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INTEROFFICE COMMUNICATION

MIDWEST RESEARCH INSTITUTE

April 9, 1997

To: Air Quality Working Group

From: Greg Muleski, MRI

Subject: Reporting of paved road loading values

Because we have had so much work on public paved road emission tests over the past 18 months, this would be a good time to review our procedures for reporting surface loading values. Some confusion arises because the term "silt" can be used in different contexts. I believe that the procedures outlined below are generally applicable to almost any situation we might encounter.

Total loading "L" is a relatively straightforward concept and is found as follows:

$$L = (B_{full} - B_{tare}) / A$$

where

L	= total surface loading
B_{full}	= weight of the full vacuum bag (i.e., before any laboratory splits)
B_{tare}	= tare weight for the bag (i.e., before use)
A	= area sampled

Silt loading "sL" is a little harder to define for all situations. For our purposes, we consider two limiting cases. The lower bound assumes that any sample mass left in the empty vacuum bag is no coarser than the portion recovered from the bag. The lower bound is found as follows:

$$sL_{lower} = f\,L$$

where L is the total surface loading and f represents the minus-200 mesh fraction of the sieved sample:

$$f = M_{pan} / (M_{sieve\,1} + M_{sieve\,2} + \ldots + M_{pan})$$

The denominator represents the total mass of the sample after sieving. This should be close to B_{full} - B_{tare} (after allowing for any laboratory splits) but some difference should be expected.

The upper bound on sL is based on the assumption that all unretrievable sample mass (i.e., that material left in the bag after sample recovery) is finer than 200 mesh. The upper bound is found as follows:

$$sL_{upper} = f\,(B_{full} - B_{empty}) / A + (B_{empty} - B_{tare}) / A$$

where

B_{empty} = weight of the empty vacuum bag (i.e., after sample recovery)

The upper and lower bounds on silt loading should be close to one another and can serve as a QA check. In general, sL_{upper} should be used to report "silt loading" or "sL."

The quantity "f" defined above represents the "silt content" of the recovered sample. However, the silt content "s" reported for the paved road sample should be determined as

$$s = sL_{upper} / L$$

Similarly to the silt loading values, f represents lower bound on the silt content and should in fact be very close to s. Again, this would provide another QA check.

EMISSION FACTOR DOCUMENTATION FOR AP-42 SECTION 13.2.2
Unpaved Roads

Ron Myer's condensation of Bill Barnard's comments.

1. INTRODUCTION

The document *Compilation of Air Pollutant Emission Factors* (AP-42) has been published by the U. S. Environmental Protection Agency (EPA) since 1972. 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 representative value that attempts to relate the 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

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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). 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) should 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.

and with other surface material descriptors

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]

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

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, kilometers per hour (km/hr) (miles per hour [mph])
- W = mean vehicle weight, megagrams (Mg) (ton)
- w = mean number of wheels (dimensionless)

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 0.1 in. (0.254 mm) of precipitation. Thus, the emission factor for annual conditions is:

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

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					
≤30μm[a]	≤30μm	≤15μm	≤10μm	≤5μm	≤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 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
1981 report included separate emission factors for (a) light-to medi
unpaved roads for use at western surface coal mines.[7] I
unpaved road emission factor (Equation 2-1). A 1991 stu
addressed emissions due to relatively high-speed traffic on

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[a]Note that during the 1970's, the exponent for the silt content w
computational ease. Recall that this equation predated inexpensi

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, the document was 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 DATA QUALITY RATING SYSTEM[1]

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 following data are to be excluded from consideration:

1. Test series averages reported in units cannot be converted to the selected reporting units.

2. Test series representing incompatible test methods.

cannot be explained by information contained in the test report, the data are suspect and were given a lower rating.

4. Analysis and calculations. The test reports contain original raw data sheets. The nomenclature and equations used were compared to those (if any) specified by EPA to establish equivalency. The depth of review of the calculations were dictated by the reviewer's confidence in the ability and conscientiousness of the tester, which in turn was based on factors such as consistency of results and completeness of other areas of the test report.

this is a very subjective criteria

3.3 EMISSION FACTOR QUALITY RATING SYSTEM[1]

The quality of the emission factors developed from analysis of the test data was rated using the following general criteria:

A—Excellent: Developed from A- and B-rated source test data taken from many randomly chosen facilities in the industry population. The source category is specific enough so that variability within the source category population may be minimized.

B—Above average: Developed only from A- or B-rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industries. The source category is specific enough so that variability within the source category population may be minimized.

C—Average: Developed only from A-, B- and/or C-rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. In addition, the source category is specific enough so that variability within the source category population may be minimized.

D—Below average: The emission factor was developed only from A-, B-, and/or C-rated test data from a small number of facilities, and there is reason to suspect that these facilities do not represent a random sample of the industry. There also may be evidence of variability within the source category population. Limitations on the use of the emission factor are noted in the emission factor table.

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 this dispersion equation. At a minimum, the wind direction and speed must be recorded on-site.

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.

The other measurement technique, exposure profiling, offers 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.

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.

The size of the sampling grid needed for exposure profiling of a particular source may be estimated by observation of the visible size of the plume or by calculation of plume dispersion. Grid size adjustments may be required based on the results of preliminary testing. Particulate sampling heads should be symmetrically distributed over the concentrated portion of the plume containing about 90 percent of the total mass flux (exposure). For example, assuming that the exposure from a point source is normally distributed, the exposure values measured by the samplers at the edge of the grid should be about 25 percent of the centerline exposure.

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.

3.4.2 Emission Factor Derivation

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

As an alternative to the presentation of a final emission factor as a single-valued geometric mean, an emission factor may be presented in the form of a predictive equation derived by regression analysis of test data. Such an equation mathematically relates emissions to parameters when characterizing source conditions. These parameters may be grouped into three categories:

1. Measures of source activity or energy expended (e.g., the speed and weight of a vehicle traveling on an unpaved road).

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

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.

Why isn't the NAPAP data from 85 WS evaluated???

4.3 DEVELOPMENT OF CANDIDATE EMISSION FACTOR EQUATION

For unpaved roads, an emission factor equation is much more successful than a single-valued average 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.

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 involved. This decision had the effect of greatly expanding the historical data base. Not only is far more data available, but a wider range of vehicle weights and travel speeds is available. The decision was based on findings from Reference 4, which dealt with the western surface coal mining industry. It was found that the general unpaved road emission factor equation (Equation 2-1) performed as well in estimating emissions from haul truck and light- to medium-duty vehicles as did factors developed specifically for those sources within western surface coal mines.

Next, the decision was made to add tests of watered roads to tests of uncontrolled roads. (Note that chemically controlled unpaved roads were not considered because those treatments cause lasting physical changes to the road surface.) This decision also 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. 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 the PM-10 NAAQSs, this represents a major departure from the way in which the current AP-42 factor was developed. The focus on PM-10 was also the approach taken in developing the newest AP-42 emission factor for paved roads. 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.

3. No emission data were included from Reference 10 because the source tested was a "simulated" unpaved road formed by artificially loading a paved road. Note, however, that ratios of different particulate size ranges were included for the purpose of developing PM-15 and PM-2.5 emission factors.

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 12, some individual tests had moisture contents reported and a few additional tests were associated with moisture contents as well. Furthermore, the data from Reference 3 had been corrected for "combustible" content (although upwind concentrations had not). Using information contained in the report, "total" (i.e., without regard to chemical composition) PM-10 emission factors were calculated for inclusion in the developmental data set.

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 is 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 purely due to chance 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.

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 contents, M;
3. Mean vehicle weight, W;
4. Mean vehicle speed, S; and
5. Mean number of wheels, w.

All variables were log-transformed in order to obtain a multiplicative model as in the past. The dependent variable of interest was the log-transformed PM-10 emission factor.

But suppose an additive or subtractive model performed better. this again seems to be "predetermination" of the model rather than evaluation of the model based on the data.

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 — I thought none of these were included. It was the reason for taking reference 10 out of the mix
3. The predominant type of vehicle traveling the road;
4. Light or medium-duty vehicles;
5. Haul trucks;
6. Scrapers in the travel mode; and — I thought these were removed as well
7. Heavy-duty, over-the-road trucks.

An alternative to Equation 4-1 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:

$$e = k\, s^{0.82}\, W^{0.46} / M^{0.28} \qquad (4\text{-}2)$$

Equations 4-1 and 4-2 represent the two candidate emission factor equations considered in this study. Initially, preference was given to Equation 4-1 because the inclusion of speed was viewed as providing additional predictive accuracy for instances involving very slow or very fast traffic. Furthermore, the resulting equation would (like the current AP-42 model) allow one to gauge the effect of speed reduction as a control technique. Equation 4-1 was initially chosen and validation of that model proceeded.

However, in performing the next step, it was found that speed did not always enter the regression when part of the data set was held back for validation purposes. When roughly 25 percent of the data set was reserved for validation purposes (as described in the next section), weight, silt and moisture entered first, but at times the number of wheels, rather than speed, entered on the fourth step. It was judged that, with a 15 percent level of significance set as the criterion for a variable entering the regression, the resulting model could be too close to being unstable. Although vehicle speed entered at the 10 percent level of significance in Equation 4-1, 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 4-1) appeared to be relatively unstable.

