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                  Paved Roads

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MRI REPORT

Emission Factor Documentation for AP-42, Sections 11.2.5 and 11.2.6

Paved Roads

For Emission Inventory Branch
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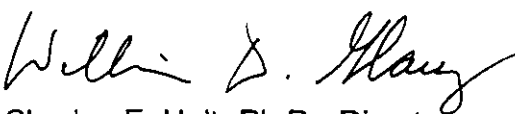
PREFACE

This report was prepared for Mr. Dennis Shipman of the Emission Inventory Branch, Technical Support Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, under EPA Contract No. 68-DO-0123, Work Assignment No. I-44. This report describes the development of a new AP-42 section to replace current sections 11.2.5, "Urban Paved Roads," and 11.2.6, "Industrial Paved Roads." Midwest Research Institute's Project Leader for the assignment is Dr. Gregory E. Muleski. Dr. Muleski and Dr. Chatten Cowherd prepared this report.

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SECTION 1

INTRODUCTION

The document "Compilation of Air Pollutant Emissions 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 periodically updated by EPA to respond to new emission factor needs of EPA, State, and local air pollution control programs and industry.

An emission factor relates the quantity (weight) of pollutants emitted to a unit of activity of the source. The uses for the emission factors reported in AP-42 include:

1. Estimates of area-wide emissions.

2. Estimates of emissions for a specific facility.

3. Evaluation of emissions relative to ambient air quality.

The purpose of this report is to provide background information from test reports and other information to support preparation of a consolidated AP-42 section to replace existing Sections 11.2.5, "Urban Paved Roads," and 11.2.6, "Industrial Paved Roads."

The principal pollutant of interest in this report is "particulate matter" (PM), with special emphasis placed on "PM-10"—particulate matter no greater than 10 μmA (microns in aerodynamic diameter). PM-10 forms the basis for the current National Ambient Air Quality Standards (NAAQSs) for particulate matter.

PM-10 thus represents the size range of particulate matter that is of the greatest regulatory interest. Nevertheless, formal establishment of PM-10 as the standard basis is relatively recent, and many emission tests have referenced other particle size ranges. Other size ranges employed in this report are:

TSP   Total Suspended Particulate, as measured by the standard high-volume (hi-vol) air sampler. TSP was the basis for the previous NAAQSs for particulate matter. TSP consists of a relatively coarse particle size fraction. While the particle capture characteristics of the hi-vol sampler are dependent upon approach wind velocity, the effective D50 (i.e., 50% of the particles are captured and 50% are not) varies roughly from 25 to 50 μmA.

SP   Suspended Particulate, which is used as a surrogate for TSP. Defined as PM no greater than 30 μmA. SP also may be denoted as "PM-30."

IP   Inhalable Particulate, defined as PM no greater than 15 μmA. Throughout the late 1970s and the early 1980s, it was clear that EPA intended to revise the NAAQSs to reflect a particle size range finer than TSP. What was not clear was the size fraction that would be eventually used, with values between 7 and 15 μmA frequently mentioned. Thus, many field studies were conducted using IP emission measurements because it was believed that IP would be the basis for the new NAAQS. IP may also be represented by "PM-15."

FP   Fine Particulate, defined as PM no greater than 2.5 μmA. FP also may
      be denoted as "PM-2.5."

This background report consists of five sections. Section 1 provides an introduction to the report. Section 2 presents descriptions of the paved road source types and emissions from those sources as well as a brief history of the current AP-42 emission factors. Section 3 is a review of emissions data collection and analysis procedures; it describes the literature search, the screening of emission test reports, and the quality rating system for both emission data and emission factors. Section 4 details the development of paved road emission factors for the draft AP-42 section; it includes the review of specific data sets and the results of data analysis. Section 5 presents the AP-42 section for paved roads.

SECTION 2

SOURCE DESCRIPTION

Particulate emissions occur whenever vehicles travel over a paved surface, such as public and industrial roads and parking lots. These emissions may originate from material previously deposited on the travel surface, or resuspension of material from tires and undercarriages. In general, emissions arise primarily from the surface material loading (measured as mass of material per unit area). Surface loading is in turn replenished by other sources (e.g., pavement wear, deposition of material from vehicles, deposition from other nearby sources, carryout from surrounding unpaved areas, and litter). Because of the importance of the surface loading, available control techniques either attempt to prevent material from being deposited on the surface or to remove (from the travel lanes) any material that has been deposited.

2.1 PUBLIC AND INDUSTRIAL ROADS

While the mechanisms of particle deposition and resuspension are largely the same for public and industrial roads, there can be major differences in surface loading characteristics, emission levels, traffic characteristics, and viable control options. For the purpose of estimating particulate emissions and determining control programs, the distinction between public and industrial roads is not a question of ownership but rather a question of surface loading and traffic characteristics.

Although public roads generally tend to have lower surface loadings than industrial roads, the fact that these roads have far greater traffic volumes may result in

a substantial contribution to the measured air quality in certain areas. In addition, public roads in industrial areas can be often heavily loaded and traveled by heavy vehicles. In that instance, better emission estimates might be obtained by treating these roads as industrial roads. In an extreme case, an industrial road or parking lot may have such a high surface loading that the paved surface is essentially covered and is easily mistaken for an unpaved surface. In that event, use of a paved road emission factor may actually result in a higher estimate than that obtained from the unpaved road emission factor, and the road is better characterized as unpaved in nature rather than paved.

2.2 REVIEW OF CURRENT PAVED ROAD EMISSION FACTORS

AP-42 currently contains two sections concerning paved road fugitive emissions. The first, Section 11.2.5, is entitled "Urban Paved Roads" and was first drafted in 1984 using test results from public paved roads.[2] Emission factors are given in the form of the following equation:

$$E = k \ (sL/0.5)^p \tag{2-1}$$

where: E =   particulate emission factor (g/VKT)

s =   surface material content silt, defined as particles $< 75 \ \mu m$ in diameter (%)

L =   surface material loading, defined as mass of particles per unit area of the travel surface (g/m^2)

k =   base emission factor (g/VKT)

p =   exponent (dimensionless)

The factors k and p are given by

Particle size fraction	k (g/VKT)	p
TSP	5.87	0.9
PM-15	2.54	0.8
PM-10	2.28	0.8
PM-2.5	1.02	0.6

The form of the emission factor model is reasonably consistent throughout all particle size fractions of interest.

The urban paved road emission factors represented by Equation 2-1 have not changed since their inclusion in the 4th Edition (September 1985). It should be noted that these emission factors have not been quality rated "A" through "E." (See Section 3 for an overview of the AP-42 quality rating scheme.)

Section 11.2.6, "Industrial Paved Roads," was first published in 1983[3] and was slightly modified in Supplement B (1988) to the 4th Edition. Section 11.2.6 contains three distinct sets of emission factor models as described below.

For TSP, the following equation is recommended:

$$E = 0.022 \ I \ (\frac{4}{n}) \ (\frac{s}{10}) \ (\frac{L}{280}) \ (\frac{W}{2.7})^{0.7} \tag{2-2}$$

where:
E	=	emission factor (kg/VKT)
I	=	industrial augmentation factor (dimensionless)
n	=	number of traffic lanes (dimensionless)
s	=	surface material silt content (%)
L	=	surface material loading across all traffic lanes (kg/km)
W	=	average vehicle weight (Mg)

The basic form of Equation 2-2 dates from a 1979 report[4] and was originally included in Supplement 14 to AP-42 (May 1983). The version currently in AP-42 was slightly revised in that the leading term (i.e., 0.022 in Eq. [2-2]) was reduced by 14%. The industrial road augmentation factor (I) was included to take into account for higher emissions from industrial roads than from urban roads; it varies from 1 to 7. The emission factor equation is rated "B" for cases with I = 1 and "D" otherwise.

For smaller particle size ranges, models somewhat similar to those in Eq. (2-1) are recommended:

$$E = k \ (sL/12)^{0.3} \qquad (2\text{-}3)$$

where   E   =   emission factor (kg/VKT)

            k   =   base emission factor (kg/VKT), see below

          sL   =   road surface silt loading (g/m^2)

The base emission factor (k) above varies with aerodynamic size range as follows:

Particle size fraction	k (g/VKT)
PM-15	0.28
PM-10	0.22
PM-2.5	0.081

These models represented by Equation 2-3 were first developed in 1984[3] from 15 emission tests of uncontrolled paved roads and they are rated "A."

