runs AQ7-G and AQ6-C are not comparable because they were conducted on surfaces treated with <u>different chemical dust suppressants</u>.
- Table 4-8 of the AP-42 background document contains a mistakenly converted emission factor for run BB-47. In the original test report, the emission factors for runs BB-46 and BB-47 are given as 3100 and 2304 g/VKT [11.0 and 8.1 lb/VMT], respectively. Entries in Table 4-8 in the background document will be corrected. (The correct values were included in the developmental data base.)

In the interest of isolating the source contribution, why wasn't the upwind section watered?

Air Control Techniques has recalculated the uncontrolled emission factors by ignoring the contribution of the upwind dust concentrations to the measured downwind concentrations. By taking this approach, the data are biased to higher-than-true levels. It is apparent that the revised emission factors (ignoring upwind dust concentrations) are only slightly higher than the emission factors reported in the test report. <u>The order of magnitude increase in the ambient air concentrations upwind of the test location did not have a significant impact on the reported uncontrolled emission factors as indicated in the table below</u>.

Recalculated Emission Factors Based on Zero Upwind Dust Concentration

	Upwind Concentration	Original PM10 Emission Factor	Revised PM10 Emission Factor	% Difference in Emission Factors, Revised /Original
Uncontrolled 1	2.28 E-04	0.528	1.10	2.08
Uncontrolled 2	2.28 E-04	1.57	1.89	1.20
Uncontrolled 3	2.28 E-04	2.34	2.59	1.11
Uncontrolled 4	1.75E-04	4.70	5.01	1.07

Except for one of the four runs, ignoring the contribution of the upwind air concentration entirely results in an increase of only 7% to 20% in the calculated emission factor.

It is important to note that a quarry haul road has an entirely different configuration than a public unpaved road and haul roads at iron and steel plants. The quarry haul road inherently has a swirl pattern necessary to allow heavy duty trucks to descend several hundred feet into the pit. Furthermore, there must be one or more approach roads to allow the heavy duty trucks, graders, and water trucks to reach the swirling quarry pit road. In most quarries, an ideal upwind ambient air monitoring site is hard to find due to the complex road pattern in a compact industrial site. Air Control Techniques believes that Entropy properly selected a monitoring site and accurately measured the actual upwind dust concentration approaching the portion of the haul road tested. There is no basis for the *"…recirculation"* criticism expressed by MRI.

4.5 Testing Was Discontinued During Certain Wind Conditions

The third sentence of the third paragraph of MRI Section 4.2.5 states the following.

> *"Testing was discontinued when speeds exceeded 3 miles per hour."*

This statement is a misinterpretation of the comments and data provided in the Entropy report. As stated in the Entropy report: *"Furthermore, the test was delayed if winds in excess of 3 miles per hour shifted and came from the North or East."* As indicated in Figure 1, the hoods were located directly west of the portion of quarry pit

What reason is there that the emission factors monotonically increased over the four uncontrolled test runs? (There is only a 6% probability of this occurring by chance alone.) How long had watering been suspended?

Note that the last column represents a ratio, rather than the percent difference shown in the column heading.

Note that the revised factors again increase monotonically. Again, how long had the watering been suspended?

As before, the issues of "representativeness" are based on geometry and physical setting criteria. As mentioned throughout, isolation of the source contribution is critical to successful source testing.

Testing under higher winds in the "proper" direction would help ensure more complete capture by the hoods, while testing under low-speed winds or winds with very oblique directions (up to 80 degrees off perpendicular, according to page 8 in the test report) would encourage material to pass over/around the hoods. <u>What is the reason that</u>

haul road tested. The testing was conducted whenever the winds were from the west or northwest. Furthermore, testing was conducted during all low wind speed conditions (<3 m) because the upwind side fans generated a west-to-east air flow of approximately 3 mph. Accordingly, the testing contributed during all conditions when the air was flowing in the proper direction. The testing was interrupted whenever there were strong winds that were not in the proper direction. The testing was restarted when the winds shifted back to the acceptable direction. Winds from the north or east that exceeded 3 mph would have caused a bias to lower-than-true emissions because the hoods were not in a proper downwind orientation during these time periods. The procedures used by Entropy were correct. Furthermore, these procedures are entirely consistent with those used by MRI in tests of unpaved roads. **[underline added; see response]**	testing would be delayed under the very conditions that enhance complete capture? Also, what is the basis for the very broad acceptance criterion for wind direction? Again, this allows testing under the conditions of very poor capture. Where was the Weather Wizard unit deployed? What height was the monitoring unit? The last sentence (underlined) in the comment is entirely mistaken. MRI's acceptance criteria is not at all similar to that used in the Entropy study. Had criteria "consistent" with MRI's ranges been used, the underlined question in the above response would not have been asked.