Further justification in selecting the "no-speed" model expressed as Equation 4-2 was based on a comparison of the power of 0.32 to exponents developed in other test programs designed to directly consider the effect of vehicle speed. For example, Reference 6 test data support a relationship between emissions and speed raised to the 1.86 power. Other studies have developed models with powers of speed ranging from roughly 1 to 2. The inconsistency between the result found here and that found in other studies appears to be a result of "fine tuning" the other models to the specific data sets.

This argument however neglects the same argument that the authors use on page 3-7, middle paragraph when the AZ study showed that moisture and silt content entered the AZ equation in opposite directions. It just didn't make any intuitive sense. Neither does leaving out speed. If you hold all other parameters equal, moisture, weight, silt, wheels, etc. I guarantee that higher speed will produce higher emissions — I know because I've run exactly those tests.

for both variables were comparable to those in the PM-10 model. The differences between the results for PM-10 and PM-15 were due mainly to difference in the size of the available data base for PM-15. Not all tests were associated with moisture content, and the dependence of PM-15 emissions on moisture content could not be discerned.

For PM-2.5, however, stepwise regression of the emission tests led to a result different from that for PM-10, PM-15 and PM-30. Silt, weight, number of wheels, moisture content, and average speed entered the regression (in that order). The powers for silt, weight and moisture were fairly comparable to the corresponding powers in the PM-10 model. Nevertheless, despite the five parameters, the resulting model has a low R-squared value and thus would be expected to have limited predictive accuracy .

Emission factors for PM-2.5 and PM-15 were developed by multiplying the PM-10 model by the mean measured ratio of that size range to PM-10 in the available data base:

	Geometric mean ratio	
	PM-2.5 / PM-10	PM-15 / PM-10
Uncontrolled (n = 108)	0.140	1.53
Watered (n=20)	0.196	1.46
Overall (n=128)	0.148	1.52

No significant difference was found between the ratios for watered versus uncontrolled conditions, so the overall mean was applied.

In summary, the following emission factor equation is recommended for inclusion in AP-42:

$$e = k\,(s/12)^{a}\,(W/3)^{b}\,(M/1)^{c} \qquad (4\text{-}5)$$

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 (%)

Couldn't these changes also be the result that in many of the tests cited, TSP was measured in the exposure profiling array with only limited samplers used to partition into?

The parameters for size-specific emission factors in Equation 4-5 are given below:

Empirical constant	PM-2.5	PM-10	PM-15	PM-30
k	0.24	1.6	2.4	5.3
a	0.8	0.8	0.8	0.8
b	0.4	0.4	0.4	0.5
c	-0.3	-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 are rated "A." The remaining factors are downgraded one letter because they were developed by scaling an A-rated model.

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.

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 1 indicates that, although the model may slightly under- or overpredict emission for 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.

a factor of 3 was used to disparage the use of upwind/downwind samples (page 3-5) yet fully 25% of the data don't fit the same criteria for the emission factor model

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 inforamtion 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.

Furthermore, it was necessary to develop default information for moisture content. Because mosture content is raised to such a low power (exponent of 0.3 in Equation 4-3), the use of default values should not result in unacceptable levels of uncertainty in the resulting emission estimates. For example, when the recommended default value of 1 percent moisture is used for uncontrolled industrial roads, then

- 96 percent of the resulting emisison factor estimates are within a factor of 2
- 72 percent of the resulting emission factor estimates are within a factor of 1.5
- 52 percent of the resulting emission factor estimates are within a factor of 1.25

of the emission factor estimate based on the site-specific moisture content. Similarly, when a default value of 0.5 percent is used for publicly accessible roads in the developmental data set, all 43 of the resulting emission factor estimates are within a factor of 2 of the value based on site-specific moisute content.

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[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.

Being within a factor of 2 may not be good enough for a NAAQS review inventory

It does not, however, allow the use of the factor for development of large scale regional/modeling inventories, since a national or regional data base of moisture test does not likely exist.

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 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 distiction between "pedalfer" and "pedocal" soils. For pedalfer soils common in the eastern U.S., precipication 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.

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 interation 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 publicly accessible unpaved roads. That assumption would underlie any statistical test undertaken.

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). Furthermore, only one default moisture content would be provided for use on any type of publicly accessible unpaved road in the country. The default values for silt content are based on the corresponding mean values in the assembled data set:

	Mean Silt Content
Gravel Roads	6.4 percent
Dirt Roads	11 percent

The mean overall moisture content for the data set is 1.1 percent. However, this value substantially differs from the mean moisture content of 0.6 percent for tests of emissions from public unpaved roads. It is recommended that this not serve as the basis for a default value in AP-42. Instead, a default value of 0.5 percent is recommended for publicly accessible unpaved roads.

4.5 SUMMARY OF CHANGES TO AP-42 SECTION

4.5.1 Section Narrative

Changes to the text in Section 13.2.2 had several blocks within the section updated to describe the new unpaved road equation. Many of the changes are the result of the addition of moisture as an equation parameter and the removal of speed, mean number of wheels, and precipitation as parameters. Also, Table 13.2.2-1 was modified and updated to provide default silt content and moisture contents from various locations within the continental United States. Section 13.2.2 follows with text removed from the old AP-42 version striked out. New wording added since the last version is in bold between brackets [ ]. The figures are not presented here, but are included in Section 5 of this report.

13.2.2 Unpaved Roads

13.2.2.1 General

Dust plumes trailing behind vehicles traveling on unpaved roads are a familiar sight in rural areas of the United States. When a vehicle travels an unpaved road, the force of the wheels on the

It is important to note that Equation 1 calls for the average characteristics of all vehicles traveling the road. For example, if 98 percent of traffic on the road are 2-ton cars and trucks while the remaining 2 percent consists of 20-ton trucks, then the mean weight is 2.36 tons. More specifically, Equation 1 is *not* intended to be used to calculate a separate emission factor for each vehicle class. Instead, only one emission factor should be calculated that represents the "fleet" average of all vehicles traveling the road.]

this is not consistent w/ PARTS nor the Trends methods. Besides won't the VMT by each vehicle type & the weight emissions correctly by distributing the emissions to the correct sources?

~~The number of wet days per year, p, for the geographical area of interest should be determined from local climatic data. Figure 13.2.2-1 gives the geographical distribution of the mean annual number of wet days per year in the United States.[17] The equation is rated "A" for dry conditions (p = 0) and "B" for annual or seasonal conditions (p > 0). The lower rating is applied because extrapolation to seasonal or annual conditions assumes that emissions occur at the estimated rate on days without measurable precipitation and, conversely, are absent on days with measurable precipitation. Clearly, natural mitigation depends not only on how much precipitation falls, but also on other factors affecting the evaporation rate, such as ambient air temperature, wind speed, and humidity. Persons in dry, arid portions of the country may wish to base p (the number of wet days) on a greater amount of precipitation than 0.254 mm (0.01 in.). In addition, Reference 18 contains procedures to estimate the emission reduction achieved by the application of water to an unpaved road surface.~~

~~The equation retains the assigned quality rating, if applied within the ranges of source conditions that were tested in developing the equation, as follows:~~

~~Ranges Of Source Conditions For Equation~~					
~~Road Silt Content (wt %)~~	~~Mean Vehicle Weight~~		~~Mean Vehicle Speed~~		~~Mean No. Of Wheels~~
	~~Mg~~	~~ton~~	~~km/hr~~	~~mph~~	
~~4.3 - 20~~	~~2.7 - 142~~	~~3 - 157~~	~~21 - 64~~	~~13 - 40~~	~~4 - 13~~

Moreover, to retain the quality rating of the equation when addressing a specific unpaved road, it is necessary that reliable correction parameter values be determined for the road in question. The field and laboratory procedures for determining road surface silt content are given in AP-42 Appendices C.1 and C.2. In the event that site-specific values for correction parameters control efficiencies associated with petroleum resins applied to unpaved roads.[19] Several items should be noted:

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

2. Because petroleum resin products must be periodically reapplied to unpaved roads, the use of a time-averaged control efficiency value is appropriate. Figure 13.2.2-2 presents control efficiency values averaged over 2 common application intervals, 2 weeks and 1 month. Other application intervals will require interpolation.

3. Note that zero efficiency is assigned until the ground inventory reaches ~~0.2 liter per square meter (L/m^2) (~~0.05 gallon per square yard ~~[gal/yd^2]).~~[(gal/yd^2)].