During the development of Eq. (2-3), tests of light-duty traffic on heavily loaded road surfaces were identified as a separate subset, for which separate single-valued emission factors were developed. Section 11.2.6 recommends the following for

light-duty (less than 4 tons) vehicles traveling over dry, heavily loaded (silt loading greater than 15 g/m^2):

$$E = k \hspace{4cm} (2\text{-}4)$$

where   E   =   emission factor (kg/VKT)

　　　　 k   =   single-valued factor depending on particle size range of interest (see below)

Particle size fraction	k (g/VKT)
PM-15	0.12
PM-10	0.093

The single-valued emission factors are quality rated "C."

Since the time that the current models first appeared in Sections 11.2.5 and 11.2.6, several users of AP-42 have noted difficulty selecting the appropriate emission factor model to use in their applications.[5,6,7] For example, inventories of industrial facilities (particularly of iron and steel plants) conducted throughout the 1980s have yielded measured silt loading values substantially lower than those in the Section 11.2.6 data base. In extreme cases when the models were used with silt loading values outside the range for which they were developed, estimated PM-10 emission factors were larger than the corresponding TSP emission factors.

Furthermore, the distinction between "urban" and "industrial" paved roads has become blurred. For the purpose of estimating emissions, it was gradually realized that source emission levels are not a question of ownership but rather a question of surface loading and traffic characteristics. Confirmatory evidence was obtained in a

1989 field program[5] which found that paved roads at an iron and steel facility far more closely resembled "urban" roads rather than "industrial" roads in terms of emission characteristics.

Finally, it is unknown how well current emission factors perform for cases of increased surface loading on public roads, such as after application of antiskid materials or within areas of trackout from unpaved areas.[6] These situations are of considerable interest to several state and local regulatory agencies, most notably in the western United States.

The current update attempts to correct as many of those shortcomings as possible. To that end, the update employs an approach slightly different than that used in the past. In addition to reviewing test data obtained since the previous update,[8] previous test data were also included for reexamination in the final data set. In assembling the data base, no distinction was made between public and industrial roads or between controlled and uncontrolled tests, with the anticipation that the reformulated emission factor will be applicable over a far greater range of source conditions.

Inclusion of controlled tests represents a break with EPA guidelines for preparing AP-42 sections.[9] Those guidelines present a clear preference that only uncontrolled tests be used to develop an emission factor. However, the principal control measures for paved roads seek to reduce the value of an independent variable in the emission factor equation, i.e., the silt loading.

2-6

SECTION 3

GENERAL DATA REVIEW AND ANALYSIS

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.

3.1 LITERATURE SEARCH AND SCREENING

Review of available literature identified three paved road testing programs
(presented later as Table 4-1) since the time of the last Section 11.2 update.[8] The
individual programs are discussed in detail in the next section. In addition, as
discussed at the end of Section 2, earlier controlled industrial road test data were
reexamined. The previous update[8] noted that Eq. (2-4) yielded quite good estimates
for emissions from vacuum swept and water flushed roads. Furthermore, it became
apparent that previous distinctions between "industrial" and "urban" roads had become
blurred as interest focused on heavily loaded urban roads (e.g., after snow/ice
controls) and on cleaner industrial roads (as the result of plant-wide control programs).

3.2 EMISSION DATA QUALITY RATING SYSTEM

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 (i.e., comparison of
     EPA Method 5 front-half with EPA Method 5 front- and back-half).

3.   Test series of controlled emissions for which the control device is not
     specified.

4.   Test series in which the source process is not clearly identified and
     described.

5.   Test series in which it is not clear whether the emissions were measured before or after the control device.

Test data sets that were not excluded were assigned a quality rating. The rating system used was that specified by EIB for preparing AP-42 sections.[9] The data were rated as follows:

A   Multiple tests that were performed on the same source using sound methodology and reported in enough detail for adequate validation. These tests do not necessarily conform to the methodology specified in EPA reference test methods, although these methods were used as a guide for the methodology actually used.

B   Tests that were performed by a generally sound methodology, but lack enough detail for adequate validation.

C   Tests that were based on an untested or new methodology or that lacked a significant amount of background data.

D   Tests that were based on a generally unacceptable method but may provide an order-of-magnitude value for the source.

The following criteria were used to evaluate source test reports for sound methodology and adequate detail:

1.   Source operation. The manner in which the source was operated is well documented in the report. The source was operating within typical parameters during the test.

2. <u>Sampling procedures</u>. The sampling procedures conformed to a generally acceptable methodology. If actual procedures deviated from accepted methods, the deviations are well documented. When this occurred, an evaluation was made of the extent such alternative procedures could influence the test results.

3. <u>Sampling and process data</u>. Adequate sampling and process data are documented in the report, and any variations in the sampling and process operation are noted. If a large spread between test results cannot be explained by information contained in the test report, the data are suspect and were given a lower rating.

4. <u>Analysis and calculations</u>. 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 was 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.

3.3 EMISSION FACTOR QUALITY RATING SYSTEM

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

<u>A—Excellent</u>: Developed only from A-rated 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-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- and 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 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- and B-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.

E—Poor: The emission factor was developed from C- and D-rated test data, and there is reason to suspect that the facilities tested 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 these factors are always noted.

The use of these criteria is somewhat subjective and depends to an extent on the individual reviewer.

3.4 METHODS OF EMISSION FACTOR DETERMINATION

Fugitive dust emission rates and particle size distributions are difficult to quantify because of the diffuse and variable nature of such sources and the wide range of particle size involved including particles which deposit immediately adjacent to the source. Standard source testing methods, which are designed for application to confined flows under steady state, forced-flow conditions, are not suitable for measurement of fugitive emissions unless the plume can be draw into a forced-flow system. The following presents a brief overview of applicable measurement techniques. More detail can be found in earlier AP-42 updates.[8,10]

3.4.1 Mass Emission Measurements

Because it is usually impractical to enclose open dust sources or to capture the entire emissions plume, only the upwind-downwind and exposure profiling methods are suitable for measurement of particulate emissions from most open dust sources.[10] These two methods are discussed separately below.

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

Net downwind (i.e., downwind minus upwind) concentrations are used as input to dispersion equations (normally of the Gaussian type) to backcalculate the particulate emission rate (i.e., source strength) required to generate the pollutant concentration measured. Emission factors are obtained by dividing the calculated emission rate by a source activity rate (e.g., number of vehicles, or weight of material transferred per unit time). A number of meteorological parameters must be concurrently recorded 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 11) 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 about 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 height 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% 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% 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 arithmetic average 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 arithmetic 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 characterize 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).

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

An emission factor equation is useful if it is successful in "explaining" much of the observed variance in emission factor values on the basis of corresponding variance sin specific source parameters. This enables more reliable estimates of source emissions on a site-specific basis.

A generic emission factor equation is one that is developed for a source operation defined on the basis of a single dust generation mechanism which crosses industry lines. An example would be vehicular traffic on unpaved roads. To establish its applicability, a generic equation should be developed from test data obtained in different industries.

3.5 EMISSION FACTOR QUALITY RATING SCHEME USED IN THIS STUDY

The uncontrolled emission factor quality rating scheme used in this study is identical to that used in two earlier updates[8,11] and represents a refinement of the rating system developed by EPA for AP-42 emission factors, as described in Section 3.3. The scheme entails the rating of test data quality followed by the rating of the emission factor(s) developed from the test data.

Test data that were developed from well documented, sound methodologies were assigned an A rating. Data generated by a methodology that was generally sound but either did not meet a minimum test system requirements or lacked enough detail for adequate validation received a B rating.

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

The minimum requirements for a sound exposure profiling program were the following. A one-dimensional, vertical grid of at least three samplers is sufficient for measurement of emissions from line or moving point sources while a two-dimensional

array of at least five samplers is required for quantification of fixed virtual point source missions. At least one upwind sampler must be operated to measure background concentration, and wind speed must be measured on-site.

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

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

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

1.   Traditionally, three tests of a source represent the minimum requirement for reliable quantification.

2.   More than two plant sites are needed to provide minimum industry representativeness.

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

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

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

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

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

Development of quality ratings for emission factor equations also required consideration of data representativeness and variability, as in the case of single-valued emission factors. However, the criteria used to assign ratings (Table 3-2) were different, reflecting the more sophisticated model being used to represent the test

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

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

[a] P denotes number of correction parameters in emission factor equation.

