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SIZE SPECIFIC PARTICULATE
EMISSION FACTORS FOR
INDUSTRIAL AND RURAL ROADS

Source Category Report

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Source Category Report

by

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ABSTRACT

Over the past few years traffic-generated dust emissions from unpaved and paved industrial roads have become recognized as a significant source of atmospheric particulate emissions, especially within those industries involved in the mining and processing of mineral aggregates. Although a considerable amount of field testing of industrial roads has been performed, most studies have focused on total suspended particulate (TSP) emissions, because the current air quality standards for particulate matter are based on TSP. Only recently, in anticipation of an air quality standard for particulate matter based on particle size, has the emphasis shifted to the development of size-specific emission factors.

This study was undertaken to derive size-specific particulate emission factors for industrial paved and unpaved roads and for rural unpaved roads from the existing field testing data base. Regression analysis is used to develop predictive emission factor equations which relate emission quantities to road and traffic parameters. Separate equations are developed for each road type and for the following aerodynamic particle size fractions: $\leqq$ 15 µm, $\leqq$ 10 µm, and $\leqq$ 2.5 µm. Finally, recommendations are made for inclusion of the resulting emission factors into AP-42.

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1.0 INTRODUCTION

Over the past few years traffic-generated dust emissions from unpaved and paved industrial roads have become recognized as a significant source of atmospheric particulate emissions, especially within those industries involved in the mining and processing of mineral aggregates. Typically, road dust emissions exceed emissions from other open dust sources associated with the transfer and storage of aggregate materials. For example, in western surface coal mines, dust emissions from uncontrolled unpaved roads usually account for more than three-fourths of the total particulate emissions, including typically controlled process sources such as crushing operations.[1] Therefore, the quantification of industrial road dust emissions is necessary to the development of effective strategies for the attainment and maintenance of the national ambient air quality standards for particulate matter.

Although a considerable amount of field testing of industrial roads has been performed, most studies have focused on total suspended particulate (TSP) emissions, because the current air quality standards for particulate matter are based on TSP. Those studies have produced emission factors that are poorly defined with regard to particle size. Although the high-volume sampler, which is the reference device for measurement of TSP concentration, has a very broad capture efficiency curve,[4] TSP is generally recognized as consisting of particles smaller than 30 μm in aerodynamic diameter.

Only recently, in anticipation of an air quality standard for particulate matter based on particle size, has the emphasis shifted to the development of size-specific emission factors in the particle size range related to adverse health effects. The following particle size fractions have been of interest in these recent studies:

IP = Inhalable particulate matter consisting of particles equal to or smaller than 15 μm in aerodynamic diameter

PM-10 = Particulate matter consisting of particles equal to or smaller than 10 μm in aerodynamic diameter

FP = Fine particulate matter consisting of particles equal to or smaller than 2.5 μm in aerodynamic diameter

In practice, these particle size fractions have been determined in the field using inertial sizing devices characterized by calibrated values of 50% cutoff diameter (D_{50}). The symbol "$\leq$" will be used in this report to define particle size fractions determined in this manner.

The purpose of this report is to derive size-specific particulate emission factors for industrial paved and unpaved roads from the existing field testing data base. Emission factors for rural unpaved roads are also derived in this report. Finally, recommendations are made for inclusion of the resulting emission factors into AP-42.

2.0 DATA REVIEW

This section presents a review of field studies directed to the development of uncontrolled particulate emission factors for industrial paved and unpaved roads and for rural unpaved roads. The particular studies selected for the derivation of size-specific emission factors are identified along with the criteria used in the selection process.

Although a substantial body of literature is available which deals in some way with road dust emissions, relatively few documents are appropriate for development of AP-42 emission factors. These documents meet the following criteria:

1. The information in the reference document must deal with actual emission factor development. Many documents discuss emission factors but do not derive them.

2. Source testing must be part of the referenced study. Some reports develop emission factor by applying assumptions to existing factors.

3. The document must constitute the original source of test data. For example, a symposium paper would not be included if the original study were already contained in a previous document.

4. The document must be readily accessible to the public.

Recently, these criteria were applied in a study[5] to identify test reports (published through 1981) which contained emission factor data on open dust sources but which had not been referenced in AP-42. Ten reports which met the criteria contained data on road dust emission factors. However, with the exception of one study to develop emission factors for western surface coal mines,[1] those studies were directed primarily to emission factors for TSP. The standard high-volume sampler was used as the primary sampling device in five of the nine other studies. Moreover, direct measurement of aerodynamic particle size was performed (at one downwind sampling height) in only two of the studies; in three other studies, microscopy was used to provide estimates of physical particle diameter.

Subsequent to the release of the test report on western surface coal mines in November 1981, two additional reports directed to size specific emission factors for road dust emissions were issued. The first report dated August 1982, dealt with paved and unpaved roads in the iron and steel industry;[2] and the second, dated December 1982, presented size specific emission factors for paved and unpaved roads in several industries (asphalt and concrete batching, copper smelting, sand and gravel processing, and stone quarrying and processing) and for rural unpaved roads.[3]

Together with the test report on surface coal mining, these additional reports constitute an extensive data base of size-specific particulate emission factors for paved and unpaved roads. The reliability of the particle size data presented in these three reports is substantially better than the data presented in the earlier reports for the following reasons:

1. Measurement of particle size distribution was an essential part of the exposure profiling strategies used to quantify emissions in these studies.

2. Particle size distribution was measured simultaneously at more than one height in the road dust plume.

3. Inertial sizing devices were used to obtain direct measurements of aerodynamic particle size distribution.

Table 1 identifies the AP-42 source categories covered by the three test reports.

TABLE 1. LIST OF PRIMARY TEST REPORTS BY AP-42 SECTION NUMBER

AP-42 Section No.	Industrial source category	Test report
7.3	Copper smelting	3
7.5	Iron and steel production	2
8.1	Asphaltic concrete plants	3
8.10	Concrete batching	3
8.19	Sand and gravel processing	3
8.20	Stone quarrying and processing	3
8.24	Western surface coal mining	1
11.2.1	Unpaved roads	1, 2, 3
11.2.6	Paved roads	2, 3

In the following sections, each of the three reports are discussed. For each report the method of field sampling is described, including sampling equipment and the number and location of test sites. Also, test data are summarized including the ranges of road and traffic conditions tested.

2.1 TEST REPORT 1 - SURFACE COAL MINING

This field study was directed to development of size-specific emission factors for western surface coal mines. Field testing was conducted at three mines, each representing a major western coal field: Powder River Basin (Mine 1); North Dakota (Mine 2); and Four Corners (Mine 3). The study included testing of unpaved haul roads and unpaved access roads in the absence of dust control measures. Table 2 lists the source testing information for this study.

TABLE 2. UNPAVED ROAD TEST MATRIX FOR SURFACE COAL MINES (TEST REPORT 1)

Vehicle type	Test method	Site (mine)	Test period	No. of tests
Haul truck	Uw-Dw[a]	1	8/79, 12/79	11
	Profiling	1, 2, 3	7/79, 8/79, 12/79	21
Light-medium duty	Profiling	1, 2, 3	8/79, 10/79, 8/80	10

[a] Uw-Dw = Upwind-downwind method.

The primary sampling method for road testing was exposure profiling, using the equipment deployment given in Table 3. Particle size distributions were determined at two or more heights in the plume by use of dichotomous samplers and high-volume cascade impactors with cyclone preseparators. Other equipment utilized were: (a) high volume samplers for determining TSP concentrations; (b) dustfall buckets for determining dust particle deposition; and (c) recording wind instruments to determine mean wind speed and direction for adjusting the exposure profiler to isokinetic sampling conditions.

Road dust emission factors in the form of predictive equations were developed for the TSP, IP, and FP size fractions. This was accomplished by regression analysis of emission factors and the corresponding values of the road and traffic parameters measured for each test.

Table 4 presents the ranges of test conditions from Test Report 1, and Table 5 presents the average emission factors. These single-valued factors were obtained by substituting geometric means of the test conditions into the respective emission factor equations developed in this study. The equations are listed in Table 6.

TABLE 3. EQUIPMENT DEPLOYMENT FOR UNPAVED ROAD TESTING AT SURFACE COAL MINES (TEST REPORT 1)

Location	Distance from source (m)	Equipment	Intake height (m)[a]
Upwind	5	1 Dichotomous sampler	2.5
		1 Hi-vol with standard inlet	2.5
		2 Dustfall buckets	0.75
		1 Continuous wind monitor	4.0
Downwind	5-10	1 MRI exposure profiler with 4 sampling heads	1.5 (1.0) 3.0 (2.0) 4.5 (3.0) 6.0 (4.0)
		1 Hi-vol with standard inlet	2.5 (2.0)
		1 Hi-vol with cyclone/cascade impactor	2.5 (2.0)
		2 Dichotomous samplers	1.5 4.5 (3.0)
		2 Dustfall buckets	0.75
		2 Warm wire anemometers	1.5 (1.0) 4.5 (3.0)
Downwind	20	2 Dustfall buckets	0.75
Downwind	50	2 Dustfall buckets	0.75

[a] Alternative heights for sources generating lower plume heights are given in parentheses.