As an example of the application of Figure 13.2.2-2, suppose that the equation was used to estimate an emission factor of ~~2.0 kg/VKT (~~[7.1 lb/VMT] for PM-10 from a particular road. Also, suppose that, starting on May 1, the road is treated with ~~1 L/m^2~~ [0.221 gal/yd2] of a solution (1 part petroleum resin to 5 parts water) on the first of each month through September. Then, the following average controlled emission factors are found:

Period	Ground inventory, ~~L/m^2~~[gal/yd^2]	Average control efficiency, %[a]	Average controlled emission factor, ~~kg/VKT~~[lb/VMT]
May	~~0.17~~[0.037]	0	~~2.0~~[7.1]
June	~~0.33~~[0.073]	62	~~0.76~~[2.7]
July	~~0.50~~[0.11]	68	~~0.64~~[2.3]
August	~~0.67~~[0.15]	74	~~0.52~~[1.8]
September	~~0.83~~[0.18]	80	~~0.40~~[1.4]

[a]From Figure 13.2.2-2, ≤10 μm. Zero efficiency assigned if ground inventory is less than ~~0.2 L/m^2 (0.05 gal/yd^2).~~[0.05 gal/yd^2. 1 lb/VMT = 281.9 kg/VKT. 1 gal/yd^2 = 4.531 L/m^2.]

Newer dust suppressants are successful in controlling emissions from unpaved roads. Specific test results for those chemicals, as well as for petroleum resins and watering, are provided in References ~~18 through 21~~ [17 through 20].

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 addition of surface moisture content to the new equation nullifies the need to account for annual precipitation, which was removed from the equation. As with the old equation, the new equation allows for the emission calculations of different particle sizes (PM-2.5, PM-10, PM-15, 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)

$$e = k\,(s/12)^a\,(W/3)^b\,M^c$$

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 (%)

I still disagree w/ not having speed. All other things being the same emissions will be higher at higher speeds.

For PM-2.5

45 of 94 (48 percent) are within a factor of 2

57 of 94 (61 percent) are within a factor of 3

73 of 94 (78 percent) are within a factor of 5

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To Lance Henning	From Brian Shrager
Co./Dept.	Co. NCO
Phone #	Phone #
Fax #	Fax #

For PM-15

42 of 94 (45 percent) are within a factor of 2

62 of 94 (66 percent) are within a factor of 3

82 of 94 (87 percent) are within a factor of 5

Because these are essentially independent applications of the predictive equation (i.e., the individual test results were not directly used in the development of the equation), a broader spread of the predicted-to-observed is to be expected. Nevertheless, both the PM-2.5 and PM-15 factors in Equation 4-5 provide very acceptable estimates of measured emission factors.

4.4 SUMMARY OF CHANGES TO AP-42 SECTION

4.4.1 Section Narrative

Changes to the text in Section 13.2.2 had several blocks within the section updated to describe the new unpaved road equation. Many of the changes are the result of the addition of moisture as an equation parameter and the removal of speed, mean number of wheels, and precipitation as parameters. Also, Table 13.2.2-1 was modified and updated to provide default silt content and moisture contents from various locations within the continental United States. Section 13.2.2 follows with text removed from the old AP-42 version striked out. New wording added since the last version is in bold between brackets [ ]. The figures are not presented here, but are included in Section 5 of this report.

13.2.2 Unpaved Roads

13.2.2.1 General

Dust plumes trailing behind vehicles traveling on unpaved roads are a familiar sight in rural areas of the United States. 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.

13.2.2.2 Emissions Calculation And Correction Parameters[1-6]

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 ~~(average vehicle speed, average vehicle weight, average number of wheels per vehicle, road surface texture, and road surface moisture)~~ that characterize the condition of a particular road and the associated vehicle traffic.[1-4]

Dust emissions from unpaved roads have been found to vary ~~in direct proportion to~~ . **[directly with]** silt (particles smaller than 75 micrometers [μm] in diameter) in the road surface materials.[1] The silt fraction is determined by measuring the proportion of loose dry surface dust that passes a 200-mesh screen, using the ASTM-C-136 method. Table 13.2.2-1 summarizes measured silt values for industrial and ~~rural~~ **[public]** unpaved roads.

Since the silt content of a rural dirt road will vary with location, it should be measured for use in projecting emissions. As a conservative approximation, the silt content of the parent soil in the area can be used. Tests, however, show that road silt content is normally lower than in the surrounding parent soil, because the fines are continually removed by the vehicle traffic, leaving a higher percentage of coarse particles.

~~Unpaved roads have a hard, generally nonporous surface that usually dries quickly after a rainfall. The temporary reduction in emissions caused by precipitation may be accounted for by not considering emissions on "wet" days (more than 0.254 millimeters [mm] [0.01 inches (in.)] of precipitation).~~

[Unpaved road dust emissions have also been found to vary indirectly with the surface moisture content of the road material. Table 13.2.2-1 also presents measured road surface moisture contents for both industrial and publicly accessible unpaved roads. Note that the

moisture values given in the table reflect <u>uncontrolled</u> conditions; that is to say, the roads had not been watered nor had rainfall occurred shortly before the sample.]

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

	Silt, %			Moisture, %		
	No. of tests	Mean	St. dev.	No. of tests	Mean	St. dev.
Location						
East of 97th Meridian	21	7.78	2.73	21	0.751	0.806
West of 97th Meridian	57	8.20	9.87	39	1.24	1.10
Road Type						
Gravel Overall ConUS	46	6.40	2.74	46	0.944	0.751
Dirt Overall ConUS	32	10.5	12.1	18	1.35	1.47
Gravel - East	15	7.69	2.78	15	0.779	0.948
Dirt - East	6	8.00	2.83	6	0.683	0.267
Gravel - West	31	5.77	4.54	27	1.04	0.617
Dirt - West	26	11.1	13.32	12	1.69	1.71
EPA Region No.						
Region 4	3	3.72	0.724	3	0.100	0.000
Region 5	6	8.00	2.83	6	0.683	0.267
Region 7	17	14.5	15.47	17	1.72	1.51
Region 8	1	5.00	NA	1	0.260	NA
Region 9	25	6.87	3.52	7	0.334	0.133
Region 10	26	5.70	4.41	26	1.07	0.609

[a]References TBD]

~~The following empirical expression may be used to estimate the quantity of size-specific particulate emissions from an unpaved road, per vehicle kilometer traveled (VKT) or vehicle mile traveled (VMT):~~

$$7)\left(\frac{s}{12}\right)\left(\frac{S}{48}\right)\left(\frac{W}{2.7}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left(\frac{365-p}{365}\right) \text{ (kilograms [kg}$$

$$9)\left(\frac{s}{12}\right)\left(\frac{S}{30}\right)\left(\frac{W}{3}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left(\frac{365-p}{365}\right) \text{ (pounds [lb]} \quad (1)$$

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
Stone quarrying and processing	Plant road	2	10	2.4 - 16	10
	Haul road	1	10	5.0 - 15	9.6
Taconite mining and processing	Service road	1	8	2.4 - 7.1	4.3
	Haul road	1	12	3.9 - 9.7	5.8
Western surface coal mining	Haul road	3	21	2.8 - 18	8.4
	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
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

a Reference[s] 1,5-16.

where:

E = emission factor

k = particle size multiplier (dimensionless)

s = silt content of road surface material (%)

S = mean vehicle speed, kilometers per hour (km/hr) (miles per hour [mph])

W = mean vehicle weight, megagrams (Mg) (ton)

w = mean number of wheels

p = number of days with at least 0.254 mm (0.01 in.) of precipitation per year (see discussion below about the effect of precipitation.)

~~The particle size multiplier in the equation, k, varies with aerodynamic particle size range as follows:~~

~~Aerodynamic Particle Size Multiplier (k) For Equation 1~~					
~~≤30 μm[a]~~	~~≤30 μm~~	~~≤15 μm~~	~~≤10 μm~~	~~≤5 μm~~	~~≤2.5 μm~~
~~1.0~~	~~0.80~~	~~0.50~~	~~0.36~~	~~0.20~~	~~0.095~~

a Stokes diameter.

please fix this! should be ~~a Stokes diameter~~

[The following empirical expression may be used to estimate the quantity of size-specific particulate emissions from an unpaved road, per vehicle mile traveled (VMT):

$$e = k\,(s/12)^a\,(W/3)^b\,(M/1)^c \qquad (1)$$

where k, a, b and c are empirical constants (REF 6) 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 (%)

Constants for Equation 1 based on the stated aerodynamic particle size

Constant	PM-2.5	PM-10	PM-15	PM-30
k (lb/VMT)	0.24	1.6	2.4	5.3
a	0.8	0.8	0.8	0.8
b	0.4	0.4	0.4	0.5
c	-0.3	-0.3	-0.3	-0.4
Quality rating	B	A	B	A

The above table also contains the quality ratings for the various size-specific versions of Equation (1). The equation retains the assigned quality rating, if applied with the ranges of source conditions that were tested in developing the equation:

Range of source conditions for Equation 1						
Road silt content, %	Mean, Mg	Vehicle weight, ton	Mean, km/hr	Vehicle speed, mph	Mean No. of wheels	Road moisture content, %
1.2-35	1.4-260	1.5-290	8-88	5-55[a]	4-7[a]	0.03-20

[a]See discussion in text.

Even though mean vehicle speed and the mean number of wheels do not explicitly appear in the predictive equation, these variables should be considered when determining quality ratings. During the validation of Equation 1, it was found that the predictive equation tends to overpredict emissions for very low vehicle speed. The equation does not exhibit this bias for mean vehicle speeds of at least 15 mph. The equation's predictive behavior should be remembered if the emission factor is used for an instance with travel speed less than 15 mph. Although the mean number of wheels was not found to exhibit a systematic bias, the reader is similarly advised the equation outside the range of mean number of wheels given above.