PORTLAND CEMENT ASSOCIATION
Letter of November 14, 1997 from Garth J. Hawkins to Ronald E. Myers, USEPA (attached)
The Portland Cement Association (PCA) has the following comments on the September 1997 draft version of the following U.S. Environmental Protection Agency (EPA) report:

> *Emission Factor Documentation for AP-42, Section 13.2.2 Unpaved Roads (the "AP-42 Unpaved Road Document"),*

PCA appreciates the opportunity to review this document.

All portland cement manufacturing facilities require large amounts of limestone and other naturally occurring materials such as slate, shale, etc. Because of this fact, each cement plant operates quarries and crushing operations to provide these materials to the manufacturing facility, and therefore, constructs and maintains unpaved haul roads for the transportation of these materials.

The quarries are developed so that the most efficient transportation as possible of raw materials from the source to the cement plant can be accomplished. To move the volume of limestone and other materials required by the manufacturing facility, only large dump trucks or similar vehicles are used, and the trucks are operated at fairly consistent speeds from the quarry operation to the crushing and screening machinery. Smaller vehicles, such as pickup trucks or cars, are a limited percentage of the vehicles traveling the unpaved roads within the facility.

Due to the availability of limestone and similar materials, the unpaved roads at the quarry and manufacturing facility are constantly constructed and maintained with the raw materials being extracted. Overall, cement plants are very similar to limestone quarries that provide crushed stone to the road-building and construction industries.

Although several studies of unpaved roads related to the stone industry are included in the *AP-42 Unpaved Road Document*, some very dissimilar industries are also included in the development of the emission factor equations. Industries such as coal mining, copper smelting, and the iron and steel industry may required different types of vehicles, have variations in the traffic patterns, and use other materials in the construction of their unpaved haul roads. For example, multiple types of aggregate may be used at the above industries due to the lack of the availability of road-building materials.

The emission factor equations in the *AP-42 Unpaved Road Document* are also dependent on data collected from unpaved roads used by pickup trucks and cars. The use of these vehicles results in great variations in possible dust generation due to the differences in tires, vehicle speeds, and vehicle aerodynamic effects.

Therefore, PCA requests that the EPA consider including the emission factor equations developed by the National Stone Association (NSA) in the *AP-42 Unpaved Road Document*. PCA believes that the NSA equations are more representative of the unpaved roads found at a cement facility. The inclusion of the NSA equations will allow a cement manufacturing facility to select the equation that best represents the possible emissions form the haul roads related to its operations. For your reference, a copy of the cover page of the report summarizing the NSA findings is attached.

The National Stone Association (NSA) emission factors utilize the mathematical form of a predictive equation developed from tests of very large haul trucks at western surface coal mines. That is to say, the factors that PCA requests be considered are in fact based on source relationships that the PCA describe as "dissimilar" to portland cement industry. (See also the discussion of the NSA equation in the responses to Air Control Techniques, P.C. comments below.)

AIR CONTROL TECNIQUES, P.C.
Letter of November 24, 1997 John Richards and Todd Brozell to Ron Myers of US EPA (attached)

1. Applicability of the Draft Unpaved Road Equation to Stone Crushing Plants

We believe that the predictive equation developed based strictly on emission factor tests at stone crushing plants is a better predictor of PM-10 and PM-2.5 emissions than the general emission factor equation for all types of unpaved roads. This position is consistent with the following statement included on page 3 of the Fifth Edition of AP-42.