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

data. As a general principle, the quality rating for a given equation should lie between the test data rating and the rating that would assigned to a single-valued factor based on the test data. The following criteria were established for an emission factor equation to have the same rating as the supporting test data:

1.   At least three test sites and three tests per site, plus an additional three tests for each independent parameter in the equation.

2.   Quantitative indication that a significant portion of the emission factor variation is attributable to the independent parameter(s) in the equation.

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

independent parameters in the equation. The rating was reduced two levels if this supplementary criterion was not met.

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

SECTION 4

AP-42 SECTION DEVELOPMENT

4.1 REVISIONS TO SECTION NARRATIVE

The draft AP-42 presented later in this background document is intended to replace the current versions of both Section 11.2.5 "Urban Paved Roads" and Section 11.2.6 "Industrial Paved Roads" in AP-42. Both sections date from the mid-1980s and only slight revisions have been made over the past 8 years.

As discussed earlier in this report, some AP-42 users have noted difficulty in selecting the appropriate emission factor model to use in particular applications. For example, field-measurement-based inventories have demonstrated that silt loading has tended to decrease at industrial facilities throughout the 1980s, so that, at present, silt loadings found on industrial roads often can be substantially lower than those in the underlying data base. In extreme cases of silt loading outside the range supporting the models, resulting PM_{10} factors may be greater than corresponding TSP factors. Due to the trend of lower silt loadings, the distinction made between "urban" and "industrial" paved roads in AP-42 has not been found as clear-cut in real-world situations.

Several investigators have also commented that the current emission factors for public paved roads may not be applicable when the equilibrium between deposition and removal processes is upset. This situation can occur for various reasons, including (a) application of snow and ice controls, (b) trackout from construction

activities in the area, and (c) wind and/or water erosion from surrounding unstabilized areas.

4.2 POLLUTANT EMISSION FACTOR DEVELOPMENT

This update to Sections 11.2.5 and 11.2.6 was planned to address the shortcomings described above. In order to achieve this goal, the following general approach was taken

1. Assemble the available test data for paved roads in a single data base, making no distinction between public and industrial roads or between controlled and uncontrolled roads.

2. Conduct a series of stepwise linear regression analyses of the revised data base to develop an emission factor model with:

    silt loading,
    mean vehicle weight,
    mean number of wheels, and,
    mean travel speeds

    as potential correction parameters.

3. Conduct an appropriate validation study of the reformulated model.

4.2.1 Review of Specific Data Sets

Table 4-1 presents the specific test reports reviewed in this update. As can be seen, test reports reviewed in the 1987 update were again reviewed to determine if

TABLE 4-1. APPLICABLE TEST REPORTS

New reports since 1987 update:

I.   PEI Associates 1989. "Street Sanding Emissions and Control Study," EPA
        Contract No. 68-02-4394, Work Assignment No. 27, prepared for U.S.
        Environmental Protection Agency, Region 8. October 1989.

II.   Midwest Research Institute 1990. "Roadway Emission Field Tests at U.S.
        Steel's Fairless Works." USX Purchase Order No. 146-0001191-0068,
        prepared for United States Steel Corporation. May 1990.

III.   RTP Environmental Associates 1990. "Street Sanding Emissions and Control
        Study," prepared for the Colorado Department of Health. July 1990.

Reports[a] considered during 1987 update:

1.   T. Cuscino, Jr., et al., *Iron and Steel Plant Open Source Fugitive Emission
        Control Evaluation*, EPA-600/2-83-110, U.S. Environmental Protection
        Agency, Research Triangle Park, North Carolina, October 1983.

5.   G. E. Muleski, *Measurement of Fugitive Dust Emissions from Prilled Sulfur
        Handling*, Final Report, MRI Project No. 7995-L, Prepared for Gardinier, Inc.,
        June 1984.

8.   T. F. Eckle and D. L. Trozzo, "Verification of the Efficiency of a Road-Dust
        Emission-Reduction Program by Exposure Profile Measurement," Presented
        at EPA/AISI Symposium on Iron and Steel Pollution Abatement, Cleveland,
        Ohio, October 1984.

[a] Same numbers as in 1987 update.[8]

controlled emissions data should be included in the final data set. Test reports I, II, and III are new since the 1987 update. Test reports 1, 5, and 8 are those from the 1987 update that were re-reviewed.

Test Report I. This test program was undertaken to characterize PM-10 emissions from six streets that were periodically sanded for anti-skid control within the Denver area. The primary objective was given as development of a predictive algorithm for clean and sanded streets, with a secondary objective stated as defining the effectiveness of control measures. Summary information is given in Table 4-2.

Sampling employed six to eight 8 PM-10 samplers equipped with volumetric flow control. Samplers were arranged in two upwind/downwind configurations. The "basic" configuration consisted of six samplers arranged in identical patterns upwind and downwind of the test road, with one sampler and one pair of samplers at nominal distances of 20 and 5 m, respectively, from the road.

The second configuration was used for tests of control measure effectiveness. The road segment was divided into two halves, corresponding to the treated and experimental control (untreated) portions. Identical sampling arrays were again used upwind and downwind on both halves, at nominal distances of 20 and 5 m. Because this array employed all eight samplers available, no collocation was possible for the second configuration.

In addition to the PM-10 concentration measurements, several other types of samples were collected:

- Wind speed/direction and incoming solar radiation were collected on-site, and the results were combined to estimate atmospheric stability class needed to calculate emission factors.

TABLE 4-2. SUMMARY INFORMATION FOR TEST REPORT I

| Operation | Location | State | Test dates | No. of tests | PM$_{10}$ emission factor (g/VKT) | |
					Geom. mean	Range
Vehicle traffic	Colfax	Colorado	3-4/89	17	1.33	0.53-9.01
Vehicle traffic	York St.	Colorado	4/89	1	1.07	1.07
Vehicle traffic	Belleview	Colorado	4/89	4	1.62	1.10-4.77
Vehicle traffic	I-225	Colorado	4/89	9	0.31	0.17-0.51
Vehicle traffic	Evans	Colorado	5-6/89	29	1.06	0.21-7.83
Vehicle traffic	Louisiana	Colorado	6/89	7	0.96	0.42-1.73

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- Colorado Air Pollution Control Division (APCD) representatives collected traffic data, including traffic counts, travel speeds, and percentage of heavy-duty vehicles.

- Vacuums with disposable paper bags were used to collect the loose material from the road surface. In addition to samples taken from the travel lanes, the field crew took daily samples of material adjacent to curbs and periodic duplicate samples.

The study collected PM-10 concentration data on 24 different days and calculated a total of 69 different emission rates for baseline, sanded and controlled paved road surfaces. Emission factors were obtained by back-calculation from the CALINE3 dispersion model[12] together with a series of assumptions involving mixing widths and heights and an effective release height. Although data collected at the 20 m distance were used to evaluate results, the test report did not describe any sensitivity analysis to determine how dependent the emission rates were on the underlying assumptions.

The testing program found difficulty in defining "upwind" concentrations for several of the runs, including cases with wind reversals or winds nearly parallel to the roadway orientation. A total of eight of the 69 tests required that either an average concentration from other test days or a downwind concentration be used to define "upwind" conditions. In addition, the test report described another seven runs as invalid for reasons such as wet road surfaces, nearby dust sources or concentrations increasing with downwind distance.

A series of stepwise regression analyses were conducted, with different predictive equations presented for (a) baseline conditions, (b) sanded roads, and (c) roads swept to remove the sand applied, and (d) all conditions combined. In each

case, only one independent variable was included in the predictive equation: silt loading, for cases (a) and (d); and time since treatment, for (b) and (c).

In general, Test Report I is reasonably well documented in terms of describing test conditions, sampling methodology, data reduction and analysis. A chief limitation lies in the fact that neither sampling configuration fully met minimum requirements for the upwind-downwind method presented in Section 3.4. Specifically, only two or three samplers were used downwind rather than the minimum of four.

Furthermore, a later report[6] drawing upon the results from Test Reports I and III effectively eliminated 24% of the combined baseline tests because of wind directions. In addition, the later report[6] noted that the baseline data should be considered as "conservatively high" because roughly 70% of the data were calculated assuming the most unstable atmospheric class (which results in the highest backcalculated emission factor). Because of these limitations, the emission data have been given an overall rating of between "B" and "C."