TABLE 4. RANGE OF TEST CONDITIONS FOR UNPAVED ROADS IN SURFACE COAL MINES (TEST REPORT 1)

Vehicle type	No. of tests	Road surface properties: Moisture content (%, w/w)	Silt content (%, w/w)	Silt loading (g/m²)	Mean vehicle properties: Speed (mph)	Weight (tons)	No. of wheels	Wind speed (mph)
Light-medium duty	10	0.9-1.7	4.9-10.1	5.9-48.2	24.8-42.9	2.0-2.6	4.0-4.1	6.5-13.0
Haul truck	27	0.3-8.5	2.8-18.0	3.8-254	14.9-36.0	24-138	4.9-10.0	1.8-15.4

TABLE 5. EMISSION FACTORS FOR UNPAVED ROADS IN SURFACE COAL MINES (TEST REPORT 1)

Vehicle type	No. of Tests	Particulate emission factor by aerodynamic size range[a]			
		≦ 30 μm	≦ 15 μm	≦ 2.5 μm	Units
Light-medium duty	10	2.9	1.8	0.12	lb/VMT
Haul truck	27	17.4	8.2	0.30	lb/VMT

[a] TSP and ≦ 15 μm emission factors were determined by applying the mean correction correlation parameters in Table 13-9 (page 13-14) of test report to the equation in Table 15-1 (page 15-2) of test report. The ≦ 2.5 μm emission factors were determined by applying the appropriate fraction found in Table 15-1 (page 15-2) of test report to the ≦ 30 μm emission factors.

TABLE 6. EMISSION FACTOR EQUATIONS FOR UNPAVED ROADS IN SURFACE COAL MINES (TEST REPORT 1)

Vehicle type	Particulate emission factor equation[a]			Units
	TSP	≦ 15 µm	≦ 2.5 µm/TSP[b]	
Light-medium duty	$\frac{5.79}{(M)^{4.0}}$	$\frac{3.22}{(M)^{4.3}}$	0.040	lb/VMT
Haul trucks	$0.0067\ (w)^{3.4}\ (L)^{0.2}$	$0.0051\ (w)^{3.5}$	0.017	lb/VMT

Note: The range of test conditions are as stated in Table 4. Particle diameters are aerodynamic.

[a] From page 15-2, Table 15-1 of test report.

[b] Multiply this fraction by the TSP predictive equation to determine emissions in the ≦ 2.5 µm size range.

M = moisture content of road surface material (%, w/w)

w = number of wheels

L = silt loading of road surface material (g/m^2)

2.2 TEST REPORT 2 - IRON AND STEEL PRODUCTION

In a second study directed to evaluation of open dust source controls in the iron and steel industry, emissions from paved and unpaved roads were tested prior to application of control measures. The testing was performed at two steel plants, in Ohio (Plant F) and Texas (Plant B). This work has been supplemented by testing in Illinois (Plant AG) and Missouri (Plant AJ). Table 7 lists the source testing information for this study.

TABLE 7. ROAD TEST MATRIX FOR IRON AND STEEL PLANTS (TEST REPORT 2)

Road type	Test site location	Vehicle type	Test period	No. of tests
Unpaved	Ohio	Light duty	July 1980	4
		Medium duty	November 1980	1
		Heavy duty	November 1980	2
	Indiana	Medium duty	June 1982	3
	Missouri	Heavy duty	September 1982	3
Paved	Ohio	Average mix	July 1980 October 1980 November 1981	7
	Texas	Average mix	July 1981	4

Exposure profiling was the primary test method using the equipment deployments given in Table 8. Particle size distributions were determined at two heights in the plume by use of high-volume cascade impactors with cyclone preseparators. Other equipment utilized were: (a) high-volume samplers with standard or size-selective inlets for measurement of TSP and IP concentrations, respectively; (b) high-volume samplers with cyclone precollectors and 37 mm filters for collection of samples to be analyzed for trace metals and for largest particle size (by microscopy); and (c) recording wind instruments to determine mean wind speed and direction for adjusting the exposure profiler to isokinetic conditions.

Tables 9 and 10 present the ranges of test conditions and the average emission factors, respectively, from test Report 2.

TABLE 8. EQUIPMENT DEPLOYMENT FOR ROAD TESTING AT IRON AND STEEL PLANTS (TEST REPORT 2)

		Distance from source (m)			
		Plant F			
Sampler	Location	Deployment 1[a]	Deployment 2[b]	Plant B	Plant AG/AJ
MRI exposure profiler	Downwind	1.0	1.0	1.0	1.5
		2.0	2.0	2.0	3.0
		3.0	3.0	3.0	4.5
		4.0	4.0	4.0	6.0
		-	5.0	5.0	-
Hi-vol with cyclone/ impactor	Downwind	1.0	1.0	1.0	1.5
		3.0	3.0	3.0	4.5
	Upwind	-	-	-	3.0
Hi-vol with size selective inlet	Downwind	2.0	-	2.0	-
	Upwind	1.0	1.0	2.0	-
		3.0	3.0	-	-
Hi-vol with standard inlet	Downwind	2.0	2.0	2.0	-
	Upwind	2.0	2.0	2.0	-
Hi-vol with cyclone	Downwind	-	-	-	1.5
37 mm cassette	Downwind	-	-	-	1.5
		-	-	-	4.5
	Upwind	-	-	-	3.0

[a] Runs F27 to F32, F34, and F35.

[b] Runs F61, F62, and F68 to F70.

TABLE 9. RANGE OF ROAD TEST CONDITIONS IN IRON AND STEEL PLANTS (TEST REPORT 2)

		Road surface properties		Mean vehicle properties			
Road type/vehicle type	No. of tests	Silt content (%, w/w)	Total loading (g/m^2)	Speed (mph)	Weight (Mg)	No. of wheels	Wind speed (m/s)
Unpaved roads/light-duty vehicles	4	-	-	15	2.7	4.0	0.72-2.8
Unpaved roads/medium-duty vehicles	4	5.8-14.0	10,200-14,200	20-27	20-25	5.9-9.8	1.9-3.3
Unpaved roads/heavy-duty vehicles	5	6.3-16	1,370-2,150	20-24	45-49	6.0-10	0.91-3.7
Paved roads/average vehicle mix	11	6.4-35.7	-	-	10-36	-	1.6-5.4

TABLE 10. EMISSION FACTORS FOR ROADS IN IRON AND STEEL PLANTS (TEST REPORT 2)

Road type/vehicle type	No. of tests	Mean emission factors by aerodynamic size range				
		TP	≦ 15 um	≦ 10 um	≦ 2.5 um	Units
Unpaved roads/light-duty vehicles[a]	4	3.33	0.860	-	0.227	kg/VKT
Unpaved roads/medium-duty vehicles[b]	4	13.1	3.36	1.01[e]	0.658	kg/VKT
Unpaved roads/heavy-duty vehicles[c]	5	17.8	4.01	0.841[f]	1.10	kg/VKT
Paved roads/average[d]	11	0.728	-	-	0.0607	kg/VKT

[a] Emission factors are arithmetic means of test runs F28, F29, F30, and F31 from page 60, Table 3-19 of test report.

[b] Emission factors are arithmetic means of test runs AG1, AG2, and AG3 from supplementary testing and F68 from page 49, Table 3-12 of test report.

[c] Emission factors are arithmetic means of test runs F69, and F70 from page 49, Table 3-12 of test report and test runs AJ1, AJ2, and AJ3 from supplementary testing.

[d] Emission factors are arithmetic means of test runs F27, F32, F34, F35, F61, F62, B57, B58, B59, and B60 from page 73, Table 3-26 of test report.

[e] Emission factors are arithmetic mean of test runs AG1, AG2, and AG3 from supplementary testing.

[f] Emission factors are arithmetic mean of test runs AJ1, AJ2, and AJ3 from supplementary testing.

2.3 TEST REPORT 3 - CONSTRUCTION AGGREGATE INDUSTRIES, COPPER SMELTING, AND RURAL ROADS

The objective of the third study was to expand the road dust emission factor data base by conducting field testing in other industries with significant road dust emissions. It was anticipated that the combined data base would include ranges of road and traffic conditions that encompass most industrial settings where road dust emissions are significant.

As indicated in the test matrix for unpaved roads (Table 11) and the matrix for paved roads (Table 12), testing was performed in five different industry categories; and testing also included rural (nonindustrial) unpaved roads. Field tests were conducted in three different geographical regions: Rocky Mountain region (sand and gravel processing, gravel rural road), Great Plains region (stone crushing, asphalt and concrete batching, and rural roads), and the southwestern region of the United States (copper smelter).

Exposure profiling was the primary test method using the equipment deployment given in Table 13. Particle size distributions were determined at two heights in the plume using high-volume cascade impactors with cyclone preseparators. Other equipment utilized were: (a) high-volume samplers with standard inlets and size-selective inlets for measurement of TSP and IP concentrations, respectively; and (b) recording wind instruments to determine mean wind speed and direction for adjusting the exposure profiler to isokinetic conditions.

Tables 14 and 15 give the ranges of test conditions for unpaved and paved industrial roads, respectively. The average emission factors are given in Tables 16 (unpaved roads) and 17 (paved roads). These statistics are based only on those tests meeting the quality assurance criteria stated on page 33 of Test Report 3.