> "If representative source-specific data cannot be obtained, emissions information from …actual test data from similar equipment, is a better source of information for permitting decisions than an AP-42 emission factor. When such information is not available, use of emissions factors may be necessary as a last resort."

The predictive equations developed based on NSA sponsored tests at stone crushing plants located at Knightdale, Garner, and Lemon Springs, NC are shown below as Equation 1 and 2.

$$E_{PM\text{-}10} = (s/3)^{0.8}(M/2)^{-0.9} \qquad \text{Equation 1}$$

$$E_{PM\text{-}2.5} = 0.25(s/3)^{0.8}(M/2)^{-0.9} \qquad \text{Equation 2}$$

Where:

$E_{PM\text{-}10}$ = PM-10 Emissions, Lb./VMT
$E_{PM\text{-}2.5}$ = PM-2.5 Emissions, Lb./VMT
s = Silt content, %
M = Moisture content, %

The use of the precipitation factor from Section 13.2.2 can be used to adapt this equation for predicting annual emissions. This results in Equations 3 and 4.

$$E_{PM\text{-}10} = (s/3)^{0.8}(M/2)^{-0.9}[(365\text{-}p)/365] \qquad \text{Equation 3}$$

$$E_{PM\text{-}2.5} = 0.25(s/3)^{0.8}(M/2)^{-0.9}[(365\text{-}p)/365] \qquad \text{Equation 4}$$

We believe that these equations are more representative of the PM-10 and PM-2.5 emissions from stone crushing plant haul roads for the following reasons:

- All tests were conducted on quarry haul roads representative of the stone crushing industry.
- One of the three tests was conducted in the quarry pit.
- The vehicle weights and speeds during the test program were representative of the

The quote from AP-42 applies to situations in which an emission test result is to applied to a different source at the same facility.

Even though Equations 1 through 4 in the comment reference stone crushing plant roads, several points should be noted about those factors and how they were developed. Those points are raised in the following paragraphs.

Equation 1 is presented as Equation 16 in a May 1996 report prepared for the National Stone Association (NSA) entitled "Review of the EPA Unpaved Road Equation and its Applicability to Haul Roads at Stone Crushing Plants." Because that report contains the recurring theme that the AP-42 unpaved road emission factor lacks a firm technical basis for application to pit roads, the report presents no discussion of the technical basis for the recommended Equation 1. The report only states that "*it was necessary to change the exponents concerning the moisture content and to adjust one of the constants"* in an equation developed for western surface coal mines. Just <u>how</u> that change and adjustment were made is never discussed. A preliminary analysis of the13 reported Knightdale, Garner and Lemon Springs tests (using the emission factors, moisture and silt contents reported) clearly shows that neither simple nor multiple linear least-squares regression was used. Just what is the technical basis for the "modification?"

Other points to note about Equations 1 through 4 in the comment:

- Combining the Knightdale and the Garner/Lemon Springs data sets mixes two types of data. The May 1996 report explains that that Garner/Lemon Springs emission factors have "subtract[ed] out the combustible particulate and organic particulate that were obviously not emitted from the road." (The test report, however, describes a correction only for "combustion particles resulting from diesel exhaust" and implies in the example calculation that organic material is included.) In any event, the Knightdale factors did not undergo this correction and, just as importantly, the corrections were not made in the <u>upwind</u> concentration measurements. (Recall from the background document that this