Equation 1 was developed by the stepwise regression of the results from field measurements of PM-10 emissions and TSP emissions (or its surrogate - PM-30) emissions from vehicles traveling over unpaved surfaces. Both uncontrolled and watered roads were included in the data base of 180 PM-10 and 92 TSP tests. The values given for the remaining particle size ranges were developed from mean measured PM2.5-to-PM-10 ratios and PM-15-to-PM-10 ratios.]

It is important to note that Equation 1 calls for the average characteristics of all vehicles traveling the road. For example, if 98 percent of traffic on the road are ~~2-ton~~ cars and trucks while the remaining 2 percent consists of ~~20-ton~~ trucks, then ~~the mean number of wheels "w" is 4.3~~ weight is 2.36 tons. More specifically, Equation 1 is *not* intended to be used to calculate a separate emission factor for each vehicle class. Instead, only one emission factor should be calculated that represents the "fleet" average of all vehicles traveling the road.

No strike out

~~The number of wet days per year, p, for the geographical area of interest should be determined from local climatic data. Figure 13.2.2-1 gives the geographical distribution of the~~

~~mean annual number of wet days per year in the United States.[17] The equation is rated "A" for dry conditions (p = 0) and "B" for annual or seasonal conditions (p > 0). The lower rating is applied because extrapolation to seasonal or annual conditions assumes that emissions occur at the estimated rate on days without measurable precipitation and, conversely, are absent on days with measurable precipitation. Clearly, natural mitigation depends not only on how much precipitation falls, but also on other factors affecting the evaporation rate, such as ambient air temperature, wind speed, and humidity. Persons in dry, arid portions of the country may wish to base p (the number of wet days) on a greater amount of precipitation than 0.254 mm (0.01 in.). In addition, Reference 18 contains procedures to estimate the emission reduction achieved by the application of water to an unpaved road surface.~~

~~The equation retains the assigned quality rating, if applied within the ranges of source conditions that were tested in developing the equation, as follows.~~

~~Ranges Of Source Conditions For Equation~~					
~~Road Silt Content (wt %)~~	~~Mean Vehicle Weight~~		~~Mean Vehicle Speed~~		~~Mean No. Of Wheels~~
	~~Mg~~	~~ton~~	~~km/hr~~	~~mph~~	
~~4.3 - 20~~	~~2.7 - 142~~	~~3 - 157~~	~~21 - 64~~	~~13 - 40~~	~~4 - 13~~

Moreover, to retain the quality rating of the equation when addressing a specific unpaved road, it is necessary that reliable correction parameter values be determined for the road in question. The field and laboratory procedures for determining road surface silt content are given in AP-42 Appendices C.1 and C.2. In the event that site-specific values for correction parameters cannot be obtained, the appropriate mean values from Table 13.2.2-1 may be used, but the quality rating of the equation is reduced by 1 letter.

[As noted earlier, Equation 1 was developed from tests of traffic on unpaved surfaces, either uncontrolled or watered. Unpaved roads have a hard, generally nonporous surface that usually dries quickly after a rainfall or watering. The quality ratings given above pertain to uncontrolled (dry) conditions. To estimate annual or seasonal conditions, one should determine an appropriate value for the average surface moisture content, taking into account natural precipitation and any anthropogenic watering. Recognizing that this may not always be practical, the factor developed for uncontrolled (dry) conditions can be extrapolated to

KC,
What factor developed for uncontrolled (dry) conditions?

annual or seasonal conditions under the simplifying assumption that emissions occur at the estimated rate on days without measurable *precipitation* and, *conversely*, are absent on days with measurable (more than 0.254 mm [0.01 inch]) precipitation. In other words, when the *simplifying assumption* is made, the emission factor for uncontrolled (dry) conditions should be multiplied by the ratio

$$\frac{365 - p}{p}$$

Bold

where p = number of days with at least 0.254 mm (0.01 inch) of precipitation per year. Figure 13.2.2-1 gives the geographical distribution for the mean annual number of "wet" days for the United States.

Clearly, the effects of water/natural mitigation depend on not only how much *precipitation* falls, but also on factors afffecting the evaporation rate, such as ambient air temperature, wind speed, humidity, and traffic rates. When the simplifying assumption is applied to annual/seasonal estimates, the quality rating should be downgraded by 1 letter.]

~~For calculating annual average emissions, the equation is to be multiplied by annual vehicle distance traveled (VDT). Annual average values for each of the correction parameters are to be substituted for the equation. Worst-case emissions, corresponding to dry road conditions, may be calculated by setting p = 0 in the equation (equivalent to dropping the last term from the equation). A separate set of nonclimatic correction parameters and a higher than normal VDT value may also be justified for the worst-case average period (usually 24 hours). Similarly, in using the equation to calculate emissions for a 91-day season of the year, replace the term (365-p)/365 with the term (91-p)/91, and set p equal to the number of wet days in the 91-day period. Use appropriate seasonal values for the nonclimatic correction parameters and for VDT.~~

13.2.2.3 Controls~~[18-21]~~

Common control techniques for unpaved roads are paving, surface treating with penetration chemicals, working stabilization chemicals into the roadbed, watering, and traffic control regulations. **[The effect that moisture addition has on emissions can be evaluated by use of Equation 1.]** Chemical stabilizers work either by binding the surface material or by enhancing moisture retention. Paving, as a control technique, is often not economically practical. Surface chemical treatment and watering can be accomplished at moderate to low costs, but frequent treatments are required. Traffic controls, such as speed limits and traffic volume restrictions, provide moderate emission reductions, but may be difficult to enforce. The control efficiency obtained by speed reduction can be calculated using the predictive emission factor equation given above.

The control efficiencies achievable by paving can be estimated by comparing emission factors for unpaved and paved road conditions, relative to airborne particle size range of interest. The predictive emission factor equation for paved roads, given in Section 13.2.4, requires estimation of the silt loading on the traveled portion of the paved surface, which in turn depends on whether the pavement is periodically cleaned. Unless curbing is to be installed, the effects of vehicle excursion onto shoulders (berms) also must be taken into account in estimating control efficiency.

The control efficiencies afforded by the periodic use of road stabilization chemicals are much more difficult to estimate. The application parameters that determine control efficiency include dilution ratio, application intensity, mass of diluted chemical per road area, and application frequency. Other factors that affect the performance of chemical stabilizers include vehicle characteristics (e. g., traffic volume, average weight) and road characteristics (e. g., bearing strength).

Besides water, petroleum resin products historically have been the dust suppressants most widely used on industrial unpaved roads. Figure 13.2.2-2 presents a method to estimate average control efficiencies associated with petroleum resins applied to unpaved roads.[19] Several items should be noted:

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

2. Because petroleum resin products must be periodically reapplied to unpaved roads, the use of a time-averaged control efficiency value is appropriate. Figure 13.2.2-2 presents control efficiency values averaged over 2 common application intervals, 2 weeks and 1 month. Other application intervals will require interpolation.

3. Note that zero efficiency is assigned until the ground inventory reaches 0.2 liter per square meter (L/m^2) (0.05 gallon per square yard [gal/yd^2]).

As an example of the application of Figure 13.2.2-2, suppose that the equation was used to estimate an emission factor of 2.0 kg/VKT (____ lb/VMT) for PM-10 from a particular road. Also, suppose that, starting on May 1, the road is treated with 1 L/m^2 of a solution (1 part petroleum resin to 5 parts water) on the first of each month through September. Then, the following average controlled emission factors are found:

Period	Ground inventory, L/m^2	Average control efficiency, %[a]	Average controlled emission factor, kg/VKT
May	0.17	0	2.0
June	0.33	62	0.76
July	0.50	68	0.64
August	0.67	74	0.52
September	0.83	80	0.40

[a]From Figure 13.2.2-2, ≤10 μm. Zero efficiency assigned if ground inventory is less than 0.2 L/m^2 (0.05 gal/yd^2).

KC, show English units instead!

Newer dust suppressants are successful in controlling emissions from unpaved roads. Specific test results for those chemicals, as well as for petroleum resins and watering, are provided in References ~~18 through 21~~ [17 through 20].

4.4.2 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 addition of surface moisture content to the new equation nullifies the need to account for annual precipitation, which was removed from the equation. As with the old equation, the new equation allows for the emission calculations of different particle sizes (PM-2.5, PM-10, PM-15, 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).

J:\dms\460402\unpvbkgd
3/28/97

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)

$$e = k\,(s/12)^{a}\,(W/3)^{b}\,(M/1)^{c}$$

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-15	PM-30
k (lb/VMT)	0.24	1.6	2.4	5.3
a	0.8	0.8	0.8	0.8
b	0.4	0.4	0.4	0.5
c	-0.3	-0.3	-0.3	-0.4

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.

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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. Current Study -- Raleigh - Grandview by Cowherd.