TABLE 11. FIELD TEST MATRIX FOR INDUSTRIAL AND RURAL UNPAVED ROADS (TEST REPORT 3)

Industrial category	Test site location	Vehicle type	Sampling period	No. of tests
Stone crushing	Kansas	Medium duty	December 1981	5
Sand and gravel processing	Kansas	Heavy duty	July 1982	3
Copper smelting	Arizona	Light duty	April 1982	3
Rural roads				
Crushed limestone road	Kansas	Light duty	August 1981 September 1981	6
Dirt road	Missouri	Light duty	March 1982	4
Gravel road	Colorado	Light duty	April 1982	2

TABLE 12. FIELD TEST MATRIX FOR INDUSTRIAL PAVED ROADS (TEST REPORT 3)

Industrial category	Test site location	Vehicle type	Sampling period	No. of tests
Sand and gravel processing	Colorado	Heavy duty	April 1982	3
Asphalt batching	Missouri	Medium duty	October 1981	4
Concrete batching	Missouri	Medium duty	November 1981	3
Copper smelting	Arizona	Medium duty	April 1982	3

TABLE 13. EQUIPMENT DEPLOYMENT FOR INDUSTRIAL ROAD TESTING (TEST REPORT 3)

Location	Distance from source (m)	Equipment	Intake height (m)
Upwind	5-10	Hi-vol with standard inlet	2.0
		Hi-vol with cyclone impactor	2.0
		Hi-vol with size-selective inlet	2.0
Downwind	5	MRI exposure profiler with 5 sampling heads	1.0 2.0 3.0 4.0 5.0
		Hi-vol with cyclone impactor	1.0 3.0
		Hi-vol with standard inlet	2.0
		Hi-vol with size selective inlet	2.0

TABLE 14. RANGE OF TEST CONDITIONS FOR UNPAVED INDUSTRIAL AND RURAL ROADS (TEST REPORT 3)

		Road surface properties		Mean vehicle properties			
Industrial category	No. of tests	Silt content (%, w/w)	Total loading (g/m^2)	Speed (mph)	Weight (Mg)	No. of wheels	Wind speed (m/s)
Stone crushing	5	10.5-15.6	3,360-7,190	10-15	10-14	4.4-5.6	1.1-4.2
Sand and gravel processing	3	4.1-6.0	13,000-15,200	5	27-29	12.5-16.6	1.0-2.1
Copper smelting	3	15.9-19.1	2,300-3,490	10	2.1-2.4	4.3-4.8	1.9-3.1
Rural roads							
Crushed limestone road	6	7.7-9.5	2,140-4,890	25-35	1.9-2.3	4.0	1.1-5.9
Dirt road	4	5.8-35.1	2,290-7,820	25	2.3	4.0	2.9-5.9
Gravel road	2	5.0	1,200	35-40	1.8-2.1	4.0	4.3-5.0

TABLE 15. RANGE OF TEST CONDITIONS FOR PAVED INDUSTRIAL ROADS (TEST REPORT 3)

Industrial category	No. of tests	Road surface properties: Silt content (%, w/w)	Road surface properties: Total loading (g/m²)	Mean vehicle properties: Speed (mph)	Mean vehicle properties: Weight (Mg)	Mean vehicle properties: No. of wheels	Wind speed (m/s)
Sand and gravel processing	3	6.4-7.9	755-1,480	23	39-42	11-17	1.4-3.4
Asphalt batching	4	2.6-4.6	2,820-4,200	10	3.6-3.8	6-7	2.1-2.7
Concrete batching	3	5.2-6.0	189-239	10-15	8.0	10.0	3.0-4.4
Copper smelting	3	15.4-21.7	1,220-1,840	10-20	3.1-7.0	4.2-7.4	2.2-3.9

TABLE 16. EMISSION FACTORS FOR INDUSTRIAL AND RURAL UNPAVED ROADS (TEST REPORT 3)

Industrial category	No. of tests	Mean emission factors by aerodynamic size range				
		TP	≦ 15 µm	≦ 10 µm	≦ 2.5 µm	Units
Stone crushing[a]	3	7,050	2,000	1,180	114	g/VKT
Sand and gravel[b] processing	3	4,010	1,580	1,120	296	g/VKT
Copper smelting[c]	3	2,540	725	471	89.4	g/VKT
Rural roads						
Crushed limestone road[d]	4	6,180	1,080	612	94.2	g/VKT
Dirt road[e]	4	14,000	2,220	1,190	236	g/VKT
Gravel road[f]	2	1,890	352	235	103	g/VKT

[a] Emission factors are arithmetic means of test runs AA1, AA4, and AA5 from page 37, Table 16 of test report.

[b] Emission factors are arithmetic means of test runs AF1, AF2, and AF3 from page 37, Table 16 of test report.

[c] Emission factors are arithmetic means of test runs AC1, AC2, and AC3 from page 37, Table 16 of test report.

[d] Emission factors are arithmetic means of test runs U2, U3, U4, and U5 from page 37, Table 16 of test report.

[e] Emission factors are arithmetic means of test runs AB1, AB2, AB3, and AB4 from page 37, Table 16 of test report.

[f] Emission factors are arithmetic means of test runs AE1 and AE2 from page 37, Table 16 of test report.

TABLE 17. EMISSION FACTORS FOR INDUSTRIAL PAVED ROADS (TEST REPORT 3)

Industrial category	No. of tests	Mean emission factors by aerodynamic size range				Units
		TP	≦ 15 μm	≦ 10 μm	≦ 2.5 μm	
Sand and gravel[a] processing	2	1,550	287	178	57.2	g/VKT
Asphalt batching[b]	4	516	136	83.1	36.6	g/VKT
Concrete batching[c]	2	1,340	468	330	107	g/VKT
Copper smelting[d]	3	3,160	1,130	784	171	g/VKT

[a] Emission factors are arithmetic means of test runs AD2 and AD3 from page 38, Table 17 of test report.

[b] Emission factors are arithmetic means of test runs Y1, Y2, Y3, and Y4 from page 38, Table 17 of test report.

[c] Emission factors are arithmetic means of test runs Z1 and Z2 from page 38, Table 17 of test report.

[d] Emission factors are arithmetic means of test runs AC4, AC5, and AC6 from page 38, Table 17 of test report.

3.0 MULTIPLE REGRESSION ANALYSIS

In deriving recommended AP-42 particulate emission factors for industrial paved and unpaved roads, the first step was to investigate whether size-specific emission factors correlated with source parameters and whether these correlations crossed industry lines. Such correlations would lead to predictive emission factor equations of greater reliability than single-valued mean emission factors.

Stepwise Multiple Linear Regression (MLR) was the basic method used to evaluate source parameters for possible use as correction factors in a predictive emission factor equation for a specific particle size fraction. Various stepwise routines are available as part of the Statistical Analysis System (SAS) computer package.[6] The MaxR^2 routine was employed in this study.

In essence, the MaxR^2 routine begins by selecting from the predictor pool the source parameter that is the best predictor of emission factors. In other words it selects the predictor that accounts for the highest percentage of the variation in emission factors. It changes the dependent variable values to reflect the impact of this variable. Then another variable, the one that would yield the largest increase in R^2, is added. Once this two-variable model is obtained, the variables in the model are compared to each variable not in the model. The MaxR^2 routine determines if replacing one of the variables in the model by another from the predictor pool, would increase the R^2. After comparing all possible switches, the one that produces the greatest increase in R^2 is made. The resulting model is considered the "best" two-variable model that the technique can find. The same process is repeated to find the three-variable model that yields maximum R^2, and so forth.

The steps followed in developing predictive emission factors are listed below:

1. Create a data array of all monitored independent variables with corresponding emissions measurements.

2. Input these data into the MLR program using appropriate code to transform both independent and dependent variables to their natural logarithms.

3. Evaluate the MLR output, using the classical significance tests (F-ratio, partial F-ratios) as guidelines in assessing the importance of potential correction parameters.

4. Determine the form of the emission factor equation, exclusive of the coefficient (base emission factor).

5. Assume typical values for the correction parameters.

6. Calculate adjusted emission factors at the average conditions for all the correction parameters, using the relationships established in the emission factor equation.

7. Determine the geometric mean for the adjusted data set. This mean is the base emission factor or coefficient in the emission factor equation.

8. Finalize the emission factor equation as the base emission factor times each correction parameter normalized to average conditions.

9. Determine the precision factor for the emission factor equation.

The independent variables evaluated initially as possible correction factors were silt content (%, w/w) silt loading (g/m^2), total loading (g/m^2), average vehicle speed (kph), average vehicle weight (Mg), and average number of vehicle wheels. Silt denotes that portion of loose surface dust that passes a 200 mesh screen during standard dry sieving. The notation used to define the various independent and dependent variables considered in the analysis is presented below.

e_{IP} = IP emission factor, expressed in kilograms per vehicle kilometer traveled (kg/VKT).

e_{PM-10} = PM-10 emission factor, expressed in kilograms per vehicle kilometer traveled (kg/VKT).

s = Silt content of roadway surface particulate matter (%, w/w).

sL = Silt loading of roadway surface particulate matter, expressed in grams per square meter (g/m^2).