stone crushing industry. • The silt and moisture contents of the road surfaces were representative of the stone crushing industry. • The surface characteristics of stone crushing plant haul roads are different from other types of unpaved roads due to the frequent watering, the compaction caused by the heavy duty trucks, and the high degree of road maintenance provided by plant operators.	omission leads to a systematic low bias in the emission factors.) • It is unknown what, if any, other culling/clean-up of the data sets may have been performed. For example, of the three Garner tests, one test has negative emission factors reported for both PM-2.5 and PM-1 and another test has $E_{PM-1} > E_{PM-2.5} > E_{PM-10}$. • Despite questions about the origin of Equation 1, it does reference back to the May 1996 report to NSA. There is, however, no indication as to how Equation 2 came to be. Presumably, it was scaled from Equation 1 using the PM-2.5/PM-10 data from the tests conducted for NSA. Because the Entropy test program (reference 5 in the background document) reports only PM-10 factors, we assume that only the six Garner and Lemon Springs tests were used to scale Equation 1 to PM-2.5. However, one of those tests resulted in a negative PM-2.5 emission and another implied a PM-2.5-to-PM-10 ratio of more than 100%. Assuming those test results were not used, the remaining ratios (58% at Garner and 8.2%, 28%, and 76% at Lemon Springs) do not yield the value of 0.25 implicit between Equations 1 and 2.
A comparison of Equation 1 with the measured PM-10 emission factors at the three stone crushing plants is shown in Figure 1. **[See figure in attached comments.]** The R^2 correlation coefficient for this equation is approximately 59%. A comparison of the measured PM-10 emission factors with the draft unpaved road equation is shown in Figure 2. **[See figure in attached comments.]** The R^2 correlation coefficient is 54%, slightly lower than for NSA's Equation 1. This means that the NSA equation explains the variability of the data slightly better than the EPA equation.	The figures are misleading in several ways. For example, the R^2 value shown in Figure 2 pertains to the least-squares best fit line between a subset of the measured and predicted emission factors. Also, because of the multiplicative form of both the AP-42 and NSA equations, the more appropriate plot (and correlation) for each figure would be log-log in nature. The R^2 shown is not the same as a multiple R-squared value for a regression-based predictive equation of a multiplicative form. Even more importantly, direct comparisons of R-squared values is misleading unless one also considers the number of "degrees of freedom." In addition to the R-squared value, the number of observations and the number of independent variables determine the "level of significance" for a predictive model. Because it is unclear how the NSA factor was derived, it was not possible to assign a meaningful level of significance for the NSA expressions. It also appears that values plotted in Figure 1 only ~70% of what is directly calculated using Equation 1. Consider, for example, the fourth uncontrolled test at Knightdale (the far right-hand data point in Figures 1 and 2). From Table 3-6D in the Entropy test report, the silt is 11.03% and the moisture content is 0.83%. In that case, Equation 1 leads to an estimated value over 6 lb/vmt which is 50% higher than the value shown on Figure 1. What are the predicted values and what silt and moisture contents were used?
The EPA unpaved road equation appears to have a significant bias to higher-than-observed PM-10 emissions for stone crushing plants having high haul road moisture levels. This bias is indicated by the intercept of the linear regression line with the y-axis at a value of approximately 2.0 lbs/VMT. We believe that this bias is due to the fact that the material present in the silt and stone crushing plants is inherently more wettable than the silt present on rural unpaved roads (e.g., clay), western surface coal mines (e.g., coal dust and clay), and iron and steel plants (e.g., slag). Use of the new	Some bias results simply because the Garner and Lemon Springs tests have undergone "correction for combustibles and organic material." In that case, a higher value from the draft AP-42 equation (which includes exhaust and other components found downwind of the roadway) is certainly to be expected. Also, recall that although downwind samples were adjusted, no corresponding adjustment was made to the upwind samples. That omission results in a systematic low bias in the resulting emission factors.

unpaved road equation may penalize the operators of stone crushing plants that are the most conscientious in maintaining high moisture levels on their haul roads.	
The emission factor data obtained in the NSA sponsored tests appear to be more representative of PM-10 and PM-2.5 emissions from stone crushing industries. This is indicated by the more reasonable form of the relationship shown between the predicted and observed emission factor data shown in Figure 1.	Although one may argue about the form of and procedure used to develop the revised AP-42 unpaved road equation, the background document describes how the predictive model was developed. In this way, arguments and discussion can proceed with all parties on equal footing. On the other hand, the procedures and data that result in Equations 1 through 4 have not clearly been presented. Even ignoring issues of negative emission factors and mixed types of data, it is still not possible to recreate the results reported. In fact, simply calculating the values in Figure 1 using Equation 1 was unsuccessful. Given the undocumented procedure used to develop the predictive models, unilateral claims about the reasonableness of the method are simply not supported.