Test Report II. This 1989 field program used exposure profiling to characterize emissions from paved roads at an integrated iron and steel plant. In many respects, this program arose because of uncertainties with paved road emission factor models used outside their range of applicability. During the preparation of an alternative emission reduction ("bubble") plan for the plant, questions arose about the use of AP-42 equations and other EPA guidance[13] in estimating roadway emissions involved in the emissions trade. This program provided site-specific data to support the bubble plan. This testing program also represents the first exposure profiling data to supplement the AP-42 paved road data base since 1984. Table 4-3 provides summary information.

The program involved two paved road test sites. The first (site "C") was along the four-lane main access route to the plant. Average daily traffic (ADT) had been

TABLE 4-3. SUMMARY INFORMATION FOR TEST REPORT II

Operation	Location	State	Test dates	No. of test	Emission factor (g/VKT) TSP		Emission factors (g/VKT) PM$_{10}$	
					Geom. mean	Range	Geom. mean	Range
Vehicle traffic	Unpaved road	Pennsylvania	11/89	2	172	110-270	45.1	40-51
Vehicle traffic	Site C	Pennsylvania	11/89	6	9.19	3.4-34	2.69	0.25-10
Vehicle traffic	Site E	Pennsylvania	11/89	4	21.9	9.3-84	6.21	2-10

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estimated as more than 4,000 vehicle passes per day, with most vehicles representative of "foreign" equipment (i.e., cars, pickups, and semi-trailers rather than plant haul trucks and other equipment). Site "E," on the other hand, was located near the iron- and steel-making facilities and had both lower ADT and heavier vehicles than site "C." The plant regularly vacuum swept paved roads, and two cleaning frequencies (two times and five times per week) were considered during the test program.

Depending on traffic characteristics of the road being tested, a 6 to 7.5 m high profiling array was used to measure downwind mass flux. This array consisted of four or five total particulate sampling heads spaced at 1.5 m heights and was positioned at a nominal 5 m distance downwind from the road. Additional concentration and particle size measurements were obtained from standard high volume ("hi-vol") sampler and cyclone/cascade impactor combination operated downwind as well as a standard hi-vol/impactor combination operated upwind. The height for downwind sizing devices (2.2 m) was selected after review of prior test results. It approximated the height in a roadway dust plume at which half the mass emissions pass above and half below.

Additional samples included:

- Average wind speeds at two heights and wind direction at one height were recorded during testing to maintain isokinetic sampling.

- Traffic data, including traffic counts, travel speeds, and vehicle class were recorded manually.

- Vacuums with disposable paper bags were used to collect the loose material from the road surface.

The sampling equipment met the requirements of a sound exposure profiling methodology specified in Section 3.4 so that the emission test data are rated "A." The

test report presents emission factors for total particulate (TP), total suspended particulate (TSP) and PM-10, for the ten paved road emission tests conducted.

Test Report II found that the emission factors and silt loadings more closely resembled those in the "urban" rather than the "industrial" data base. That is to say, emissions agreed more closely with factors estimated by the methods of AP-42 Section 11.2.5 than by methods in Section 11.2.6. Given the traffic rate of 4000 vehicles per day at Site "C," this finding was not terribly surprising. What was far more surprising was that emissions at Site "E" were also more "urban" than "industrial." Although the TSP and PM-10 models in Section 11.2.5 showed a slight tendency to underpredict, the Section 11.2.6 PM-10 model overestimated measured emissions by at least an order of magnitude. The performance of the industrial TSP model, on the other hand, was only slightly poorer than that for the urban TSP model.

Test Report III. This test program was quite similar to that described in Test Report I and used an essentially identical methodology. In fact, the two test reports are very similar in outline, and many passages in the two reports are identical. The primary objective was given as expanding the data base in Test Report I to further develop predictive algorithms for clean and sanded streets. Summary information is given in Table 4-4.

The test program employed the same two basic PM-10 sampling arrays as did Test Report I. A third configuration was used for "profile" tests, in which additional samplers were placed at 10 and 20 ft heights. (Analysis of results from elevated samplers is not presented in Test Report III.)

As was the case in Test Report I, additional samples were collected including:

- Wind speed/direction were collected on-site, and the results used in estimating atmospheric stability class needed to calculate emission

TABLE 4-4. SUMMARY INFORMATION FOR TEST REPORT III

Operation	Location	State	Test dates	No. of test	PM-10 emission factor (g/VKT)	
					Geom. mean	Range
Vehicle traffic	Mexico	Colorado	2/90	3	2.75	1.08-6.45
Vehicle traffic	State Hwy 36	Colorado	1-3/90	13	1.31	0.14-4.18
Vehicle traffic	Colfax	Colorado	2-4/90	41	1.32	0.27-5.04
Vehicle traffic	Park Rd.	Colorado	4/90	11	1.26	0.69-3.33
Vehicle traffic	Evans	Colorado	2-3/90	11	2.10	0.87-7.27
Vehicle traffic	Louisiana	Colorado	1,3/90	9	3.24	1.40-5.66
Vehicle traffic	Jewell	Colorado	1/90	1	6.36	6.36
Vehicle traffic	Bryon	Colorado	4/90	3	8.38	5.53-14.72

factors. (Unlike Test Report I, solar radiation measurements were not collected.)

- Traffic data, including traffic counts, travel speeds, and percentage of heavy-duty vehicles were collected.

- Vacuums with disposable paper bags were used to collect the loose material from the road surface. The program developed an extensive set of collocated samples of material along the edges of the roadway.

The study collected PM-10 concentration data on 33 days and calculated a total of 131 different emission rates for baseline, sanded and controlled paved road surfaces. Emission factors were obtained by back-calculation from the CALINE3 dispersion model[12] together with essentially the same assumptions as those in Test Report I. This report also noted the same difficulty as Test Report I in defining "upwind" concentrations in cases with wind reversals or winds nearly parallel to the roadway orientation. Unlike Test Report I, however, this report does not provide readily available information on how many tests used either an average concentration from other test days or a downwind concentration to define "upwind" conditions. Test Report III does, however, describe seven tests as invalid because of filter problems or because upwind concentrations were higher than downwind values.

As with the Test Report I program, a series of stepwise regression analyses were conducted. This test program combined data from Test Reports I and III and considered predictive equations for (a) baseline conditions, (b) sanded roads, and (c) roads swept to remove the sand applied, and (d) all conditions combined.

Unlike Test Report I, however, Test Report III appears to present silt loading values that are based on <u>wet sieving</u> (see page 8 of the test report) rather than the dry sieving technique (as described in Appendix E to AP-42) routinely used in fugitive

dust tests. (MRI could not obtain any clarifying information during telephone calls to the testing organization and the laboratory that analyzed the samples.) Wet sieving disaggregates composite particles and results from the two types of sieving are not comparable.

There is additional confusion over the silt loading values given in Test Report III for cleaning tests. Specifically, the same silt loading value is associated with both the treatment and the experimental control. This point could not be clarified during telephone conversation with the testing organization. Attempts to clarify using test report appendices were unsuccessful. Two appendices appear to interchange silt loading with silt percentage. More importantly, it could not be determined whether the surface sample results reported in Appendix D to Test Report III pertain to treated or the experimental control segment, and with which emission rate a silt loading should be associated.

Test Report III contains substantial amounts of information, but is not particularly well documented in terms of describing test conditions, sampling methodology, data reduction and analysis. In addition, the same limitations mentioned in connection with Test Report I are equally applicable to Test Report III, as follows:

- not meeting the minimum number of samplers.

- numerous tests conducted under variable wind conditions.

- frequent use (70% to 80% of the tests) of the most unstable atmospheric stability class in the CALINE 3 model which will result in the highest calculated emission rate.

Because of these limitations, emission rate data have been given an overall rating of "C." Furthermore, the silt loading data in this report are considered suspect for reasons noted above.

Reexamination of Earlier Data Sets. As remarked earlier, it was decided to assemble paved road test data distinguishing neither between public and industrial roads nor between controlled and uncontrolled tests. In addition to simply combining the data bases supporting Sections 11.2.5 and 11.2.6, this involved reexamining earlier reports for controlled test results. Specifically, the paved road Test Reports 1, 5, and 8 identified in the 1987 update (see Table 4-1) were reexamined.