W = Mean vehicle weight (Mg).

w = Mean number of vehicle wheels.

S = Mean vehicle speed expressed in kilometers per hour (kph).

3.1 UNPAVED ROADS

3.1.1 Analysis and Results

Based on the criteria discussed in Section 2, it was determined that three data sets (Test Reports 1 to 3) were available for the development of IP and PM-10 emission factor equations. These data sets are tabulated in Appendix A. It should be noted that each data set contains only those tests which met the quality assurance guidelines outlined in the respective test reports. A summary by industry of pertinent source characteristics is presented in Table 18.

The correlation matrix associated with MLR analysis of the entire data base (n = 49), indicated relationships that are consistent with those obtained in an earlier nonparametric analysis of the data.[7] For example, silt content and vehicle weight both exhibited reasonably strong relationships with IP and PM-10 emissions. However, the results of the MLR analysis for the entire data set were disappointing in the sense that the "best" equations accounted for only about 40% and 38% of the variation in the respective IP and PM-10 emission factors. The equations output from the SAS MaxR^2 routine, were as follows:

$$e_{IP} = 0.098\ (s)^{0.85}\ (W)^{0.32} \tag{1}$$

$$e_{PM\text{-}10} = 0.064\ (s)^{0.81}\ (W)^{0.34} \tag{2}$$

Analysis of the residuals from regression indicated that these models performed reasonably well for much of the data base, but that they did not adequately account for emissions variability in the surface mining industry. The models tended to significantly overpredict emissions from mine roads. This was thought to be due to the high degree of compaction of mine roads which are designed to handle heavy mine vehicles. In support of this reasoning, the silt loadings on the test mine roads were much lower than the loadings found in other industries (see Table 18).

Based on the above considerations, the decision was made to exclude the surface mining data set from the data base. The correlation matrix associated with the resultant final data set (n = 26) is presented in Table 19. Perhaps the most significant feature of the matrix is the fact that the silt loading parameter exhibits stronger correlation with the IP and PM-10 emission factors than does silt content, the road surface parameter used in MRI's suspended particulate (SP) emission factor equation.[7] Examination of the matrix also suggests that the influence of vehicle type on emissions, as parameterized by mean weight and wheels, increases when considering smaller particle size fractions.

It should also be noted that the weak simple correlations between vehicle speed and emissions imply that speed is not a primary influence on emissions variability. However, as indicated below, speed and emissions do exhibit substantial partial correlation after taking into account the influences of roadway surface loading and vehicle type.

The "best" MLR equations, as determined from the SAS MaxR^2 output, were as follows:

$$e_{IP} = 0.00097\ (sL)^{0.68}\ (W)^{0.34}\ (S)^{0.84} \tag{3}$$

$$e_{PM\text{-}10} = 0.00059\ (sL)^{0.65}\ (W)^{0.44}\ (S)^{0.75} \tag{4}$$

These equations explain 72% and 73% of the variation in IP and PM-10 emissions, respectively.

TABLE 18. GEOMETRIC MEAN SOURCE PARAMETERS FOR UNPAVED INDUSTRIAL ROADS

Industry	No. of tests	Road surface parameters: Silt Content (%, w/w)	Road surface parameters: Silt Loading (g/m^2)	Vehicle parameters: Weight (Mg)	Vehicle parameters: Speed (kph)	Vehicle parameters: No. of wheels
Surface coal mining[1]						
• Haul trucks	14	7.9	27.4	70	41	7.9
• Light/medium duty vehicles	9	6.3	12.9	2.0	54	4.0
Iron and steel production[2]	7	8.6	395	34	27	6.9
Various industries[3]						
• Industrial roads	9	10.6	607	9.2	13	6.9
• Rural roads	10	9.8	255	2.1	46	4.0
	49					

TABLE 19. CORRELATION MATRIX FOR "FINAL" UNPAVED ROAD DATA BASE (n = 26)

	IP emission factor	PM-10 emission factor	Silt	Silt loading	Total loading	Vehicle weight	Vehicle wheels	Vehicle speed
IP Emission factor	1.0	0.97	0.42	0.67	0.51	0.41	0.24	-0.05
PM-10 Emission factor		1.0	0.33	0.64	0.54	0.52	0.33	-0.12
Silt			1.0	0.51	-0.11	-0.29	-0.42	0.11
Silt loading				1.0	0.80	0.20	0.31	-0.40
Total loading					1.0	0.52	0.66	-0.55
Vehicle weight						1.0	0.78	-0.54
Vehicle wheels							1.0	-0.73
Vehicle speed								1.0

Equations 5 and 6 present the comparable predictive emission factor equations normalized to typical values of the correction parameters.

$$e_{IP} = 1.22 \left(\frac{sL}{400}\right)^{0.7} \left(\frac{W}{7}\right)^{0.4} \left(\frac{S}{24}\right)^{0.8} \quad (5)$$

$$e_{PM\text{-}10} = 0.766 \left(\frac{sL}{400}\right)^{0.7} \left(\frac{W}{7}\right)^{0.4} \left(\frac{S}{24}\right)^{0.8} \quad (6)$$

The normalization procedure consists of steps 5-9 as outlined at the beginning of this section. It should be noted that previous MRI research indicates that very little predictive accuracy is lost by rounding the exponents to one figure. The validity of this procedure was verified for the above equations.

Table 20 presents the predicted versus observed IP and PM-10 emission factors, and provides a comparative statistic--the ratio of predicted to actual emission factors for each test. As indicated, the equations generally provide very acceptable estimates of the actual emission factors. In the case of the IP equation, all 26 predictions are within a factor of 2.5 of the actual emissions; for the PM-10 equation, 25 of the 26 predictions are within a factor of 2.5.

It should also be noted that a nonparametric analysis of the residuals from the MLR indicated that the equations do not show any systematic predictive bias with respect to industry category.

3.1.2 Comparative Evaluation

Equations 5 and 6 predict the data set with precision factors of 1.60 and 1.64 for the IP and PM-10 emissions, respectively. The precision factor is defined such that the 68% confidence interval for a predicted value (P) extends from P/f to Pf. The precision factor is determined by exponentiating the standard deviation of the differences (standard error of the estimate) between the natural logarithms of the predicted and actual emission factors. The precision factor may be interpreted as a measure of the "average" error in predicting emissions from the regression equation. The effective outer bounds of predictability are determined by exponentiating twice the standard error of the estimate. The resultant estimates of predictive accuracy, in this case 2.55 and 2.68 for IP and PM-10 emission, respectively, then encompass approximately 95% of the predictions.

As a basis for evaluating the emission factor equations developed in this study, Table 21 presents three alternative models that may be used to represent the IP and PM-10 emission factor data base. The first alternative (Model 2) consists of MRI's suspended particulate (SP) emission factor equation (based on particles less than 30 µm Stokes diameter) with adjustments to the coefficient to approximate IP and PM-10 emission factors.[5] It should be noted that the modified coefficients were developed from limited particle sizing information that is not of the same quality as the measurements comprising the study data base analyzed in this section. Limitations

TABLE 20. PREDICTED VERSUS ACTUAL IP AND PM-10 EMISSION FACTORS FOR UNPAVED ROADS

Industry category	Run ID	IP emission factor (kg/VKT) predicted	IP emission factor (kg/VKT) actual	IP ratio[a]	PM-10 emission factor (kg/VKT) predicted	PM-10 emission factor (kg/VKT) actual	PM-10 ratio[a]
Copper smelting							
	AC-1	0.667	0.716	0.93	0.373	0.460	0.81
	AC-2	0.608	0.623	0.98	0.338	0.412	0.82
	AC-3	0.806	0.838	0.96	0.445	0.539	0.84
Iron and steel production							
	F-68	4.27	9.45	0.45	2.98	7.28	0.41
	F-70	3.91	9.25	0.42	2.98	7.01	0.42
	AG-2	3.71	2.11	1.76	2.61	1.56	1.67
	AG-3	3.52	1.49	2.36	2.51	1.08	2.32
	AJ-1	0.906	1.45	0.62	0.693	1.18	0.59
	AJ-2	0.825	1.01	0.84	0.626	0.739	0.85
	AJ-3	1.15	0.829	1.39	0.866	0.603	1.44
Stone quarrying and processing							
	AA-1	1.59	0.902	1.76	1.05	0.606	1.73
	AA-4	1.93	2.38	0.81	1.30	1.27	1.02
	AA-5	1.88	2.73	0.69	1.26	1.64	0.77
Sand and gravel processing							
	AF-1	0.960	1.12	0.86	0.694	0.733	0.95
	AF-2	1.35	0.945	1.42	0.965	0.660	1.46
	AF-3	2.11	2.67	0.79	1.52	1.96	0.78
Rural roads							
	U-2	1.75	1.41	1.24	0.965	0.871	1.11
	U-3	1.21	0.894	1.35	0.667	0.494	1.35
	U-4	0.719	1.00	0.72	0.397	0.527	0.75
	U-5	0.956	1.02	0.94	0.537	0.556	0.96
	AE-1	0.495	0.310	1.60	0.276	0.201	1.37
	AE-2	0.425	0.392	1.08	0.233	0.270	0.86
	AB-1	5.06	5.98	0.85	2.84	3.41	0.83
	AB-2	1.27	0.919	1.38	0.716	0.268	2.67
	AB-3	0.607	1.18	0.51	0.341	0.561	0.61
	AB-4	1.34	0.798	1.68	0.751	0.524	1.43

[a] Predicted divided by actual.