COMMENT LOG — 4604-02

Page	Comment	Response
2-1	*Editorial Addition*: "and PM less than 2.5 microns in aerodynamic diameter (PM-2.5)"	Added
2-5	How was the control efficiency of the chemical dust suppressants determined? If the method was by re-evaluating the silt content of the road material, then it would be worthwhile including that into the section.	Changed: "Past experience has shown......." To "Past test reports have shown....intervals"
3-5	*Include*: More information on criteria for the best possible sampling and analysis criteria for performing an acceptable upwind/downwind emission factor determination, e.g., winds within ±45° during almost all of the sampling time. Proper selection of surface roughness parameters, initial dispersion mixing height ($\sigma_z o$)? and measurement of all of the critical parameters such as surface silt percent, moisture, vehicle weights, vehicle speed, etc.	
3-5	*Include*: More details needed on appropriate and acceptable sampling criteria are required for profiling. The objective is to educate the reviewers of this report, the users of this report, future researchers that may want to reproduce or check these factors or tests.	
3-6	present the equation(s) for calculating the initial dispersion ($\sigma_z o$) for a line source	No Change - not appropriate GREG?

3-6	*Geometric Mean*: emission factors are more typically arithmetic means. Only in unusual instances would a geometric mean be used. Emission factors are for developing average values that are good predictors of an area's emissions.	No Change - let geometric mean stand
3-6	*Editorial Addition*: "arithmetic"	No Change - let geometric mean stand
3-6	*Editorial Addition*: "number of wheels"	No Change - list only emission equation parameters here, see Section 4.3 for discussion of all parameters.
3-6	*Editorial Addition*: "In rare instances"	Change to: "Frequently, test reports present the range of individual emission factor values." Note - Clay Manufacturing Background Document presented ranges
3-6	*Editorial Addition*: "Moisture content of the surface material"	No Change - list only emission equation parameters here, see Section 4.3 for discussion of all parameters.
3-6	*Editorial Addition*: "The general method employed in regression analysis 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"	Added statement as is

3-6	Use the Air Control Technique document for the Crushed Stone Haul Roads (page 11-22) as a guide in the description of the physical forces and probable effects. Also identify some parameters that may be important but that would be difficult to quantify either retrospectively or prospectively (e.g., aerodynamics, tire treated design) # Wheels Tire and design Tire pressure Area of contact/disturbance Road structure (hard base, washboard) Weight Disturbance of road surface Aerodynamics of vehicle/turbulence Vehicle clearance Compaction of road base Speed Aerodynamics Tangential velocity of wheels	No Change here -- discussion of possible parameters in Section 4.3
3-8	*Profiling Minimum Requirements*: What about wind direction, speed, mass increase, height of samples, upwind/downwind disturbances	Add Insert 3-1B
3-8	The test data rating scheme does not seem appropriate. A profile test should have a precision of ±20-30% and even under ideal conditions an upwind/downwind evaluation would have a precision of ±200-300% (factor of 2-3). I would say that the best rating achievable by upwind/ downwind analysis and receptor analysis is a C without many samples then only a B.	Add Insert 3-1A

3-8	Other criteria for rating the data would be the collection of the activity and process information for each test (e.g., silt percent, moisture, average weight, speed, wheels)	Added: "The collection and reporting of activity and precess information such as silt content, moisture %, and average vehicle wight are also considered in the evaluation."
3-9	Current internal criteria are a sum of 100 for A, 50 for B, 25 for C, 5 for D and less than 15 on E. The sums are determined by adding all data values with Adata=5, Bdata = 4, Cdata = 2 and Ddata = 1. The assumption is that the RSD of the population is 1.	If you group the test data into test series we have approxiamtely 25 test series. Greater than 20 "A" rated test series X 5 points per A = > 100, thus by EPA internal rating the emission equation will be an A.
3-9	In light of the changes in the single value emission factor ratings the equation should be revised.	No significant changes - Equation remains A rated, see above
3-10	The evaluation criteria should be based to some extent on the same criteria for single value factors. However, the evenness of test data across the range of the data for each parameter should be considered. The following criteria for the single valued factors are important: 1. Three runs comprise a test. 2. The estimate of uncertainty of the population mean is: 3. An evaluation is made to attempt to subcategorize the population. This could be expanded to allow a test series that makes a significant change in one or more of the variables to be considered as more than one test. For example, Ref. 1 would be one test while Ref. 2 would be 4 tests due to moisture and weight. Ref. 3 would be one or 2½ tests due to slight variation in H_2O and since two facilities were involved.	No Change - Greg Muleski briefly reviewed the data grouped as test series and found little difference in the results.

3-10	Figures which present the ratio of predicted vs. Actual by value of the parameter should be developed (X is the value of the parameter and Y is the ratio of pred/actual). So figures for silt content, moisture, average weight, speed and even wheels. A statistical calculation can present an estimate of population uncertainty for the range of these values.	Already developed - Include in Appendix or as electronic file????
	GENERAL COMMENTS FOR SECTION 4-2	
4-1 to 4-13	What was the width of the road?	
4-1 to 4-13	What were the height and disturbances upwind and downwind of the road and what would the angles be?	
4-1 to 4-13	How does the height of the highest sampler compare to the initial dispersion ($\sigma_z o$)	
4-1 to 4-13	A comment about the lack of measured moisture content should be added where appropriate. This may be reason for downgrading the test rating to B	
4-1 to 4-13	What about wind direction. Was wind direction within ±30 or ±45° during all of the testing.	
4-1 to 4-13	The table needs the results of the PM-2.5 tests or TSP orIP	
4-1 to 4-13	What other data were collected?	
4-1 to 4-13	Describe Method for drying samples	
4-1 to 4-13	What data was included in the analysis?	

4-1 to 4-13	What are truck heights? How valid are sampling results from an array that's shorter than the vehicle?	
4-3	*Editorial Addition to rating of AirControl Tech report Ref #3*: "at the Garner quarry. The Lemon Springs test data was assigned an "A" rating."	Added
4-9	*SoRI Study at Gary, IN Ref #10*: Disagree that the simulated road is not representative of unpaved road.	Explanation by insert 4-3. GREG please add on to explanation.
4-11	*Coherex in L-4 study*: An evaluation of whether silt analysis and moisture analysis are good measures of control effectiveness for these chemical additives.	GREG - is this necessary?
4-14	*Emission factor development*: Put an explanation of the physical forces that produce the emissions, a general relationship that may be expected in the absence of measured data, some of the interrelationships that may exist. See Air Control tech presentation for specific issues to address. Explain the sum of the parameters are difficult to measure any more difficult to document the effect on emissions and that a limited set of information was available to use in an empirical model the unknowns of which can be determined through statistical methods.	
4-14	*Chemically Controlled Unpaved Road*: Just because the changes are lasting and produce physical changes is not as important as whether the physical parameters change can be measured by either a change in surface moisture content or the silt content.	
4-14	*Inclusion of graders*: The low speed should not be the reason. The reason should be the extra physical disturbance of the road surface.	

4-14	*Chemically Controlled Unpaved Road*: It would be educational to see if measurement moisture or silt is a good predictor of control efficiency and emissions.	
4-15	*Inclusion of watered surfaces*: I don't see why the duration of the effect is important, see previous comment.	
4-15	*Editorial Addition*: "and PM-2.5"	
4-15	*Exclusion of Ref. 7 (fairless)*: What about the other tests that included chemical treatment. A check should be made on whether any type of treatments control effectiveness could be determined by physical measurement of the road material.	
4-15	*Exclusion of Ref. 10 (SoRI)*: I don't agree with this. An unpaved road could have s hard of a base as provided by the pavement. The availability of silt and loose material is more important.	
4-16	Is a 5 or 10 percent significance level appropriate for an equation that needs less precision. For example, if I only expect the emission to be within 20% on average, can a less stringent significance level be used?	
4-16	A justification on why a log transform is appropriate based upon the expected affects of the physical forces creating the emissions (the empirical relationships)	
4-16	*Log transform used in past*: the past is not the important item. The important items are the expected effects of the physical forces that cause emissions. However an overly complex model may be too difficult to use.	

4-16	*Number list 4-7*: Shouldn't these be a, b, c, d?	
4-17	Another consistency check that should be identified is the general agreement with the empirical relationships, e.g., emission increase with increasing speed (by some range of power) or decrease in surface moisture.	
4-17	*Discussion of equation development*: present the equation and some small amount of goodness of fit information.	
4-18	*Discussion of equation development*: Present the equations and some goodness of fit information.	
4-18	*Equation 4-1*: Would the number of wheels enter the equation if the significance level were relaxed to 20%?	
4-18	*Equation 4-1*: The constant should be presented. Also, information on the diagnostics of the regression should be available and present a discussion of some of these (such as R^2, examination of the goodness of fit, etc., predicted vs. actual). Four graphs would be worthwhile. The graphs would be one of the parameters vs. The ratio of predicted vs. actual.	
4-19	*Equation 4-2*: See comments on previous equation and example figures.	