Test Report 1 in 1987 update: This study evaluated paved road control techniques at two different iron and steel plants. (See Tables 9 and 10 in Reference 8.) Data were quality rated as "A," and uncontrolled test results were incorporated into the data base for Section 11.2.6. The only use of the controlled test results, however, has been the following addition to Section 11.2.6.4 in 1988:

"Although there are relatively few quantitative data on emissions from controlled paved roads, those that are available indicate that adequate estimates generally may be obtained by substituting controlled loading values into .. [Equations (2-2) and (2-3)].... The major exception to this is water flushing combined with broom sweeping. In that case, the equations tend to overestimate emissions substantially (by an average factor of 4 or more)."

In the current update, the controlled emission factors have been used as part of the overall data base to develop predictive models. Although PM-10 emission data are not specifically presented in the report, appropriate values were previously developed by log-normal interpolation of the PM-15 and PM-2.5 factors.[8]

<u>Test Report 5 in 1987 update</u>: This was first report identified to suggest that heavily loaded paved roads may be better considered as unpaved in terms of emission estimates. The program produced three tests of emissions from end-loader travel over paved surfaces. Two of the three tests were conducted on very heavily loaded surface, while the third was on a cleaned paved surface. (See Tables 20 and 21 of the 1987 update.)[8]

No PM-10 emission factors were reported; results were presented for total particulate (TP) and suspended particulate (SP, or PM-30). Data were quality rated "A" in the 1987 report.

Because no PM-10 data were given, Test Report 5 data were most directly useful as independent data against which the TSP emission factor model (Eq. (2-2)) could be assessed. This comparison showed generally good agreement between predicted and observed with agreement becoming better as source conditions approached those in the underlying data base.

The 1987 update[8] developed PM-10 emission factors based on information contained in the test report. When compared to the single valued factors (Equation [2-4]), agreement for the first two tests was within a factor of approximately two. The third test—that of the cleaned surface—could not be used to assess the performance of either Eq. (2-1) or Eq. (2-3) because the surface loading value could not be converted to the necessary units with information presented in the report.

<u>Test Report 8 in 1987 update</u>: This paper discussed the development of an exposure profiling system as well as an evaluation of the effectiveness of a paved road vacuum sweeping program. Because no reference is made to an earlier test report, this paper is considered to be the original source of the test data. Although ten uncontrolled and five controlled tests are mentioned, test data are reported only in terms of averages. (See Tables 24 and 25 in Reference 8.) Only TSP emission

factors are presented. Although data were obtained using a sound methodology, data were rated "B" because of inadequate detail in the paper.

Averaged data from Test Report 8 were used in an independent assessment of Eq. (2-2). Although only average emission levels could be compared, the data suggested that TSP emissions could be estimated within very acceptable limits.

4.2.2 Compilation of Final Data Base

In keeping with the results from the data set review, a final data base was compiled by combining the following sets:

1. Data base supporting Section 11.2.5

2. Data base supporting Section 11.2.6

3. The controlled tests of Test Report 1 in the 1987 update

4. All data contained in Test Report II

The final PM-10 data base is shown in Figure 4-1, with the origin of each of the 64 data points indicated by a key letter:

I -   Data point used to develop the predictive equations in Section 11.2.6.

i -   Data point used in developing the single-valued factors in Section 11.2.6.

U -   Data point used to develop the predictive equation in Section 11.2.5.
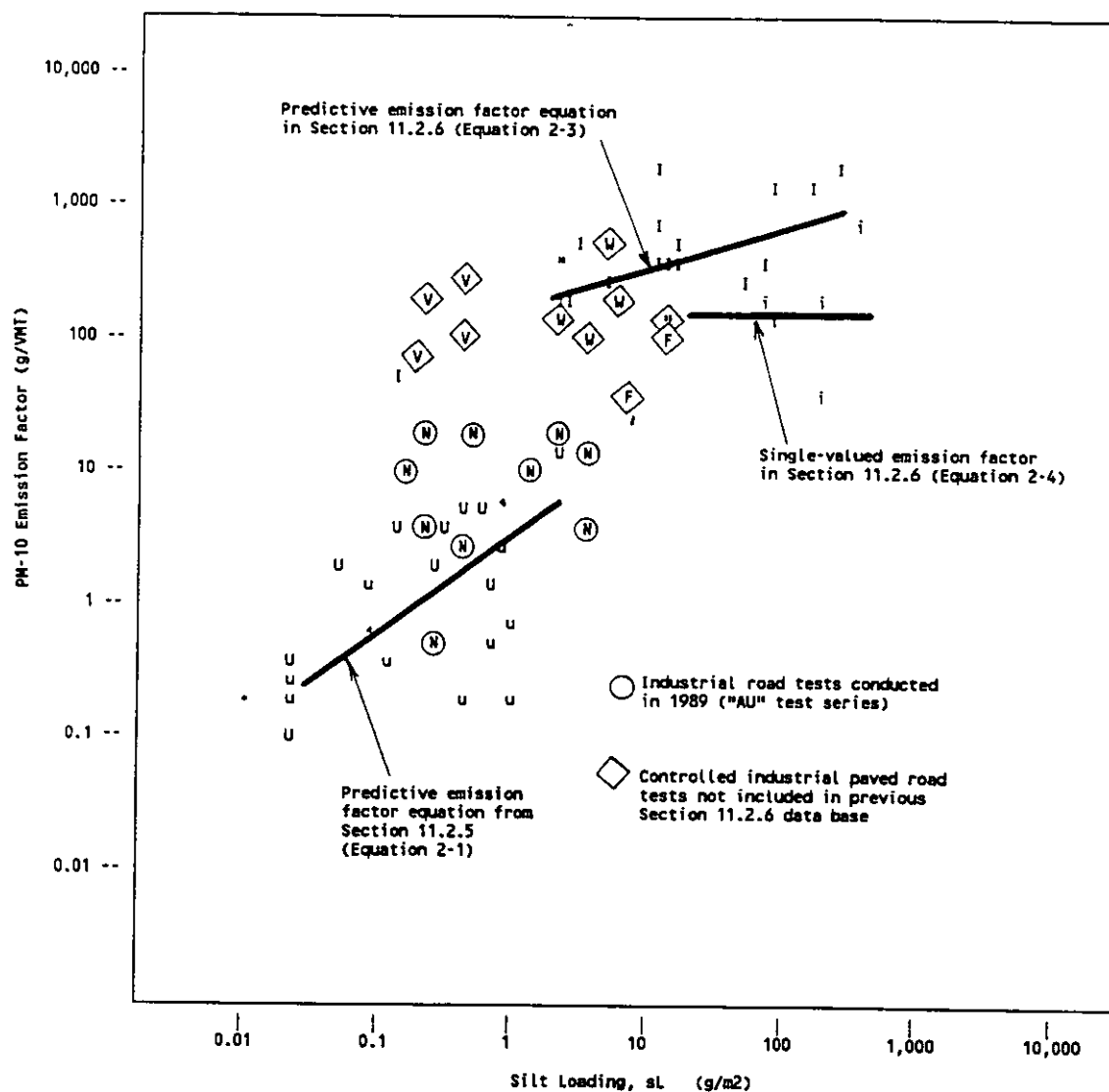
Figure 4-1.   Final data set.   See text for key letters.

u - Data point excluded during development of the urban paved road equation (Section 11.2.5).

V,W,F - Controlled industrial test in Test Report 1 corresponding to vacuum swept, water flushed or flushed/broom swept.

N - Data from Test Report II

The "new" data, namely those in data sets (3) and (4), are shown in diamonds or circles in the figure. Note that the new data sets function somewhat like "glue" in combining the old industrial and urban data sets in the sense that the new data effectively bridge the two older data sets.

Test data from Test Reports I and III were excluded from the final data base for the following reasons:

a. Only PM-10 emission factors were available, rather than a group of particle size ranges.

b. Unresolved questions about the silt loading values in Test Report III remain.

Note, however, that Test Report I data provide very useful information about the accuracy of the revised emission factor model. Figure 4-2 presents the 43 data points from Test Report I used in the validation study.