2. General Comments

Road Surface Moisture Levels

We believe that the EPA draft equation in its present form underestimates the benefits of moisture. Extrapolation of the curve defined by the equation to the 20% moisture level yields predicted PM-10 emission factors in the range of 1.0 lbs/VMT as shown in Figure 3. **[See figure in attached comments.]** Air Control Techniques, P.C. believe that the new equation overpredicts PM-10 emissions at high moisture levels.	MRI agrees that 15% represents a reasonable estimate of surface moisture content above which essentially no road dust is emitted. On the other hand, extensive watering should have no effect on emissions due to exhaust or any material entrained from the truck's load, undercarriage, etc.
The curve generated by the equation should approach very low emission factor values at 20 percent moisture levels. The particulate emissions from essentially all unpaved road surfaces should be very low at this very high moisture level. The mathematical form of the equation should be reviewed to determine if there is a more appropriate exponent for moisture that provides a better representation of emissions from highly moist unpaved road surfaces.	Recall that the Garner and Lemon Springs data have had at least diesel exhaust removed from the reported emission factors. Furthermore, the adjustment systematically biased emission factors low by not correcting the upwind background samples.
Despite the apparent deficiencies at high moisture levels, the equation appears to have the proper form for low moisture levels. As indicated in Figure 3, the predicted emissions have an asymptotic relationship with moisture at levels below approximately 0.3%. We have observed the same relationship in tests conducted for the National Stone Association.	Emissions should increase as the surface moisture content decreases, but it is also reasonable that each road has some "effective lower limit" for its surface moisture content. In that case, the asymptotic behavior in Figure 3 would not be observed, but instead emissions would follow a flatter portion. In other words, once a road is "dry," becoming "bone dry" would not greatly increase emission levels.

Precipitation Factor

We agree with the inclusion of the precipitation factor, [(365-p)/365] in Equation 2 of Draft Section 13.2.2, and with the statement that, "…all roads are subject to some natural mitigation because of rainfall and other precipitation." However, it would be helpful to add a statement that the precipitation days should include all days that the road surface is covered by snow or ice, irregardless of the amount of precipitation occurring on each specific day.	As mentioned elsewhere in the response log, EPA has drafted additional guidance to better account for the effects of precipitation within the AP-42 section.

Vehicle Speed and Other Factors

It is apparent in the Emission Factor Documentation report and in the draft Section 13.2.2 that the EPA and MRI authors are not entirely confident in the form of the new unpaved road equation. For example, the following statement is included in Section 1.2.2.3. “Although vehicle speed does not appear as a correction parameter, it is obvious to anyone who has driven on an unpaved road that (visible) emissions increase with vehicle speed.”	The statement pertains to dust generated by individual vehicle passes over a road while the recommended emission factor equation references emissions due "fleet average" conditions over a road. MRI believes that the statement does not connote a lack of confidence in the equation but rather implies that a) that every road probably has a fairly narrow range of "natural" average speeds and b) there are insufficient test data available to fully define the influence of average speed on emissions.
Air Control Techniques, P.C. agrees with this comment regarding the importance of the speed factor. Furthermore, we believe that there are a number of other important factors that have a direct and significant impact on PM-10 and PM-2.5 emissions. A partial list of these factors include the following. • Vehicle road clearance and the associated magnitude of the turbulent wake as a function of the vehicle speed • The tire tread characteristics with respect to the tendency to pick-up and entrain particles into the turbulent wake of the vehicle • The tire tangential velocity with respect to the tendency to release particles from the tire into the turbulent wake of the vehicle • The actual pressure exerted by the vehicle tire on the road surface that causes pulverization of silt particles to form PM-10 and PM-2.5 particles • The grindability of the silt particles • The extent of compaction of the road surface under various wet suppression and/or natural precipitation conditions • The extent to which tailpipe exhaust contributes to particle entrainment into the turbulent wake of the vehicle	MRI agrees that there are many factors that can influence emission levels from vehicle travel over unpaved surfaces. However, two points must be reiterated: 1. Many of the factors listed (and, for that matter, other potentially important variables) are highly intercorrelated. For example, speed is inversely correlated with weight; and tire tangential velocity, tread design, and footprint pressure are all interrelated. In developing a phenomenological model from available empirical data, inclusion of highly intercorrelated independent variables is usually not appropriate. 2. Related to the previous item, it would be necessary to obtain emission data under tightly controlled conditions to fully address factors of the type listed. In the case of tread design, for example, one would ideally want at least duplicate tests of 2 or 3 different tread designs on the same trucks driven by the same operators at the same speed over the same road. Even so, because tread design potentially affects the "steady-state" road surface properties, one would also need to allow the road to "condition" itself to each design over a period of at least several days or weeks. Even assuming one could achieve extensive experimental control over a "real-world" source, one would still need to contend with test conditions beyond control, such as antecedent meteorology.
Obviously, neither EPA nor NSA has the budget necessary to accurately analyze the possible impact of all of these important variables. Accordingly, Air Control Techniques, P.C. recommends that EPA conduct a fundamental particle formation and emission study using modern computational fluid dynamic modeling (CFD) techniques. These are “First Principle” models that are being actively used in a wide variety of aerospace design projects, automotive design projects, process equipment design projects, and air pollution control equipment optimization projects. We have had the opportunity to work on a number of projects involving CFD, and we are very impressed with the capability and accuracy of this technology. CFD would provide an economical way to provide a sound technical basis to the unpaved road equation. For too long, this equation has been based simply on layer after layer of empirical studies concerning only a few of the important variables affecting emissions. There is now a readily available technology to provide improved emission factor equations.	The comments regarding CFD are interesting, but it is not clear how such an approach could be "operationalized." For example, one could use CFD to determine the near-source air flow field for analysis of the trajectory of an individual particle released tangentially from a tire. Similarly, one might simulate air flow due to the turbulent wake that mixes entrained particles. However, the feasibility of CFD would depend on the analyst's ability to specify initial and boundary conditions that would be used relative to the entrainment of particles? From what point along the tire is the particle released? How would that change with size of a particle? A much more thorough prospectus of how CFD could be used is necessary before one can reach the conclusion of the last sentence in the comment.