TABLE 21. COMPARISON OF UNPAVED ROAD MODEL PERFORMANCE FOR IP AND PM-10 EMISSION FACTORS

Model No.	Model origin	Model	Precision factor[a] PM-10	Precision factor[a] IP
1	This study	$e_{IP} = 1.22 \left(\frac{sL}{400}\right)^{0.7} \left(\frac{W}{7}\right)^{0.4} \left(\frac{S}{24}\right)^{0.8}$		1.60
		$e_{PM\text{-}10} = 0.766 \left(\frac{sL}{400}\right)^{0.7} \left(\frac{W}{7}\right)^{0.4} \left(\frac{S}{24}\right)^{0.8}$	1.64	
2	Modification to MRI SP equation (coefficient only)	$e_{IP} = 0.95 \left(\frac{s}{12}\right) \left(\frac{S}{48}\right) \left(\frac{W}{3}\right)^{0.7} \left(\frac{w}{4}\right)^{0.5}$		2.04
		$e_{PM\text{-}10} = 0.745 \left(\frac{s}{12}\right) \left(\frac{S}{48}\right) \left(\frac{W}{3}\right)^{0.7} \left(\frac{w}{4}\right)^{0.5}$	1.93	
3	Modification to MRI SP equation (coefficient and exponents)	$e_{IP} = 1.34 \left(\frac{s}{10}\right) \left(\frac{W}{7}\right)^{0.3} \left(\frac{w}{6}\right)^{1.2} \left(\frac{S}{24}\right)^{0.8}$		1.76
		$e_{PM\text{-}10} = 0.847 \left(\frac{s}{10}\right) \left(\frac{W}{7}\right)^{0.3} {\frac{w}{6}}^{1.2} \left(\frac{S}{24}\right)^{0.8}$	1.81	
4	Single-valued emission factor	$e_{IP} = \bar{x}_g = 1.29$		2.28
		$e_{PM\text{-}10} = \bar{x}_g = 0.814$	2.41	

[a] Represents the interval encompassing 68% of the predicted values.

e_{IP}	= IP emissions	kg/VKT
$e_{PM\text{-}10}$	= PM-10 emissions	Kg/VKT
sL	= Road surface silt loading	g/m^2
S	= Average vehicle speed	kph
s	= Silt content of road surface material	%, w/w
W	= Average vehicle weight	Mg
w	= Average number of wheels per vehicle	--

notwithstanding, these equations still predict the IP and PM-10 emissions more accurately than do single-value emission factors.

The second alternative (Model 3) retains the same form as the MRI SP equation but with adjustments to both the coefficient and the exponents of the correction terms based on regression analysis against the study data base. The fact that these equations provide reasonably accurate predictions suggests that the original SP model formulation is also valid for smaller particle size fractions. It reduces the uncertainty in estimating emissions considerably over the use of single-value emission factors. In addition to indicating slightly different relationships between correction parameters and particulate emissions, the changes in exponents for the vehicle parameters in the MRI SP equation may partially reflect the greater diversity in traffic characteristics present in the study data base.

Based on a comparison of precision factors, it is apparent that the model incorporating silt loading to characterize the amount of surface material available for entrainment, provides better estimates of IP and PM-10 emission factors than do the alternative models that use silt percent.

3.1.3 Extension of the Predictive Equations to FP Emissions

The FP emission factor equations were developed using a slightly different approach than that used in the case of the IP and PM-10 equation. Rather than develop estimates of the model exponents and coefficients directly through MLR, constant multipliers--the geometric mean ratios of FP/IP and FP/PM-10 emission factors--were computed. These were then applied to the various IP and PM-10 emission factor equations. The resultant models are presented in Table 22.

For the unpaved road situation, Model Nos. 1/IP and 3/IP represent the IP silt loading and silt models scaled by the geometric mean ratio of FP/IP emission factors to approximate FP emissions. Similarly Model Nos. 1/PM-10 and 3/PM-10 are scaled by the geometric mean FP/PM-10 ratio. As indicated, the models scaled by the FP/PM-10 ratio provide better estimates of FP emission factors than do the corresponding models scaled by the FP/IP ratio; all are considerably better than the single-value factor. Perhaps more importantly, the silt model (3/PM-10) provides better estimates of FP emissions than does the silt loading model (1/PM-10).

3.1.4 Applicability

Recommendations for incorporation of unpaved road emission factors into AP-42 must balance the reliability of each candidate factor against the relative ease with which the factor can be used for emission inventory purposes. Although the emission factor equations presented above have greater precision than the single-valued counterparts, the equations require determination of suitable input parameters. An important consideration in deciding which set of size-specific emission factor equations for unpaved roads is most appropriate, centers on the reproducibility of the surface characterization parameters for situations in which a potential user intends to collect independent observations to apply in the predictive equation.

TABLE 22. COMPARISON OF UNPAVED ROAD MODEL PERFORMANCE FOR FP EMISSION FACTORS

Model origin[a]	Model[a]	Precision factor[b]
1/IP	$e_{FP} = 0.150 \left(\frac{sL}{400}\right)^{0.7} \left(\frac{W}{7}\right)^{0.4} \left(\frac{S}{24}\right)^{0.8}$	2.27
1/PM-10	$e_{FP} = 0.161 \left(\frac{sL}{400}\right)^{0.7} \left(\frac{W}{7}\right)^{0.4} \left(\frac{S}{24}\right)^{0.8}$	2.21
3/IP	$e_{FP} = 0.165 \left(\frac{s}{10}\right) \left(\frac{W}{7}\right)^{0.3} \left(\frac{w}{6}\right)^{1.2} \left(\frac{S}{24}\right)^{0.8}$	2.14
3/PM-10	$e_{FP} = 0.176 \left(\frac{s}{10}\right) \left(\frac{W}{7}\right)^{0.3} \left(\frac{w}{6}\right)^{1.2} \left(\frac{S}{24}\right)^{0.8}$	2.05
Single-valued emission factor	$e_{FP} = \bar{x}_g = 0.159$	2.71

[a] See Table 21 for starting models and definition of symbols.

[b] Represents the interval encompassing 68% of the predicted values.

Recognizing that any surface characterization measurement requires some judgment on the part of the sampling personnel, it is felt that silt percent is more easily quantified than silt loading, primarily because it is not as sensitive to variations in sampling procedure. In this context, it should be noted that reproducibility comparisons performed as part of an internal MRI QA program indicate that co-located silt measurements are on the average within 15%, while silt loading measurements are normally within approximately 20%. Though based on limited data, these comparisons are generally consistent with previous experience which indicates that the collection of a silt loading measurement does not typically pose any additional problems (beyond that for silt content) except for instances in which there is no well developed hard pan underlying the loose road surface material.

The models incorporating silt percent may also be preferable to those using silt loading for some applications in which no independent measurements of the parameters will be made. This follows from the fact that there is more information currently available on the expected range of percent silt for industrial roads. For example, some industrial facilities may already have developed emission inventories based on measured silt content values. To provide a comparable amount of information for the silt loading parameter, it would be necessary to perform additional road surface characterization work.

For these reasons the better of the two models incorporating silt percent (Model 3) is recommended over the model incorporating silt loading (Model 1) for the IP and PM-10 particle size fractions. For the FP size fraction, the recommended model is 3/PM-10 which incorporates silt content and is also the most accurate model.

3.2 PAVED ROADS

3.2.1 Analysis and Results

Applying the criteria of Section 2, it was determined that two data sets (Test Reports 2 and 3) were available for the development of paved road IP and PM-10 emission factor equations. These included test data collected within the following industry categories: iron and steel production; copper smelting; concrete batching; and sand and gravel processing. One test was deleted from the former data set due to incomplete collection of the source characterization parameters; two tests were dropped from the latter set because they did not meet the QA guidelines for acceptable wind direction. After deletion of these tests, the data base consisted of 21 tests, as tabulated in Appendix A. The independent variables considered initially as possible correction factors were the same as those in the unpaved roads analyses.

Prior to the analysis, it was recognized that the measured correction factors would probably not account for a substantial portion of the variability in IP and PM-10 emissions. One of the major reasons for this is that any direct contribution of particulate from vehicle underbodies, exposed haulage loads (i.e., aggregate materials), or vehicle exhaust is not parameterized by the available correction factors. Similarly, the influence of emissions from unpaved shoulders generated by the wakes of large vehicles is not considered in the correction parameters. Because paved road emissions are generally much lower than those from unpaved roads, the influence of these sources is potentially greater in paved road emission factors. It should be noted that previously published equations for paved road emissions have used augmentation or judgment factors in an attempt to partially account for the influence of these sources.[7,8]

The initial correlation matrix for the paved road data base is presented in Table 23. As indicated, the correlations between emissions and the correction parameters are generally low, with the road surface characterization parameters--silt and silt loading--exhibiting the strongest relationships ($r \cong 0.30$) with emissions.