4.2.3 Emission Factor Development

Stepwise multiple linear regression[14] was used to develop a predictive model with the final data set. The potential correction factors included:
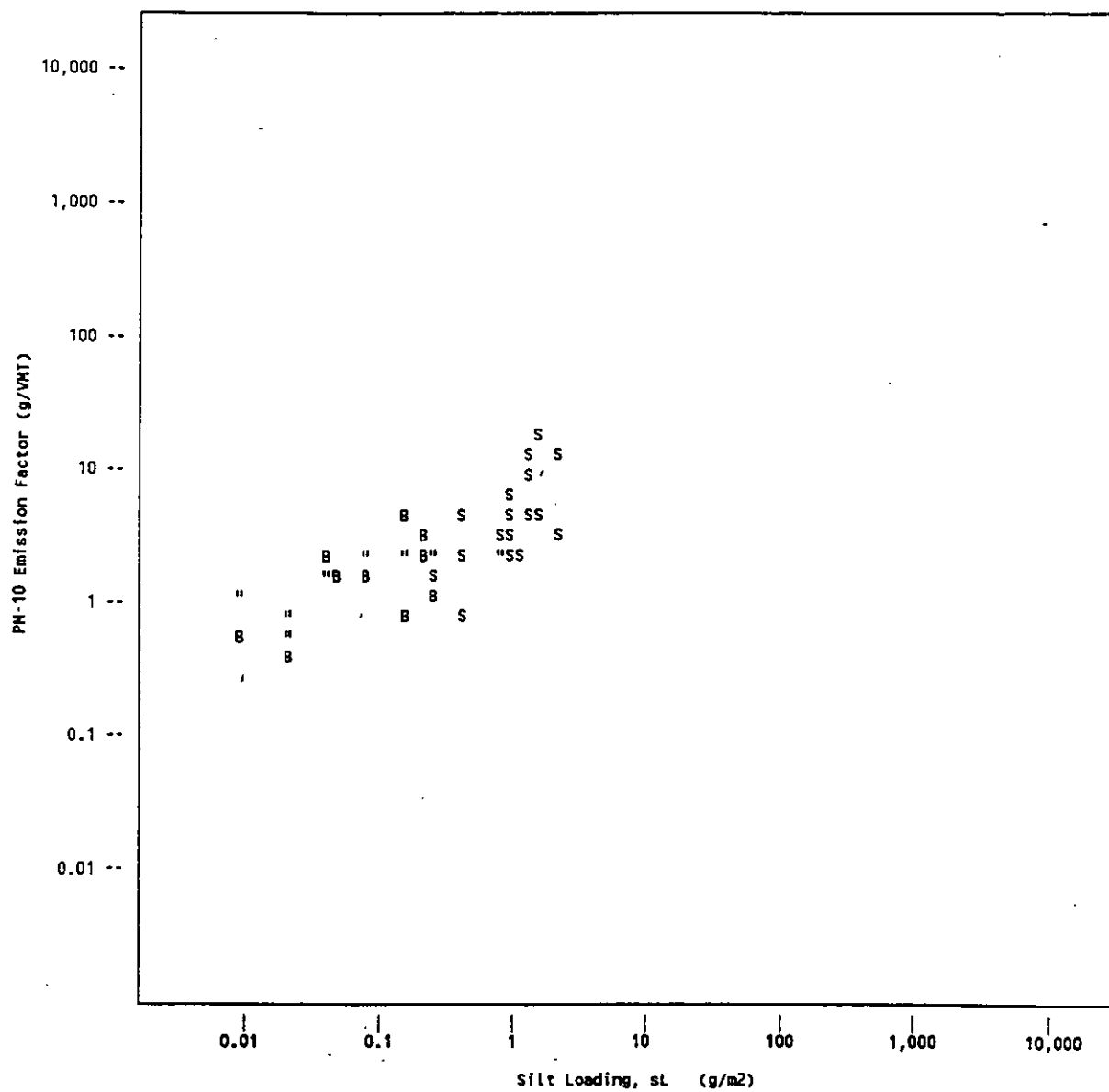
Figure 4-2.   Validation data from Test Report I.   "B" represents a
               baseline while "S" indicates a sand road test.

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- silt loading, sL
- 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. Figure 4-3 presents the correlation matrix of the log-transformed independent and dependent variables, as well as the multiple regression results. The most notable features of the correlation matrix are the high degree of interdependence between silt loading, emission factors, and speed; and the low degree of interdependence between silt loading and weight. This suggests that silt loading and weight may be effectively used to derive an emission factor model.

Several points should be noted about the regression results. First, the expression for PM-10 was always considered first so that a series of models comparable over several size ranges would result. As Figure 4-3 shows, the models for PM-30 and PM-15 are quite similar to that for PM-10; the expression for PM-2.5, on the other hand, has substantially lower exponents for both sL and W.

Second, during an initial exploratory phase, it was found that models with essentially equivalent accuracy could be developed using only the independent variables of weight W and speed S. Nevertheless, those two variables cannot be expected to vary substantially during the year. In other words, a model based on W and S could not be expected to predict higher emission levels known to occur after road sanding, etc. Models incorporating surface loading values as an independent variable were pursued because surface loading represents a reasonable means of introducing seasonal variability.

Multiple Linear Regression for PM-10

DEP VAR: LGVMT   N: 64   MULTIPLE R: .873   SQUARED MULTIPLE R: .761
ADJUSTED SQUARED MULTIPLE R: .754   STANDARD ERROR OF ESTIMATE: 1.393

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-0.099	0.424	0.000	.	-0.232	0.817
LSL	0.648	0.074	0.586	0.880	8.790	0.000
LTONS	1.487	0.209	0.474	0.880	7.117	0.000

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	377.698	2	188.849	97.371	0.000
RESIDUAL	118.309	61	1.939		

Multiple Linear Regression for PM-2.5

DEP VAR: LGVMT   N: 52   MULTIPLE R: .839   SQUARED MULTIPLE R: .705
ADJUSTED SQUARED MULTIPLE R: .693   STANDARD ERROR OF ESTIMATE: 1.264

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	0.007	0.457	0.000	.	0.015	0.988
LSL	0.487	0.070	0.559	0.920	6.912	0.000
LTONS	1.258	0.209	0.468	0.920	6.030	0.000

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	186.960	2	93.480	58.472	0.000
RESIDUAL	78.337	49	1.599		

Multiple Linear Regression for PM-15

DEP VAR: LGVMT   N: 64   MULTIPLE R: .879   SQUARED MULTIPLE R: .772
ADJUSTED SQUARED MULTIPLE R: .765   STANDARD ERROR OF ESTIMATE: 1.383

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	0.182	0.422	0.000	.	0.432	0.667
LSL	0.678	0.073	0.604	0.879	9.264	0.000
LTONS	1.470	0.208	0.462	0.879	7.081	0.000

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	395.337	2	197.669	103.275	0.000
RESIDUAL	116.754	61	1.914		

Multiple Linear Regression for PM-30

DEP VAR: LGVMT   N: 18   MULTIPLE R: .868   SQUARED MULTIPLE R: .753
ADJUSTED SQUARED MULTIPLE R: .720   STANDARD ERROR OF ESTIMATE: 0.876

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	1.342	0.815	0.000	.	1.648	0.120
LSL	0.596	0.210	0.443	0.677	2.843	0.012
LTONS	1.638	0.477	0.535	0.677	3.434	0.004

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	35.115	2	17.557	22.883	0.000
RESIDUAL	11.509	15	0.767		

PEARSON CORRELATION MATRIX FOR PM-2.5

	LGVMT	LSL	LTONS	LMPH	LWHEELS
LGVMT	1.000				
LSL	0.697	1.000			
LTONS	0.646	0.282	1.000		
LMPH	-0.812	-0.809	-0.208	1.000	
LWHEELS	-0.006	-0.596	0.885	0.513	1.000

FREQUENCY TABLE

	LGVMT	LSL	LTONS	LMPH	LWHEELS
	52	52	52	30	13
		52	52	30	13
			30	13	

PEARSON CORRELATION MATRIX FOR PM-10

	LGVMT	LSL	LTONS	LMPH	LWHEELS
LGVMT	1.000				
LSL	0.751	1.000			
LTONS	0.676	0.347	1.000		
LMPH	-0.768	-0.837	-0.202	1.000	
LWHEELS	0.141	-0.596	0.885	0.513	1.000

FREQUENCY TABLE

	LGVMT	LSL	LTONS	LMPH	LWHEELS
	65	64	65	42	13
		64	42	13	

PEARSON CORRELATION MATRIX FOR PM-15

	LGVMT	LSL	LTONS	LMPH	LWHEELS
LGVMT	1.000				
LSL	0.765	1.000			
LTONS	0.672	0.348	1.000		
LMPH	-0.775	-0.837	-0.202	1.000	
LWHEELS	0.159	-0.596	0.885	0.513	1.000

FREQUENCY TABLE

	LGVMT	LSL	LTONS	LMPH	LWHEELS
	64	64	64	42	13
		64	42	13	

PEARSON CORRELATION MATRIX FOR PM-30

	LGVMT	LSL	LTONS	LMPH	LWHEELS
LGVMT	1.000				
LSL	0.748	1.000			
LTONS	0.787	0.568	1.000		
LMPH	-0.737	-0.875	-0.338	1.000	
LWHEELS	.	.	.	.	0

FREQUENCY TABLE

	LGVMT	LSL	LTONS	LMPH	LWHEELS
	18	18	18	12	0
		18	12	0	

Figure 4-3. Correlation and regression results for the data set.