4-19	*Selecting no-speed model*: Justification should be based on the predicted vs. actuals and the other diagnostics of the model. Also an examination of the figures of the ratio of predicted to actual vs. the parameters. Additionally, a criteria should be how stupid we look by saying that a parameter is not important given "common" knowledge. For example, it is intuitive to people that follow vehicles on unpaved roads, that speed is important in the generation of dust, it is also supported by the physical forces in the system. Therefore, even though it does not always center the regression equation, it should be added. We can put some restrictions on it though.	
4-19	*Withhold part of data set*: Our statisticians indicate that it is preferable to keep al of the data in for developing the equation and that this process only validates the regression technique. They indicate that the diagnostics of the regression are better indicators of the predictive accuracy of the equation. They specifically mentioned the predicted vs actuals. I would like to see the graphs relating each of the variables to the ratio of predicted to actual (perfect agreement would be a horizontal line at 1.0).	
4-20	I don't think the normalizing factors add much to the equation. However, if we do we should include moisture at the default level as well.	
4-20	*Regression of additional particle sizes*: The same process as was used for PM-10 should be presented for TSP and PM-2.5	

4-21	*Discussion of Regression of other particle sizes*: Present it here along with the diagnostics and figures like with PM-10	
4-21	*Geometric Mean Ratio of particle sizes*: Why use the ratio of geometric means and not the average of the ratio __________ the PM-2.5/PM-10.	
4-21	*No difference between watered versus uncontrolled*: How about weight of vehicle, the silt level or the speed or with the final emissions. The ambient data Chat sent to Bill Kuykendal showed that at high PM-10 concentrations the ratio between PM-10 and PM-2.5 was different than at low PM-10 concentrations.	
4-22	*Validation Studies*: All this is a complicated methodology to get to an evaluation of the predicted vs actual values. I think a better method is to present not only this information but also what is the average, standard development, median, log mean, skewness and ketosis for the whole population. Also it would be worthwhile to constrain this analysis to the various quantities of the parameter (speed, weight, silt, moisture, wheels and emissions) Or rather than quantities, that portion of the data that is various 25% of the range of the data, e.g., if rate is 5-25. The portions would be 5-10; 10-15; 15-20; 20-25	
4-23	*AP-42's goal is represent the average conditions*: This is partially true. I would want an equation to predict the average of the emissions through a broad range of the parameters that affect emissions.	

4-23	*Geometric mean of ratio of predicted to observed*: Use arithmetic means and std dev in addition to this ratio	
4-24	*PM-30 equation does not appear to under/over predict at very fast/slow speeds*: really only just slow.	
4-26	*Silt and moisture difficult*: A table which shows some __________ information about all of these samples should be in this document	
4-29	*Editorial Addition*: "Correlate with an engineering analysis of those physical forces created by the moving vehicular traffic and resisted by the physical characteristics of the"	
4-29	*Silt content of parent soil*: It should be noted that the methodology used by USDA to measure silt is different than the ASTM method. If we know of a conversion we should give it (background report or document name)	
4-39	*Table 4-2*: The PM-2.5 data should be presented	
4-43	*Table 4-8*: Were these tests done during a hurricane?	
4-67	Table 4-28: The TSP and PM-2.5 data should be presented also	
4-68	*Table 4-29*: Were all the data collected during misty conditions or only some	
4-68	*Reference 15 - PM-2.5 Study*: Also the study needs to be included in the descriptions portion of this report	

4-69	*Table 4-30, Results of Cross Validation*: This needs to be described in validation area of this report. Also, if it would not confuse the figures. This information could be used to code the individual points on the various predicted vs actual figures	
13.2. 2-5	*AP-42 Controls*: The equation for estimating the control level that may be achievable by periodic watering should be placed in this part of the section. Both of the control efficiencies should be framed at only prospective analysis and not for use in determining the emission from existing roadway. Also a paragraph should be spent identifying the relevant physical characteristics at work.	
13.2. 2-5	Chemical Stabilizers: Since it appears that we have included some of the roads controlled by chemical stabilizers in the database for EF development, can't we indicate that the mesurement of silt and moisture is a viable method to estimate control efficiency.	

4.5 SUMMARY OF CHANGES TO AP-42 SECTION

4.5.1 Section Narrative

Changes to the text in Section 13.2.2 had several blocks within the section updated to describe the new unpaved road equation. Many of the changes are the result of the addition of moisture as an equation parameter and the removal of speed, mean number of wheels, and precipitation as parameters. Also, Table 13.2.2-1 was modified and updated to provide default silt content and moisture contents from various locations within the continental United States. Section 13.2.2 follows with text removed from the old AP-42 version striked out. New wording added since the last version is in bold between brackets [ ]. The figures are not presented here, but are included in Section 5 of this report.

13.2.2 Unpaved Roads

13.2.2.1 General

Dust plumes trailing behind vehicles traveling on unpaved roads are a familiar sight in rural areas of the United States. 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.

13.2.2.2 Emissions Calculation And Correction Parameters[1-6]

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 (average vehicle speed, avacrage vehicle weight, avacrage number of wheels per vehicle, road surface testure, and road surface moisture) that characterize~~ **correlate with an engineering analysis of those physical forces created by the moving vehicular traffic and resisted by the physical characteristics of the** particular road. ~~and the associated vehicle traffic.[1-4] (average vehicle speed, average vehicle weight, average number of wheels per vehicle, road surface texture, and road surface moisture) that characterize the condition of a~~

Dust emissions from unpaved roads have been found to vary ~~in direct proportion to~~ **[directly with the fraction of]** silt (particles smaller than 75 micrometers [μm] in diameter) in the road surface materials.[1] The silt fraction is determined by measuring the proportion of loose dry surface dust that passes a 200-mesh screen, using the ASTM-C-136 method. Table 13.2.2-1 summarizes measured silt values for industrial and ~~rural~~ **[public]** unpaved roads.

Since the silt content of a rural dirt road will vary with **[geographic]** location, it should be measured for use in projecting emissions. As a conservative approximation, the silt content of the parent soil in the area can be used. Tests, however, show that road silt content is normally lower than in the surrounding parent soil, because the fines are continually removed by the vehicle traffic, leaving a higher percentage of coarse particles. **The methodology used by the U.S. Department of Agriculture (USDA) to determine silt content varies from the ASTM method. No conversion currently exists.**

~~Unpaved roads have a hard, generally nonporous surface that usually dries quickly after a rainfall. The temporary reduction in emissions caused by precipitation may be accounted for by not considering emissions on "wet" days (more than 0.254 millimeters [mm] [0.01 inches (in.)] of~~

~~precipitation).~~

$$k(1.7)\left(\frac{s}{12}\right)\left(\frac{S}{48}\right)\left(\frac{W}{2.7}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left(\frac{365-p}{365}\right) \text{ (kilograms [kg]/V}$$

$$k(5.9)\left(\frac{s}{12}\right)\left(\frac{S}{30}\right)\left(\frac{W}{3}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left(\frac{365-p}{365}\right) \text{ (pounds [lb]/VT} \qquad (1)$$

[Draft] 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
	[Yard 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	**4**	**20**	**5.0-15**	**8.3]**
Taconite mining and processing	Service road	1	8	2.4 - 7.1	4.3
	Haul road	1	12	3.9 - 9.7	5.8
Western surface coal mining	Haul road	3	21	2.8 - 18	8.4
	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~~

Industry	Road Use Or Surface Material	Plant Sites	No. Of Samples	Silt Content (%)	
				Range	Mean
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	**8**	**24**	**0.83-68**	**11]**

[a] References 1,5-16.

~~where:~~

~~E = emission factor~~
~~k = particle size multiplier (dimensionless)~~
~~s = silt content of road surface material (%)~~
~~S = mean vehicle speed, kilometers per hour (km/hr) (miles per hour [mph])~~
~~W = mean vehicle weight, megagrams (Mg) (ton)~~
~~w = mean number of wheels~~
~~p = number of days with at least 0.254 mm (0.01 in.) of precipitation per year (see discussion below about the effect of precipitation.)~~

~~The particle size multiplier in the equation, k, varies with aerodynamic particle size range as follows:~~

~~Aerodynamic Particle Size Multiplier (k) For Equation 1~~					
~~≤30 µm[a]~~	~~≤30 µm~~	~~≤15 µm~~	~~≤10 µm~~	~~≤5 µm~~	~~≤2.5 µm~~
~~1.0~~	~~0.80~~	~~0.50~~	~~0.36~~	~~0.20~~	~~0.095~~

[a] ~~Stokes diameter.~~

[The following empirical expression may be used to estimate the quantity of size-specific particulate emissions from an unpaved road, per vehicle mile traveled (VMT):

$$e = k\,(s/12)^a\,(W/3)^b\,M^c \qquad (1)$$

where k, a, b and c are empirical constants (REF 6) 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 constants for Equation 1 based on the stated aerodynamic particle size are as follows:

Constant	PM-2.5	PM-10	PM-15	PM-30
k (lb/VMT)	0.24	1.6	2.4	5.3
a	0.8	0.8	0.8	0.8
b	0.4	0.4	0.4	0.5
c	-0.3	-0.3	-0.3	-0.4
Quality rating	B	A	B	A

The above table also contains the quality ratings for the various size-specific versions of Equation (1). The equation retains the assigned quality rating, if applied with the ranges of source conditions that were tested in developing the equation:

Range of source conditions for Equation 1						
Road silt content, %	Mean, Mg	Mean vehicle weight, ton	Mean, km/hr	Mean vehicle speed, mph	Mean No. of wheels	Road moisture content, %
1.2-35	1.4-260	1.5-290	8-88	5-55[a]	4-7[a]	0.03-20

[a]See discussion in text.