Plots of the simple linear relationships between road surface loading parameters and emission factors were constructed to determine whether the low correlations could be attributed to a particular test series or set of source conditions. One plot, IP emissions versus silt loading, is shown in Figure 1. It suggests that much of the "scatter" in the relationship is associated with four tests conducted at an asphalt batching facility. The roads at this facility had relatively heavy silt loadings yet produced relatively low emissions. This situation is not consistent with either previous MRI research or the remainder of the tests in the data base, which tend to indicate a positive relationship between loading and emissions. This apparently incongruous result may be linked to the fact that the roads were traveled by predominantly light-duty vehicles; the mean vehicle weight for each test was less than 4 Mg. One of the tests from the iron and steel control efficiency program also deviated considerably from the positive relationship between loading and emissions. In this case, the vehicle mix included predominantly light-duty traffic (~ 80% pick-up trucks and cars), with a mean vehicle speed considerably higher than that of the other tests in the data base.

Based on these considerations, the decision was made to partition the data base into two subsets. Comparative statistics for each subset are provided in Table 24. As indicated, Subset 1 includes tests for relatively heavily loaded roads traveled by predominantly light-duty vehicles (i.e., mean vehicle weight < 4 Mg). In contrast, Subset 2 includes tests for roads with generally moderate surface loadings and vehicle mixes that can be considered more typical of industrial facilities (i.e., mean vehicle weight ~ 16 Mg). It is also important to note that the mean emission factors (IP and PM-10) for Subset 1 are less than 50% of those of Subset 2.

The correlation matrix based on Subset 2 is presented in Table 25. It shows that for this data set the relationship between roadway surface loadings and emissions is reasonably strong. The inverse relationships between emissions, and vehicle weight and speed cannot be explained by current knowledge of the physical mechanisms responsible for the generation of fugitive emissions. For this reason, the latter correlations should not be construed as being applicable to the population of industrial paved roads. Rather, they should be interpreted as products of this specific sample.

TABLE 23. CORRELATION MATRIX FOR "INITIAL" PAVED ROAD DATA SET (n = 21)

	IP emission factor	PM-10 emission factor	Silt	Silt loading	Total loading	Vehicle weight	Vehicle wheels	Vehicle speed
IP Emission factor	1.0	0.99	0.32	0.28	0.12	-0.02	0.18	0.16
PM-10 Emission factor		1.0	0.37	0.19	0.02	0.01	0.12	0.19
Silt			1.0	-0.22	-0.56	0.42	-0.36	0.12
Silt loading				1.0	0.93	-0.51	0.11	-0.24
Total loading					1.0	-0.59	0.22	-0.35
Vehicle weight						1.0	0.45	0.62
Vehicle wheels							1.0	0.04
Vehicle speed								1.0

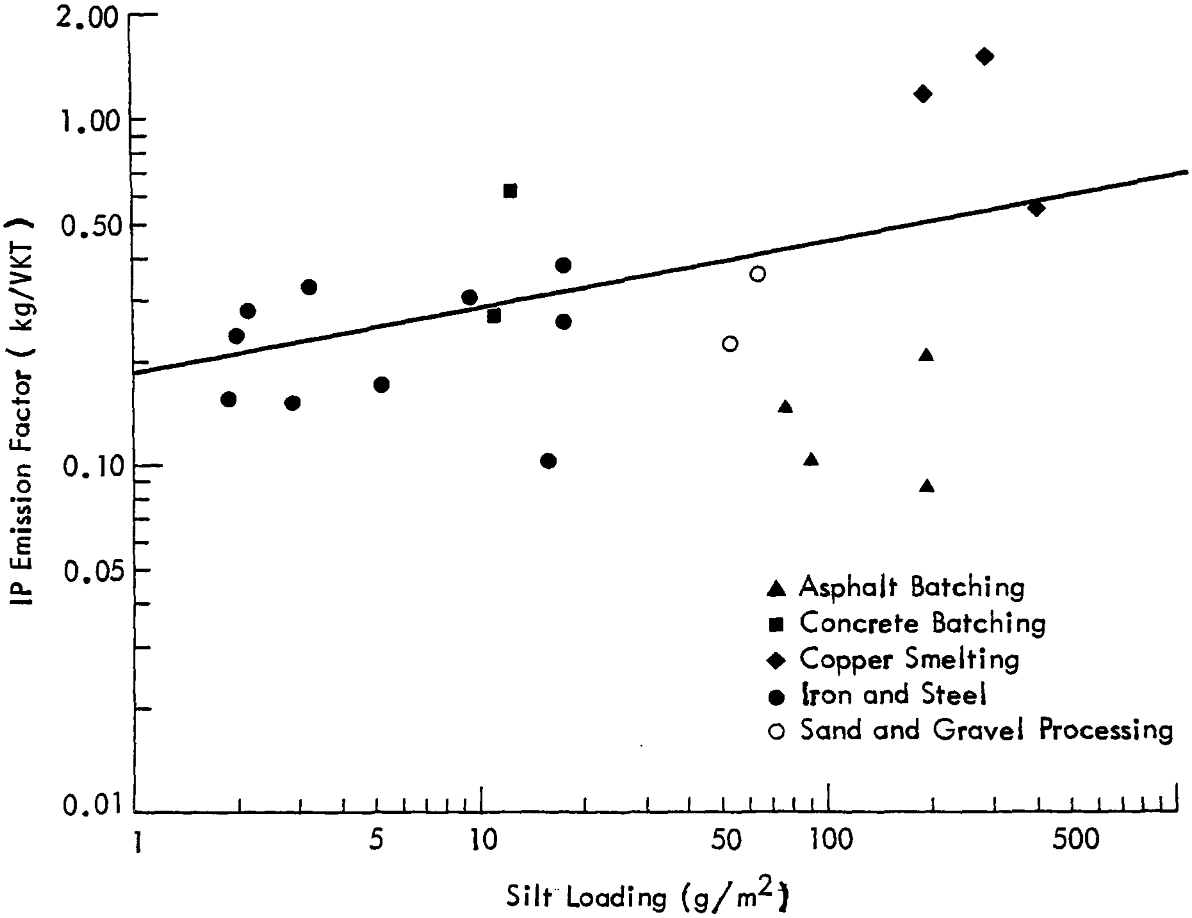

Figure 1. IP emission factor versus silt loading for industrial paved roads.

TABLE 24. PAVED ROADS--COMPARISON OF EMISSION FACTORS AND SOURCE CHARACTERIZATION PARAMETERS BY DATA SUBSET[a]

Data subset description	n	IP emission factor (kg/VKT)		PM-10 emission factor (kg/VKT)		Silt loading (g/m^2)		Vehicle weight (Mg)		Vehicle speed (kph)	
		$\bar{x}_g$	σ_g	$\bar{x}_g$	σ_g	$\bar{x}_g$	σ_g	$\bar{x}_g$	σ_g	$\bar{x}_g$	σ_g
Subset 1: Light-duty traffic[b]	6	0.158	2.03	0.110	1.97	108	3.08	3.9	1.26	22	1.67
Subset 2: Medium- and heavy-duty traffic[c]	15	0.336	2.00	0.247	1.95	12.5	5.09	15.6	1.96	27	1.52

[a] All statistics are geometric means and standard geometric deviations.

[b] Includes four tests at asphalt batching facility, one test copper smelter, one test iron and steel plant.

[c] Includes nine tests at iron and steel plants, two tests each at copper smelter, concrete batching plant, and sand and gravel processing plant.

TABLE 25. CORRELATION MATRIX FOR "FINAL" PAVED ROAD DATA SET (n = 15)

	IP emission factor	PM-10 emission factor	Silt	Silt loading	Total loading	Vehicle weight	Vehicle wheels	Vehicle speed
IP Emission factor	1.0	0.99	0.09	0.77	0.71	-0.53	0.10	-0.47
PM-10 Emission factor		1.0	0.14	0.70	0.63	-0.58	-0.01	-0.50
Silt			1.0	0.08	-0.26	0.09	-0.59	0.38
Silt loading				1.0	0.94	-0.09	0.49	0.03
Total loading					1.0	-0.12	0.67	-0.17
Vehicle weight						1.0	0.38	0.71
Vehicle wheels							1.0	0.01
Vehicle speed								1.0

The "best" MLR equations as determined from the SAS MaxR^2 output, were as follows:

$$e_{IP} = 0.148\ (sL)^{0.32} \tag{7}$$

$$e_{PM\text{-}10} = 0.120\ (sL)^{0.29} \tag{8}$$

These equations explain 59% and 49% of the variation in IP and PM-10 emission factors, respectively. It should be noted that though a greater percentage of the emissions variability could be accounted for by including either vehicle weight or speed as a second correction factor, the resulting equation would probably not provide stable emission factor estimates in independent applications.

Equations 9 and 10 present the comparable predictive emission factor equations normalized to the typical value for silt loading.

$$e_{IP} = 0.322\ \left(\frac{sL}{12}\right)^{0.3} \tag{9}$$

$$e_{PM\text{-}10} = 0.244\ \left(\frac{sL}{12}\right)^{0.3} \tag{10}$$

Table 26 presents (for Equations 9 and 10) the predicted versus actual IP and PM-10 emission factors as well as the ratio of predicted to actual emission factors for each test. As indicated, the equations generally provide very acceptable estimates of the actual emission factors. In the case of the IP equation, all 15 of the predictions are within a factor of 2.5; for the PM-10 equation, 14 of the 15 predictions are within a factor of 2.5.