The following equation presents the final recommended emission factor models.

$$e = k \, (sL)^{0.65} \, (W)^{1.5}$$

where e is emission factor in g/vehicle-mile traveled (g/VMT), sL is silt loading in g/m^2, W is mean vehicle weight in tons, and k is constant given in Table 4-5.

TABLE 4-5. RECOMMENDED EMISSION FACTOR MODELS

Size range	Sample size	k	Multiple R^2
PM-2.5	52	0.41	NA
PM-10	64	0.90	0.761
PM-15	65	1.1	0.765
PM-30	18	4.7	0.752

All models, except that for PM-2.5, are quality rated "A." The expression for PM-2.5 was based on a mean ratio of PM-2.5 to PM-10 because of slightly different powers on the sL and W terms; the PM-2.5 factor is rated "B." The high R2 values for the other size ranges indicate that approximately 75% of variability in emission factors are "explained" by the predictive equation.

4.2.4 Validation Studies

Two sets of validation studies were undertaken to assess the predictive capability of the revised paved road emission model for PM-10. The first employed a standard cross-validation (CV) technique.[15] Using this technique, each point in the underlying data base is excluded one at a time, and the equation generated from the reduced data base is used to estimate the missing value. The second evaluation applied the new PM-10 expression to the independent data of Test Report I.

By using a CV technique, "n" quasi-independent estimates are obtained from a data base of "n" tests, and the overall validity of using stepwise regression to obtain a model of the form

$$e = k \, (sL)^a \, (W)^b$$

is evaluated. Summary information is shown in Table 4-6.

TABLE 4-6. RESULTS OF CROSS-VALIDATION STUDY

	Variable	Minimum	Maximum	Mean	Std. deviation
a	Exponent of sL	0.63	0.67	0.649	0.009
b	Exponent of W	1.42	1.57	1.49	0.027
k	Leading term	0.79	1.07	0.90[a]	1.058[a]
	Ratio of quasi-independent estimate to measured emission factor	0.050	30	1.004[a]	4.23[a]

[a] Geometric mean/standard deviation.

Figure 4-4 presents the cumulative frequency distribution of the ratio of the quasi-independent estimate to the measured emission factor. A little over half of the estimates are within a factor of 3 and approximately 70% are within a factor of 5. The 90% confidence interval corresponds to a factor of approximately 8.

The second validation study applied the recommended PM-10 emission factor model to the data of Test Report I (see Figure 4-2). This represents an independent application of the equation in that none of the Test Report I data were used to develop the equation. Summary information is given in Table 4-7:
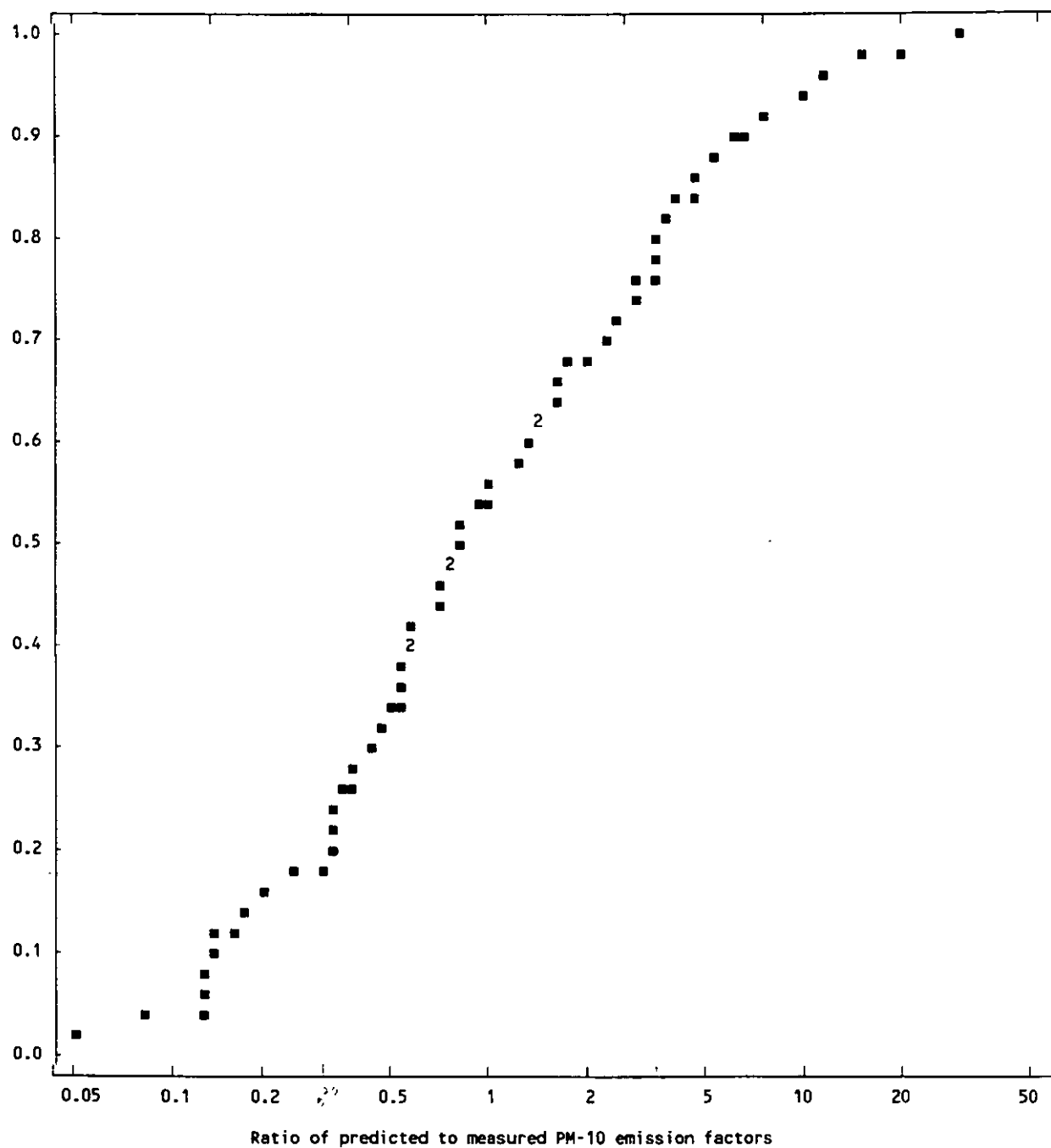
Figure 4-4. Cumulative frequency distribution obtained during cross-validation study.

TABLE 4-7. RESULTS FROM INDEPENDENT APPLICATION OF THE PM-10 MODEL

| | Sample size | Ratio of predicted to observed PM-10 emission factor | | | |
		Minimum	Maximum	Geo. mean	Geo. std. deviation
Baseline roads	23	0.23	1.59	0.528	1.69
Sanded roads	20	0.35	2.51	1.03	1.69
Overall	43	0.23	2.51	0.724	1.86

As can be seen, agreement is generally quite good, especially for sanded roads.

For baseline (unsanded) roads, the new PM-10 emission factor model tends to underpredict emissions. Recall that a later report[6] making use of Test Reports I and III stated that the combined baseline data "should be considered to be conservatively high." If that is true, then the tendency of the new model to underpredict could be expected.

One final examination compared performance of the new PM-10 versus the current AP-42 factors and EPA guidance.[13] The document "Control of Open Fugitive Dust Sources" (EPA-450/3-88-008) presented the following decision rule for paved road emission estimates (Table 4-8).