Although mean vehicle speed and the mean number of wheels do not explicitly appear in the predictive equation, these variables should be considered when determining quality ratings. During the validation of Equation 1, it was found that the predictive equation tends to overpredict emissions for very low mean vehicle speed. The equation does not exhibit this bias for mean vehicle speeds of at least 15 mph. The equation's predictive behavior should be remembered if the emission factor is used for an instance with mean vehicle speed less than 15 mph. Although the mean number of wheels was not found to exhibit a systematic bias, the reader is similarly advised of the equation's predictive behavior outside the range of mean number of wheels given above.

Equation 1 was developed by the stepwise regression of the results from field measurements of PM-10 emissions and TSP emissions (or its surrogate - PM-30 emissions) from vehicles traveling over unpaved surfaces. Both uncontrolled and watered roads were included in the data base of 180 PM-10 and 92 TSP tests. The values given for the remaining particle size ranges were developed from mean measured PM-2.5 to PM-10 ratios and PM-15 to PM-10 ratios.

It is important to note that Equation 1 calls for the average characteristics of all vehicles traveling the road. For example, if 98 percent of traffic on the road are 2-ton cars and trucks while the remaining 2 percent consists of 20-ton trucks, then the mean weight is 2.36 tons. More specifically, Equation 1 is *not* intended to be used to calculate a separate emission factor for each vehicle class. Instead, only one emission factor should be calculated that represents the "fleet" average of all vehicles traveling the road.|

~~The number of wet days per year, p, for the geographical area of interest should be determined from local climatic data. Figure 13.2.2-1 gives the geographical distribution of the mean annual number of wet days per year in the United States.[17] The equation is rated "A" for dry conditions (p = 0) and "B" for annual or seasonal conditions (p > 0). The lower rating is applied because extrapolation to seasonal or annual conditions assumes that emissions occur at the estimated rate on days without measurable precipitation and, conversely, are absent on days with measurable precipitation. Clearly, natural mitigation depends not only on how much precipitation falls, but also on other factors affecting the evaporation rate, such as ambient air temperature, wind speed, and humidity. Persons in dry, arid portions of the country may wish to base p (the number of wet days) on a greater amount of precipitation than 0.254 mm (0.01 in.). In addition, Reference 18 contains procedures to estimate the emission reduction achieved by the application of water to an unpaved road surface.~~

~~The equation retains the assigned quality rating, if applied within the ranges of source conditions that were tested in developing the equation, as follows:~~

~~Ranges Of Source Conditions For Equation~~					
~~Road Silt Content (wt %)~~	~~Mean Vehicle Weight~~		~~Mean Vehicle Speed~~		~~Mean No. Of Wheels~~
	~~Mg~~	~~ton~~	~~km/hr~~	~~mph~~	
~~4.3 - 20~~	~~2.7 - 142~~	~~3 - 157~~	~~21 - 64~~	~~13 - 40~~	~~4 - 13~~

Moreover, to retain the quality rating of the equation when addressing a specific unpaved road, it is necessary that reliable correction parameter values be determined for the road in question. The field and laboratory procedures for determining road surface silt content are given in AP-42 Appendices C.1 and C.2. In the event that site-specific values for correction parameters cannot be obtained, the appropriate mean values from Table 13.2.2-1 may be used, but the quality rating of the equation is reduced by 1 letter.

[As noted earlier, Equation 1 was developed from tests of traffic on unpaved surfaces, either uncontrolled or watered. Unpaved roads have a hard, generally nonporous surface that usually dries quickly after a rainfall or watering. The quality ratings given above pertain to uncontrolled (dry) conditions. To estimate annual or seasonal conditions, one should determine an appropriate value for the average surface moisture content, taking into account natural precipitation and any anthropogenic watering. Recognizing that this may not always be practical, Equation 1 can be extrapolated to annual or seasonal conditions under the simplifying assumption that emissions occur at the estimated rate on days without measurable precipitation and, conversely, are absent on days with measurable (more than 0.254 mm [0.01 inch]) precipitation. In other words, when the simplifying assumption is made, the emission factor for uncontrolled (dry) conditions should be multiplied by the ratio

$$\frac{365 - p}{365}$$

where p = number of days with at least 0.01 inch (0.254 mm) of precipitation per year. Figure 13.2.2-1 gives the geographical distribution for the mean annual number of "wet" days for the United States.

Clearly, the effect of water/natural mitigation depend on not only how much precipitation falls, but also on factors afffecting the evaporation rate, such as ambient air temperature, wind speed, humidity, and traffic rates. When the simplifying assumption is applied to annual/seasonal estimates, the quality rating should be downgraded by 1 letter.]

For calculating annual average emissions, the equation is to be multiplied by annual vehicle distance traveled (VDT). Annual average values for each of the correction parameters are to be substituted for the equation. Worst-case emissions, corresponding to dry road conditions, may be calculated by setting p = 0**[.]** ~~in the equation (equivalent to dropping the last term from the equation).~~ A separate set of ~~nonclimatic~~ correction parameters and a higher than normal VDT value may also be justified for the worst-case average period (usually 24 hours). Similarly, in using the equation to calculate emissions for a 91-day season of the year, replace the term (365-p)/365 with the term (91-p)/91, and set p equal to the number of wet days in the 91-day period. Use appropriate seasonal values for the nonclimatic correction parameters and for VDT.

13.2.2.3 Controls~~[18-21]~~[17-21]

Common control techniques for unpaved roads are paving, surface treating with penetration chemicals, working stabilization chemicals into the roadbed, watering, and traffic control regulations. **[The effect that moisture addition has on emissions can be evaluated by use of Equation 1 if the cycle of moisture content is known.]** Chemical stabilizers work either by binding the surface material or by enhancing moisture retention. Paving, as a control technique, is often not economically practical. Surface chemical treatment and watering can be accomplished at moderate to low costs, but frequent treatments are required. Traffic controls, such as speed limits and traffic volume restrictions, provide moderate emission reductions, but may be difficult to enforce. ~~The control efficiency obtained by speed reduction can be calculated using the predictive emission factor equation given above.~~

The control efficiencies achievable by paving can be estimated by comparing emission factors for unpaved and paved road conditions, relative to airborne particle size range of interest. The predictive emission factor equation for paved roads, given in Section 13.2.4, requires estimation of the silt loading on the traveled portion of the paved surface, which in turn depends on whether the pavement is periodically cleaned. Unless curbing is to be installed, the effects of vehicle excursion onto shoulders (berms) also must be taken into account in estimating **[the]** control efficiency **[of paving]**.

The control efficiencies afforded by the periodic use of road stabilization chemicals are much more difficult to estimate. The application parameters that determine control efficiency include dilution ratio, application intensity, mass of diluted chemical per road area, and application frequency. Other factors that affect the performance of chemical stabilizers include vehicle characteristics (e. g., traffic volume, average weight) and road characteristics (e. g., bearing strength).

Besides water, petroleum resin products historically have been the dust suppressants most widely used on industrial unpaved roads. Figure 13.2.2-2 presents a method to estimate average control efficiencies associated with petroleum resins applied to unpaved roads.[19] Several items should be noted:

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

2. Because petroleum resin products must be periodically reapplied to unpaved roads, the use of a time-averaged control efficiency value is appropriate. Figure 13.2.2-2 presents control efficiency values averaged over 2 common application intervals, 2 weeks and 1 month. Other application intervals will require interpolation.

3. Note that zero efficiency is assigned until the ground inventory reaches ~~0.2 liter per square meter (L/m²) (~~0.05 gallon per square yard ~~[gal/yd²]).~~**[(gal/yd²)].**

As an example of the application of Figure 13.2.2-2, suppose that the equation was used to estimate an emission factor of ~~2.0 kg/VKT (~~**[7.1 lb/VMT]** for PM-10 from a particular road. Also, suppose that, starting on May 1, the road is treated with ~~1 L/m²~~ **[0.221 gal/yd2]** of a solution (1 part petroleum resin to 5 parts water) on the first of each month through September. Then, the following average controlled emission factors are found:

Period	Ground inventory, ~~L/m²~~**[gal/yd²]**	Average control efficiency, %[a]	Average controlled emission factor, ~~kg/VKT~~**[lb/VMT]**
May	~~0.17~~**[0.037]**	0	~~2.0~~**[7.1]**
June	~~0.33~~**[0.073]**	62	~~0.76~~**[2.7]**
July	~~0.50~~**[0.11]**	68	~~0.64~~**[2.3]**
August	~~0.67~~**[0.15]**	74	~~0.52~~**[1.8]**
September	~~0.83~~**[0.18]**	80	~~0.40~~**[1.4]**

[a]From Figure 13.2.2-2, ≤10 µm. Zero efficiency assigned if ground inventory is less than ~~0.2 L/m² (0.05 gal/yd²).~~**[0.05 gal/yd². 1 lb/VMT = 281.9 kg/VKT. 1 gal/yd² = 4.531 L/m².]**

Newer dust suppressants are successful in controlling emissions from unpaved roads. Specific test results for those chemicals, as well as for petroleum resins and watering, are provided in References ~~18 through 21~~ **[17 through 20]**.