3.2.2 Comparative Evaluation

The emission factor equations, as developed above, predict the data set with precision factors of 1.59 and 1.64 for IP and PM-10 emissions, respectively. Table 27 presents alternative models that may be used to represent the emission factor data base. It is clear that the equations developed in this study predict the IP and PM-10 emissions more accurately than do single-value emission factors. The remaining alternative consists of MRI's suspended particulate (SP) emission factor equation (< 30 μm Stokes diameter) with adjustments to the original coefficient to approximate IP and PM-10 emission factors.[5] As indicated, this model does not provide acceptable prediction of the new emission factor data base.

The relatively poor performance of the scaled SP model may be attributed largely to two factors. First, the proportionality constants probably introduce significant error in the emission factor estimates, because as noted in connection with the unpaved road equation, these constants are based on limited particle sizing information. Second and more importantly, the range of source conditions that provided the basis for the SP equation, is much smaller than that of the new data base. This is reflected in the fact that the surface loading term in the SP equation is raised to the first power, while the newly developed equations indicate a much lower dependence

TABLE 26. PREDICTED VERSUS ACTUAL IP AND PM-10 EMISSION FACTORS FOR PAVED ROADS

Industry category	Run ID	IP emission factor (kg/VKT) predicted	IP emission factor (kg/VKT) actual	IP ratio[a]	PM-10 emission factor (kg/VKT) predicted	PM-10 emission factor (kg/VKT) actual	PM-10 ratio[a]
Copper smelting							
	AC-4	0.860	1.57	0.55	0.632	1.09	0.58
	AC-5	0.757	1.25	0.60	0.556	0.883	0.63
Iron and steel production							
	F-34	0.214	0.151	1.42	0.158	0.117	1.35
	F-35	0.194	0.239	0.81	0.142	0.184	0.77
	F-45	0.257	0.172	1.49	0.189	0.132	1.43
	F-61	0.372	0.381	0.98	0.273	0.288	0.95
	F-62	0.372	0.262	1.42	0.273	0.197	1.38
	B-57	0.191	0.156	1.22	0.140	0.121	1.16
	B-58	0.310	0.305	1.02	0.228	0.229	1.00
	B-59	0.198	0.280	0.71	0.145	0.233	0.62
	B-60	0.223	0.333	0.67	0.164	0.273	0.60
Concrete batching							
	Z-1	0.326	0.275	1.18	0.240	0.197	1.22
	Z-2	0.335	0.660	0.51	0.246	0.460	0.54
Sand and gravel processing							
	AD-2	0.548	0.355	1.54	0.403	0.212	1.90
	AD-3	0.518	0.221	2.34	0.381	0.145	2.63

[a] Predicted divided by actual.

TABLE 27. COMPARISON OF PAVED ROAD MODEL PERFORMANCE FOR IP AND PM-10 EMISSION FACTORS

Model origin	Model	Precision factor[a] PM-10	Precision factor[a] IP
This study (Equations 9 and 10)	$e_{IP} = 0.332 \left(\frac{sL}{12}\right)^{0.3}$		1.59
	$e_{PM-10} = 0.244 \left(\frac{sL}{12}\right)^{0.3}$	1.64	
Modification to MRI SP equation	$e_{IP} = 0.058\ I \left(\frac{4}{n}\right)\left(\frac{s}{10}\right)\left(\frac{L}{1000}\right)\left(\frac{W}{3}\right)^{0.7}$		2.02
	$e_{PM-10} = 0.046\ I \left(\frac{4}{n}\right)\left(\frac{s}{10}\right)\left(\frac{L}{1000}\right)\left(\frac{W}{3}\right)^{0.7}$	2.28	
Single-valued emission factor	$e_{IP} = \bar{x}_g = 0.336$		1.99
	$e_{PM-10} = \bar{x}_g = 0.247$	1.95	

[a] Represents the interval encompassing 68% of the predicted values.

e_{IP}	=	IP emissions	kg/VKT
e_{PM-10}	=	PM-10 emissions	kg/VKT
I	=	Industrial road augmentation factor	--
L	=	Surface dust loading on traveled portion of road	kg/km
n	=	Number of traffic lanes	--
sL	=	Road surface silt loading	g/m^2
s	=	Silt content of road surface material	%, w/w
w	=	Average number of wheels per vehicle	--
W	=	Average vehicle weight	Mg

of emissions on silt loading (0.3). In this context it should be noted that the scaled SP equation consistently overpredicts the IP and PM-10 emission factors of the new data set.

Table 28 provides a summary of selected source characterization parameters for a number of paved road data sets. It clearly shows the differences in source conditions between the SP data set, and that used in developing the new equation. For example, the mean road surface silt loading for the SP data set is less than 25% of that for the new data set. Similarly, the mean vehicle weight for the former data set is only about one-third of that of the latter data set. In addition, it should be noted that the vehicle weight range for the new data set is about four times greater than that used in developing the SP equation.

3.2.3 Extension of the Predictive Equations to FP Emissions

Using the same approach described in Section 3.1.3 for unpaved roads, FP emission factor equations were developed for paved roads. The resultant models are shown in Table 29.

Examination of the precision factors for the paved road models suggests that little predictive accuracy would be gained by using the silt loading model in preference to the single-value factor. However, it should be noted that the precision factor associated with the single-value indicates that there is not a great deal of inherent variability in paved road FP emissions.

3.2.4 Applicability

Partitioning the data base into two subsets as explained in Section 3.2.2, restricts the applicability of the newly developed equations to roads traveled by predominantly medium- and heavy-duty vehicles, at mean speeds less than 48 kph (30 mph). As guidance, it is recommended that use of the equations be limited to roads for which the mean vehicle weights (based on all traffic) fall within the range of 6 to 42 Mg.

For roads that are traveled by predominantly light-duty traffic, the single-value emission factors represented by the geometric mean emission factors for Subset 1, should provide reasonable upper limits for IP and PM-10 emissions. The geometric mean emission factors developed from the SP data set, probably represent reasonable lower limits for industrial paved road emissions. As indicated in Table 30, these mean emission factors developed from the SP data set are approximately 50% of the mean emissions factors for the new data set.

TABLE 28. PAVED ROADS--COMPARISON OF SOURCE CHARACTERISTICS BY DATA SET[a]

Data base description	n	Silt loading (g/m²) $\bar{x}_g$	σ_g	Range	Vehicle weight (Mg) $\bar{x}_g$	σ_g	Range
Data set for SP Equation	13	2.96	6.00	2.62-124	5.0	1.64	3-12
New data - Subset 2	15	12.5	5.09	1.91-287	15.6	1.96	5.7-42
New data - Subset 1	6	108	3.08	15.4-400	3.9	1.08	3.1-5.1

[a] Reported values are geometric means and standard geometric deviations.

TABLE 29. COMPARISON OF PAVED ROAD MODEL PERFORMANCE FOR FP EMISSION FACTORS

Model origin[a]	Model[a]	Precision factor[b]
Equation	$e_{FP} = 0.0795 \left(\frac{sL}{12}\right)^{0.3}$	1.66
Single-valued emission factor	$e_{FP} = \bar{x}g = 0.0788$	1.75

[a] See Table 27 for starting models and definition of symbols.

[b] Represents the interval encompassing 68% of the predicted values.

TABLE 30. PAVED ROADS--COMPARISON OF SINGLE VALUE EMISSION FACTORS

Data Base Description	N	Emission factors (kg/VKT)	
		IP	PM-10
SP Equation data set	13	0.0781	0.0622
New data - Subset 1	6	0.158	0.110
Ratio[a]		0.49	0.56

[a] Ratio of SP equation data set emission factor to new data Subset 1 emission factor.

4.0 PROPOSED AP-42 SECTIONS

Appendix B and Appendix C present the proposed revisions to the AP-42 sections for unpaved roads (Section 11.2.1) and for industrial paved roads (Section 11.2.6), respectively. Updates for these sections were recently developed by MRI[5] and are included in Supplement 14 to AP-42. To the extent possible, the format used in Supplement 14 was retained for the purpose of incorporating the size-specific particulate emission factors developed in this document.

Based on the rating quality scheme developed in the earlier study,[5] all of the recommended size-specific particulate emission factors are A-rated based on two criteria. First, the test data were developed from well documented sound methodologies. Second, a total of at least six tests were performed at two or more plant sites.

With regard to unpaved road emission factors for western surface coal mining, it is recommended that the new AP-42 Section 8.24 be used without modification. That section, which was developed in the earlier study,[5] contains predictive emission factor equations for specified particle size fractions (see Table 6).

Exposure profiling was the primary test method used for collecting the emission data reported in the source category report. Particle size distributions were determined using high-volume cascade impactors with cyclone preseparators. The manufacturer reported a 50% cut point of 11 microns for the cyclone preseparator at the flow conditions used. However, the cyclone preseparator was calibrated by Midwest Research Institute, and it was determined that the 50% cut point was actually 15 microns.