TABLE 4-8. DECISION RULE FOR PAVED ROAD EMISSION ESTIMATES

Silt loading (sL) (g/m^2)	Average vehicle weight (W) (tons)	Use model given by
sL < 2	W > 4	Equation (2-3)
sL < 2	W < 4	Equation (2-1)
sL > 2[a]	W > 6	Equation (2-3)
2 < sL < 15	W < 6	Equation (2-3)
sL > 15[a]	W < 6	Equation (2-4)

[a] For heavily loaded surfaces (i.e., sL < ~ 300 to 400 g/m^2) it is recommended that the resulting estimate be compared to that from the unpaved road models.

Table 4-9 presents the results from this comparison. As can be seen, in almost every data set comparison, results using the new model are comparable, if not better, than those using the three different equations currently contained in AP-42, together with the selection method of Table 4-8.

4.3 DEVELOPMENT OF OTHER MATERIAL IN AP-42 SECTION

Concurrent with the development of the revised AP-42 section for paved roads, a separate effort was conducted to assemble a silt loading data base for nonindustrial roads. Over the past 10 years, numerous organizations have collected silt loading samples from public paved roads. Unfortunately, uniformity—in sampling and analysis methodology as well as roadway classification schemes—has been sorely lacking in these studies.

Silt loading data were compiled in the following manner. Persons knowledgeable about PM-10 at each EPA regional office were asked to identify sL data for public roads. In many instances, the EPA representatives identified state/local air regulatory personnel who were then asked to supply the data. Given that the relative importance of PM-10 emissions from public sources is greater in the western United States, it is not surprising that most of the data are from that area of the country. What is surprising, perhaps, is that Montana has collected roughly two-thirds of all data. Furthermore, only Montana had data collected from the same road over extended periods of time, thus permitting examination of temporal variation.

The assembled data set did not yield any readily identifiable, coherent relationship between silt loading and road class, average daily traffic (ADT), etc. Much of the difficulty is probably due to the fact that not all variables were reported by each organization. Further complicating the analysis is the fact that, in many parts of the country, paved road silt loading varies greatly over the course of the year. Recall that repeated sampling at Montana municipalities indicated a very noticeable annual

TABLE 4-9. RATIO OF PREDICTED TO MEASURED PM-10 EMISSION FACTORS

Data set code[a]	Sample size	Minimum[b]	Maximum[b]	Geo. mean[b]	Std. geo. deviation[b]
l	19	0.086 / 0.056	2.9 / 12	0.80 / 0.70	2.3 / 4.5
i	5	0.24 / 0.39	4.1 / 5.5	0.96 / 1.0	2.8 / 2.8
U	10	0.39 / 0.38	170 / 6.6	8.8 / 1.2	6.8 / 2.4
u	9	0.61 / 0.56	300 /18	14 / 3.4	7.7 / 2.9
V, F, W	11	0.52 / 0.14	8.6 / 3.7	1.7 / 0.54	2.4 / 2.9
N	10	0.13 / 0.094	79 / 28	5.8 / 1.1	10 / 5.5
Overall	64	0.086 / 0.056	300 / 28	2.7 / 1.0	6.4 / 3.9

[a] Same data subset code as for Figure 4-1.

[b] First entry represents value using current AP-42 factors and decision rule in Table 4-8. Second entry represents value using new PM-10 equation.

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$\frac{21.3}{(APT)}$

$9^{h} = 46$

cycle. Nevertheless, it is questionable whether the seasonal variation noted in the Montana data base could successfully predict variations for many other sites. While one could possibly expect similar variations for, say, Idaho or Wyoming roads, there is far less reason to suspect a similar cycle in, say, Maine or Michigan, in the absence of additional information.

Because no meaningful relationship could be established between sL and an independent variable, the decision was made to directly employ the nonindustrial data base in the AP-42 section. The draft AP-42 section presents the cumulative frequency distribution for the sL data base, with subdivisions into (a) low-ADT (< 5000 vehicles/day) and high-ADT roads and (b) first and second halves of the year. Suggested default values are based on the 50th and 90th percentile values.

The second use of the assembled data set recognizes that the end users of AP-42 are the most capable in identifying which roads in the data base are similar to roads of interest to them. The draft AP-42 section presents the paved road surface loading values together with the city, state, road name, collection date (samples collected from the same road during the same month are averaged), road ADT if reported, classification of the roadway, etc. Readers of AP-42 are invited to review the data base and to select values that they deem appropriate for the roads and seasons of interest.
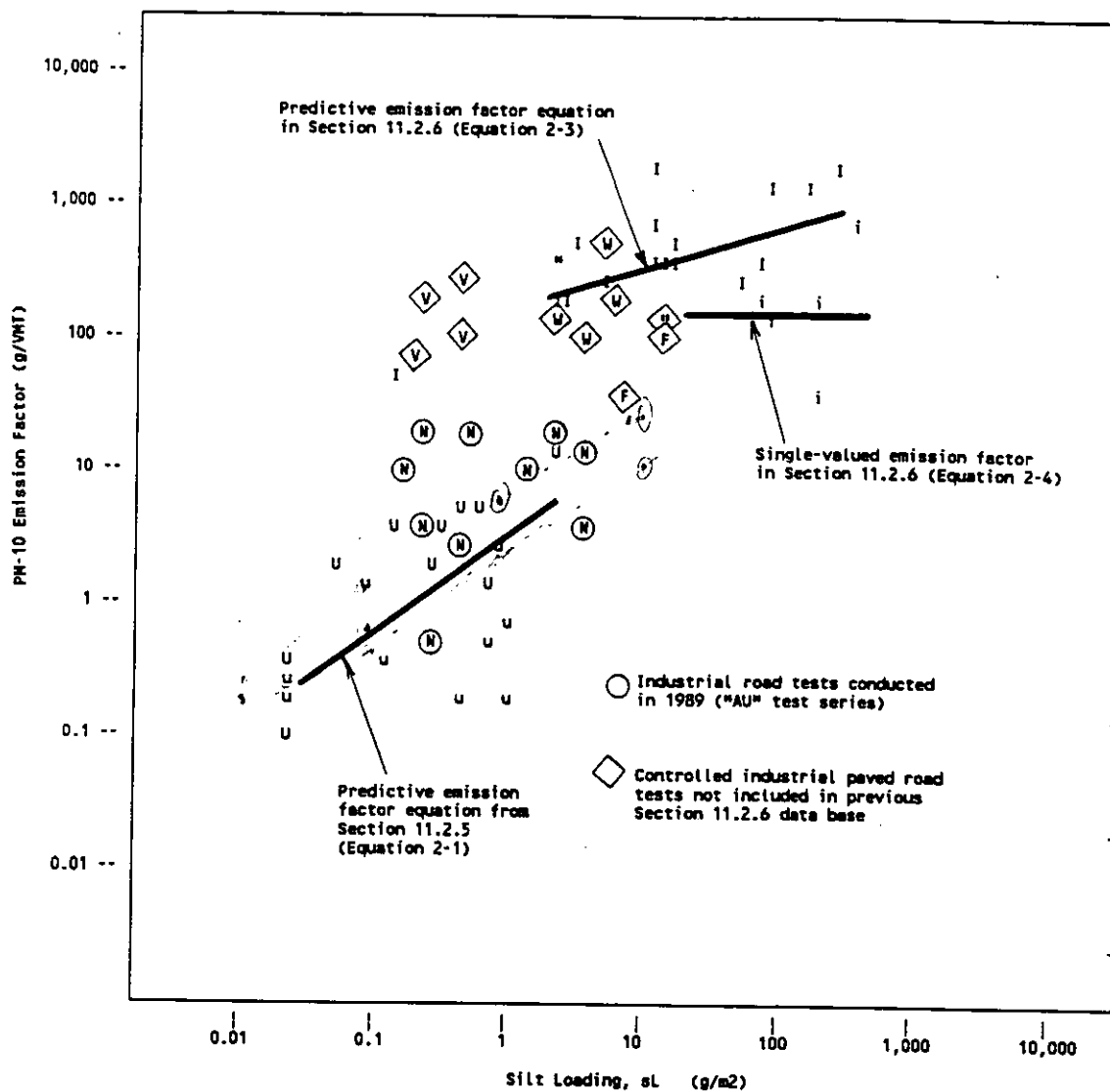
Figure 4-1. Final data set. See text for key letters.