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, PM-15, 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)

$$e = k\,(s/12)^a\,(W/3)^b\,M^c$$

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-15	PM-30
k (lb/VMT)	0.24	1.6	2.4	5.3
a	0.8	0.8	0.8	0.8
b	0.4	0.4	0.4	0.5
c	-0.3	-0.3	-0.3	-0.4

INTEROFFICE COMMUNICATION

MIDWEST RESEARCH INSTITUTE

January 2, 1997

To: Ron Myers, EPA

From: Greg Muleski

Subject: Regression results for unpaved road PM10 emission tests

This memo summarizes the results of the stepwise regressions that you and I have talked about over the past few months. As we discussed, I assembled the unpaved road PM10 emission factor data base without regard to the type of vehicle (e.g., haul trucks) as long as the vehicle is moving along an unpaved surface. Thus, test results for public rural roads with light-duty traffic would be included with tests of haul trucks at steel plants, quarries and surface mines. Furthermore, scrapers in the "travel" mode (i.e., fully loaded or unloaded and moving) would be included. The ranges of vehicle weights/speeds are shown below:

Type of Road	Vehicle Weight (tons)		Vehicle Speed (mph)	
	Geometric Mean	Range	Geometric Mean	Range
Industrial	40	2 - 280	20	5 - 43
Public	1.8	1.5 - 2.5	36	15 - 55

The assembled data set is shown in Attachment A. Note that only tests of uncontrolled and watered roads were considered. The assembled data sets comprises 203 individual test results. This includes the 6 "total" PM10 tests I developed from the report to the National Stone Association and presented in the set of comments that I sent you last month. It also includes the Reno, NV unpaved road tests conducted as part of Bill Kuykendal's PM2.5/PM10 study. On the other hand, the tests from Raleigh, NC and the first tests that Chat conducted at our Field Station in Grandview, MO are not included because those tests (BJ-1 through BJ-4 in Raleigh and BG-1 through BG-5 at the Field Station) have not yet been formally reported. However, I did reserve the 9 tests for validation purposes. This is discussed later in the memo.

<u>Emission Factor Development</u>

Stepwise multiple linear regression was used with the data set. The potential correction factors include:

- surface silt content, s
- surface moisture content, M
- mean vehicle weight, W

- mean vehicle speed, S
- mean number of wheels, w

All variables were log-transformed in order to obtain a multiplicative model as in the past.

The data base was then sorted by whether the test represented uncontrolled or watered conditions. The first analysis involved the stepwise regression of the uncontrolled tests using the potential correction parameters of s, W, S, and w (silt, weight, speed and number of wheels). Note that moisture content was not considered. In this case, W entered the regression first, and silt on the second step. The resulting model is of the following form:

$$e \alpha \; s^{0.81} W^{0.36} \tag{2}$$

(This first regression is roughly analogous to repeating how the unpaved road emission factor was derived. As before, only uncontrolled tests were included in the data set. In this case, however, the effort focused on the PM10 size fraction of emissions. The resulting emission factor is roughly comparable to the current AP-42 unpaved road emission factor equation. The silt content has almost a linear ("power of 1") relationship with the emission factor. In addition, emissions follow a "less-than-linear" relationship with vehicle weight. In Equation (1), however, the exponent for W is roughly half that in the current AP-42 equation.

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. Moisture entered on the third step and speed on the fourth, with the resulting model of the form:

$$e \alpha \; s^{0.85} W^{0.49} S^{0.29} / M^{0.25} \tag{2}$$

Inclusion of speed is somewhat tentative, in that its level of significance is just slightly greater than 10%. Had the requirement for a variable to enter been tightened, speed would not have entered.

For the 43 watered tests, only two correction parameters entered the regression, silt and weight. The resulting model is of the form

$$e \alpha \; s^{0.72} W^{0.57} \tag{3}$$

Finally, both uncontrolled and watered tests were considered as one data set, again with M included as a potential correction parameter. In this instance, weight and silt again entered first and second, with moisture entering on the third step. As before, speed S entered on the fourth iteration. The resulting model is of the form

$$e \alpha \; s^{0.85} W^{0.50} S^{0.32} / M^{0.29} \tag{4}$$

Again, inclusion of the variable S may be viewed as somewhat contingent. As opposed to Equation (2), S enters at the 10% level of significance in this regression. Still, its inclusion is definitely the product of the data set being used. For example, the exclusion of only one or two certain low-speed tests from the data set would probably result in S not entering the regression at all. On the other hand, dropping those tests would essentially have not effect on the rest of the model.

Unlike vehicle weight (which spans two orders of magnitude), most speeds in the data set lie in a fairly tight band between 15 and 35 mph. In addition, the emission factor is found to have a reasonably weak (0.3 power) dependence on speed. Had the requirement for a variable to enter the regression been tightened from 10% to 5% level of significance, speed would not enter the equation, and the resulting model would have the form:

$$e \ \alpha \ \ s^{0.82} \, W^{0.46} \, / \, M^{0.28} \qquad (5)$$

Fairly strong cases could be argued for selecting either Equation (4) or Equation (5). I first thought that (4) is preferrable for the following reasons:

1. For the majority of cases when the average speed is roughly between 15 and 35 mph, the two equations have roughly the same predictive accuracy.

2. Equation (4) would allow an AP-42 user to account for instances with either low- or high-speed traffic. Equation (4) is likely to have greater accuracy in those cases.

However, in performing some of the validation studies, I found that, when part of the data base was held back for validation purposes, the number of wheels rather than speed would enter on the last step. It appears to me that the fourth variable is just a little too much on the "ragged" edge. Equation (5) somewhat sidesteps the issue, but it is still based on good science and allows one to perform more straightforward validation analyses.

The unpaved road emission model I recommend incorporating into AP-42 is based on Equation (5) and thus has the general form,

$$e = 1.6 \, (s/12)^{0.8} \, (W/3)^{0.5} \, / \, (M/1)^{0.3} \qquad (6)$$

where

e = PM10 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% silt and 3 tons are the same as for the current AP-42 model. This allows one to compare the leading term of 1.6 lb/vmt in Equation (6) to the factor of 2.1 lb/vmt inherent in the current version of the unpaved road predictive model. This is consistent with my earlier finding that "re-centering" the current factor to PM10 data would require reducing the leading term by about 30%.

Validation Studies

The first validation study made use of a cross-validation analysis. 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 cross-validation (CV) shows that the model is fairly accurate for a very broad range of source conditions. Table 1 indicates that, although the model may slightly under- or overpredict emission for 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,

- 52% are within a factor of 2
- 73% are within a factor of 3
- 90% are within a factor of 5
- 98% are within a factor of 10

In examining the residuals (i.e., the error between the predicted and observed emission factors), I found that Equation (6) tends to overpredict the lowest and underpredict the highest observed factors. In other words, the model appears to have a systematic bias at the extremes of the parent data base. This is not believed to be overly restrictive, given AP-42's goal to represent "average" conditions. No other significant relationship was found for the residuals.

A limited second validation study involved reserving approximately 20 to 25% 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 model

$$e = 1.55\ (s/12)^{0.78}\ (W/3)^{0.44}\ /\ (M/1)^{0.35}$$

and Development Set 2 led to the following model

$$e = 1.72\ (s/12)^{0.80}\ (W/3)^{0.43}\ /\ (M/1)^{0.26}$$

Note that both development sets led to models very similar to that in Equation (6). When the two models were used to predict data in the validation sets, the following summary statistics result:

	No. of	Ratio of Predicted to Observed			
Validation Set	Cases	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

A final validation study involved the 9 emission tests that have not yet been formally reported. Table 2 shows the results of the comparisons of predicted to observed PM10 emission factors. Predictions based on both Equation (6) and the current AP-42 model are considered. In general, agreement is quite good for the new unpaved road model.

Summary

A revised unpaved road emission factor of the type presented in Equation (6) satisfactorily predicts emissions from a broad range of vehicles traveling over unpaved surfaces. It appears that this model could replace not only the "generic" unpaved factor in Section 13.2 but also the haul truck factor in the surface coal mine section.

Table 2. Application of new model to Raleigh and Grandview data

Run	Silt (%)	Moisture (%)	Weight (tons)	Speed (mph)	No. of Whls	Measured PM10 EF (lb/vmt)	Ratio of Predicted to Observed	
							Equ. (6)	Current AP-42
BJ-1	4.01	0.1	2	30	4	1.23	0.88	0.43
BJ-2	2.9	0.1	2	30	4	1.29	0.65	0.30
BJ-3	4.26	0.07	2	30	4	0.84	1.51	0.67
BJ-4	3.7	0.09	2	30	4	1.32	0.80	0.37
BG-1	7.2	7.2	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	7.56	1.38	2	30	4	0.118	6.95	8.44
BG-5	7.97	1.12	2	30	4	0.0884	10.30	11.88

NOTE: BG-4 and -5 conducted under mist and rainy conditions.

Table 1. 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**