NORTH CAROLINA DEPARMENT OF ENVIRONMENT AND NATURAL RESOURCES
Letter dated October 22, 1997 from Jim Southerland to Ronald E. Myers (with attached marked-up copies of background document and draft AP-42 section)

Table 13.2.2-1 could use some additional clarity. For example, “yard area” should clearly state that this is the storage area. “Haul” and “Access” should clearly indicate that these are to the pit or wherever. Is “mean” in the header an arithmetic or geometric variety? Can more definition be given to the road surface “dirt?” Again, additional explanation of what the new information in the table are as opposed to old, etc., should be added to provide clarity to the user who might be familiar with using the old tables in separate sections.**[underline added; see response]**	In general, the suggested wording changes will be incorporated into the draft section. As pertains to the underlined portion of the comment, note that only the western surface coal mining section would be affected -- in fact, the appropriate change has drafted and sent to the EPA work assignment manager. Also note that the current version of Table 13.2.2-1 already includes road material information for surface mining.
Page 3: The first paragraph does not seem to describe satisfactorily what was done. Additional detail and clarity with a reference to the further discussions in the background report might be helpful. Also on same page, I suggest writing out each equation (PM-30, PM-10, PM-2.5) separately for clarity. Footnote meaning or equivalence of PM-30, and drop PM-15 as it has little relevance/meaning. I do not believe these resulting equations technically merit the “A” and “B” ratings and should be downgraded at least a letter due to the statistics in the background report and personal judgment.	Reference to the background document will be added on page 13.2.2-3. Quality ratings will be re-evaluated in conjunction with suggestions made by other reviewers (most notably Minnesota Pollution Control Agency).
Page 5: The discussion talks about defaults but stops short of a “presumptive default” equation or expression for crude approximation. Since this is likely to be done anyway, I suggest providing such an equation with calculated extremes that can occur if applied without regard to real input data.	As mentioned elsewhere in the response log, the predictive equation will re-written with a normalizing value of 0.2% for moisture and text will be added to clearly indicate that 0.2% is the default value.
Page 8: The first full paragraph discusses collecting new road samples after 6 months of use. I sincerely doubt that anyone will likely do this. It is difficult to even get a facility to take samples at all to estimate emissions.	The recommendation concerns speed controls. Although it may be difficult to convince a facility to collect any samples, this seems to be a reasonable request if a facility claims control credit for speed reduction.
Page 10: The section does not explain “Class A pan evaporation,” and it should. Some other word changes recommended on enclosed copies.	Text will be added to better explain Class A pan evaporation and its use in the prospective analysis.
Page 12: How does one determine “ground inventory?” is there a rule of thumb for default?	Additional text will be added the example in Table 13.2.2-4 to supplement the explanation of ground inventory given in item 1 on page 13.2.2-12. Because Figure 13.2.2-2 is used either to estimate the effectiveness of an existing control application plan or for planning a program to meet a certain efficiency level, it does not seem that a default value is necessary.

Background Report

Page 1-1: The Second Edition of AP-42 was published in 1972. The earlier “Duprey” edition was in 1968 or 1969. Earlier versions of similar documents were issued in 1965 or so. However, I don’t believe fugitive dusts were addressed until the Third Edition, or perhaps a supplement to the Second or Third Edition.	The statement is based on page 1-1 of EPA-454/R-95-015, Procedures for Preparing Emission Factor Documents. The paragraph will be rewritten to remove the date reference.

In the definitions section, “filterable particulate” should be included for completeness. I would suggest dropping the IP or PM-15 as it is not now used and could be confusing.	Filterable particulate will be added. In addition, the material will be rewritten to follow a "PM-x" format.
In Section 3, measurement methods are discussed. However, the “stone association” method seems avoided somewhat. Since it has been used and the data evaluated, it should be included in the descriptions. Here and in Section 4, the evaluations seem a bit biased against data not collected by MRI. Their data may be better or not, but “outside” tests seem more rigorously critiqued than the other tests. Comments may be valid, but need to be equal and balanced in presentation so as to not give this impression. For example, “unacceptable” is a judgment given without any documentation or reasons. Also, it is not reasonable that road widths and such basic information not included in test reports, even by the same contractor, are not recoverable in some fashion.	MRI will expand Section 3 to indicate that both the upwind-downwind and exposure profiling methods doe not interfere with plume development/dispersion by forcing or blocking the flow. Furthermore, as evidenced in the National Stone Association comments, the Knightdale test report did not clearly establish how emission factors were developed. However, MRI believes that the background document was lenient in the assignment of quality ratings to the Garner and Lemon Springs test data. For example, consider that • It is unclear what run the example calculation on page 17 refers to. The example states "Run Number G-UW-M201A-3 8/15/95." However, the end result of the example is an emission factor that corresponds to the reported value for run "G-U-AMB-2 / G-DW-M201A-2" in Table 3-12. • The example calculation also based the emission factor on 204 vehicle passes, but does not imply where that information is to be found. Table 3-7 gives 95 and 122 loaded truck passes during Runs G-UW-AMB-2 and G-UW-AMB-3, respectively. (Apparently, the traffic counts given in Appendix D are used.) • It remains unclear why, if one were to correct the downwind concentration for mineral content, etc., one would not also make the same correction for the background concentration. To not do so creates an "apples and oranges" situation, systematically biasing the results to lower than actual emission levels of mineral and organic particulate. • Issues of upwind composition notwithstanding, there are also questions about how the size distributions were used to correct for combustion particulate vs. stone dust. The data used in the correction are based on microscopy, but no mention is made of translating the number-based distribution to a mass-based distribution that would be needed to made the correction. • Surprisingly little discussion is offered for some unusual results reported. For example, in the three tests conducted at the Garner site, there is a ratio of 300 between the highest to lowest emission factors. Nothing is said about this. Assuming that the same types of trucks traveled at roughly the same speed over the same road during the 3 tests would lead one to the conclusion that the reproducibility of the measurements is not very good. Also, no discussion is offered for findings of negative PM2.5/PM1 emission factors nor of a PM1 emission factor being greater than a PM2.5 factor, which in turn is greater than the PM10 factor. In spite of the above, the Garner and Lemon Springs testing programs were still assigned B and A ratings. Given the issues raised about recirculation and source isolation in response to NSA's comments, it appears that the quality rating for Garner was even more lenient than originally believed.

Page 4-29 and thereabouts: Would it not make sense to view the data bases for PM-30, PM-10 and PM-2.5 separately and independently? There may likely be forces (e.g., static) acting upon the different sized particles that would best be represented by this treatment. With the <u>statistics presented on page 4-30 and 31</u>, the "A" rating on page 4-29 does not seem warranted. **[underline added; see response]**	The background document notes that all the PM data sets were originally analyzed separately and independently. The problem arose in that the resulting factor for PM-2.5 was not consistent with the result for PM-10/PM-30 and had only limited predictive accuracy. Also, note that the statistics for the underlined portion of the comment deal only with hypothetical data and not with any emission factor developed in the background document. Rather, these are only hypothetical data that serve illustrate why a geometric mean is more appropriate for the ratio-based statistics.
Mid-page 4-37: "0.5 percent" seems to materialize out of the air. Explain "pan evaporation" and its relevance on the next page.	Following a reevaluation of the public road data base the default surface moisture content and thus the moisture normilization parameter was revised to 0.2%. The background document will be modified to more fully explain why a value of 0.2% is recommended. As noted above and elsewhere in the response log, the moisture normalization in Equation 1 of Section 13.2.2 also will be changed to 0.2% with an explanation that it is a default value.

General Observations

There continues to be a generally insufficient level of information and detail for confidently estimating emissions from fugitive dust sources of all types. This includes information which would assist in relating sources more closely with their ambient impact. The parameters upon which the emissions should be based are fairly intuitive and the existing equations seem to address those. However, there is a gap of acceptance of these emissions as being part of the "real world" of sources which are emitting into the ambient air and for which we are comfortable with emissions being well correlated with their ambient impact. The complexity of resulting equations generally precludes a majority of facilities from estimating their emissions in this manner. The availability of a simple, stable, defensible and usable (user friendly) computerized model to accomplish this would be of assistance, but perhaps be only a partial solution. It might be helpful to develop several (based on aridity, soil characteristics, etc.) models which could represent different parts of the country and types of facilities and make the calculations simpler, although somewhat more crude. Facilities and agencies are somewhat geared to permit conditions, so this might provide a means to categorize further the estimation of emissions, application of controls and operations.	MRI agrees that fugitive sources are indeed a unique class of emissions unto themselves. In essence, this type of source is defined by what it is not (i.e., not directly through a stack or vent). Nevertheless, fugitive sources are pervasive throughout industry. Admittedly, in an ideal situation, one would have sufficient information to develop industry-specific factors for use in different regions of the country. However, one is always forced to work with the data that are available. Over the past 20 years, emission estimation methods have relied on similarities in the basic emission process over the broad range of source conditions throughout different industries.
Reading the section, I could not help but wonder if some future reviews and updates should not address this problem a little differently. For example, would an approach to separate the mechanical lifting forces and the air turbulent forces in the analysis be productive? Also, for PM-10 and PM-2.5, I doubt if it is still appropriate to look at just silt analysis. I am sure silt is still a crude and somewhat commonly available indicator, but the size particles being simulated are so much smaller than silt that one can not help but wonder if there is not a finer delineation within "silt" that is necessary before a determination of this sector can be appropriately made.	Again, in an ideal situation, one would have access to data that clearly delineate emissions from wakes, tire/road interactions, etc. Nevertheless, the practical constraints on developing this type of information are overwhelming, as discussed in response to an Air Control Techniques comment.

This report on fugitives from unpaved roads does not sufficiently show the comparison of old parameters and results with the newer ones. I recommend that each estimation process, including those for aggregate operations, coal mines, paved roads, etc., be examined in a case study comparison approach so the reader can view them side by side and evaluate the impacts of the revisions. One is understandably reluctant to adapt and apply a new set of numbers without having some concern about and evaluation for what this will do to the existing data structure and integrity built up over the previous years of application. A clear concise comparison detailed in the background report and summarized in the sections themselves would facilitate this level of confidence. A cross reference to any applicable (EIIP) estimation methods would be helpful.	MRI agrees that such a side-by-side comparison would be useful. Nevertheless, MRI believes that regular AP-42 users are in the best position to conduct such a study in order to provide information most applicable to their particular situation.