Although most of the test results reported in the source category report were calculated using 11 microns as the cut point, these results were recalculated for the AP-42 section using a 15 micron cutpoint. This change has made the particle size multipliers used in the emission factor equations in the AP-42 section slightly different from those presented with the same equations in the source category report.

5.0 REFERENCES

1. K. Axetell, Jr. and C. Cowherd, Jr., Improved Emission Factors for Fugitive Dust from Western Surface Coal Mining Sources, Volumes 1 and 2, EPA Contract No. 68-03-2924, U.S. Environmental Protection Agency, Cincinnati, Ohio, July 1981.

2. T. Cuscino, 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.

3. J. Patrick Reider, Size Specific Particulate Emission Factors for Uncontrolled Industrial and Rural Roads, Draft Final Report, EPA Contract No. 68-02-3158, Technical Directive No. 12, Midwest Research Institute, Kansas City, Missouri, January 1983.

4. Wedding, J. B., "Ambient Aerosol Sampling: History, Present Thinking, and a Proposed Inlet for Inhalable Particulate Matter," prepared at the Air Pollution Control Association Specialty Conference, Seattle, Washington, April 1980.

5. C. Cowherd and B. Peterman, AP-42 Update, Section 11.2, Fugitive Dust Sources, EPA-450/4-83-010, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, March 1983.

6. Statistical Analysis System - SAS User's Guide, SAS Institute, Inc., Raleigh, North Carolina, 1979.

7. C. Cowherd, et al., Iron and Steel Plant Open Source Fugitive Emission Evaluation, EPA-600/2-79-103, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, May 1979.

8. J. A. Maser and C. L. Norton, "Uncontrolled and Controlled Emissions from Nontraditional Sources in a Coke and Iron Plant: A Field Study Analysis," presented at the Air Pollution Control Association Specialty Conference on Air Pollution Control in the Iron and Steel Industry, Chicago, Illinois, April 1981.

APPENDIX A

TEST DATA USED IN REGRESSION ANALYSIS

TABLE A-1. INPUT DATA FOR DEVELOPMENT OF SIZE-SPECIFIC EMISSION FACTOR EQUATIONS FOR UNPAVED INDUSTRIAL AND RURAL ROADS

Industry category	Run ID	Emission factors			Source characterization parameters					
		IP (kg/VKT)	PM-10 (kg/VKT)	FP (kg/VKT)	Silt (%, w/w)	Silt loading (g/m^2)	Vehicle weight (Mg)	Total loading (g/m^2)	Vehicle wheels	Vehicle speed (kph)
Copper smelting										
	AC-1	0.716	0.460	0.0798	19.1	440	2.2	2,300	4.8	16
	AC-2	0.623	0.412	0.0837	15.9	394	2.1	2,480	4.0	16
	AC-3	0.837	0.538	0.104	16.0	558	2.4	3,490	4.3	16
Iron and steel production										
	F-68	9.45	7.28	2.18	14.0	1,100	20	7,860	5.9	32
	F-70	9.25	7.01	2.40	16.0	667	48	4,170	10	32
	AG-2	2.11	1.56	0.280	5.8	1,050	22	18,100	7.3	27
	AG-3	1.49	1.08	0.137	7.2	1,020	25	14,200	6.6	25
	AJ-1	1.45	1.18	0.258	6.3	114	49	1,810	6.0	24
	AJ-2	1.01	0.739	0.206	7.4	101	47	1,370	6.0	24
	AJ-3	0.829	0.603	0.140	7.7	165	45	2,150	7.1	24
Stone quarrying and processing										
	AA-1	0.902	0.606	0.0809	13.7	484	11	3,530	5.0	24
	AA-4	2.38	1.27	0.110	15.6	911	14	5,840	5.6	16
	AA-5	2.73	1.64	0.151	15.6	911	13	5,840	5.0	16
Sand and gravel processing										
	AF-1	1.12	0.733	0.176	4.2	545	29	13,000	14.5	8
	AF-2	0.944	0.660	0.175	6.0	908	27	15,100	16.6	8
	AF-3	2.67	1.96	0.539	4.1	583	27	14,200	12.5	8
Rural roads										
	U-2	1.41	0.871	0.115	9.1	445	1.9	4,890	4.0	56
	U-3	0.894	0.493	0.0857	7.7	262	1.9	3,400	4.0	56
	U-4	1.01	0.527	0.0913	8.6	184	1.9	2,140	4.0	40
	U-5	1.02	0.555	0.0846	9.2	255	2.3	2,770	4.0	40
	AE-1	0.310	0.201	0.0708	5.0	60.0	2.1	1,210	4.0	64
	AE-2	0.392	0.270	0.136	5.0	60.0	1.8	1,210	4.0	56
	AB-1	5.98	3.41	0.699	35.1	2,740	2.3	7,820	4.0	40
	AB-2	0.919	0.268	0.0253	16.7	414	2.3	2,480	4.0	40
	AB-3	1.18	0.561	0.0792	16.8	384	2.3	2,280	4.0	40
	AB-4	0.798	0.524	0.143	5.8	133	2.3	2,290	4.0	40

TABLE A-2. INPUT DATA FOR DEVELOPMENT OF SIZE-SPECIFIC EMISSION FACTOR EQUATIONS FOR PAVED INDUSTRIAL ROADS

Industry category	Run ID	Emission factors: IP (kg/VKT)	Emission factors: PM-10 (kg/VKT)	Emission factors: FP (kg/VKT)	Source characterization parameters: Silt (%, w/w)	Source characterization parameters: Silt loading (g/m²)	Source characterization parameters: Total loading (g/m²)	Source characterization parameters: Vehicle weight (Mg)	Source characterization parameters: Vehicle wheels	Source characterization parameters: Vehicle speed (kph)
<u>Subset 2 - Medium- and Heavy-Duty Vehicles</u>										
Copper smelting										
	AC-4	1.57	1.09	0.239	19.8	287	1,450	5.7	7.4	16
	AC-5	1.25	0.882	0.202	15.4	188	1,220	7.0	6.2	24
Iron and steel production										
	F-34	0.151	0.117	0.0414	16.0	2.80	17.7	25	6.1	43
	F-35	0.239	0.184	0.0584	10.4	2.00	19.6	23	6.0	42
	F-45	0.172	0.132	0.0488	28.4	5.10	18.0	15	5.3	40
	F-61	0.381	0.288	0.0922	21.0	17.5	83.4	36	7.6	40
	F-62	0.262	0.197	0.0691	20.3	17.5	83.4	33	7.4	40
	B-57	0.156	0.121	0.0417	6.4	1.91	36.0	11	6.2	18
	B-58	0.305	0.229	0.0556	17.9	9.58	53.5	16	5.9	18
	B-59	0.280	0.233	0.0942	14.0	2.14	14.7	10	5.3	18
	B-60	0.333	0.273	0.122	13.5	3.21	23.8	11	6.4	18
Concrete batching										
	Z-1	0.275	0.197	0.0564	6.0	11.0	189	8.0	10	16
	Z-2	0.660	0.460	0.158	5.2	12.0	239	8.0	10	24
Sand and gravel processing										
	AD-2	0.355	0.212	0.0547	7.9	64.0	805	39	17	37
	AD-3	0.221	0.145	0.0595	7.0	53.0	755	40	15	37
<u>Subset 1 - Light-Duty Vehicles Traveling on Heavily Loaded Roads</u>										
Asphalt batching	Y-1	0.100	0.0725	0.0392	2.6	91.0	3,490	3.6	6.0	16
	Y-2	0.148	0.113	0.0603	2.7	76.0	2,820	3.7	7.0	16
	Y-3	0.0862	0.0226	0.0120	4.6	193	4,200	3.8	6.5	16
	Y-4	0.209	0.124	0.0350	4.6	193	4,200	3.7	6.0	16
Copper smelting										
	AC-6	0.570	0.381	0.0733	21.7	400	1,840	3.1	4.2	32
Iron and steel production	F-27	0.101	0.0813	0.0299	35.7	15.40	43.1	13.0[a]	4.4	b

[a] Approximately 80% of the vehicle passes during this test were pickup trucks and cars; the mean value reflects the influence of < 5% of the passes by very heavy equipment.

[b] No speed data obtained

APPENDIX B

RECOMMENDED UPDATE OF AP-42 SECTION 11.2.1

11.2.1 UNPAVED ROADS

11.2.1.1 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.

11.2.1.2 Emissions And Correction Parameters

The quantity of dust emissions from a given segment of unpaved road varies linearly with the volume of traffic. Also, field investigations 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 the fraction of silt (particles smaller than 75 micrometers 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 11.2.1-1 summarizes measured silt values for industrial and rural unpaved roads.

The silt content of a rural dirt road will vary with location, and it should be measured. As a conservative approximation, the silt content of the parent soil in the area can be used. However, tests 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 nonporous surface that usually dries quickly after a rainfall. The temporary reduction in emissions because of precipitation may be accounted for by not considering emissions on "wet" days (more than 0.254 millimeters [0.01 inches] of precipitation).

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), with a rating of A:

$$E = k(1.7) \left(\frac{s}{12}\right) \left(\frac{S}{48}\right) \left(\frac{W}{2.7}\right)^{0.7} \left(\frac{w}{4}\right)^{0.5} \left(\frac{365-p}{365}\right) \quad \text{(kg/VKT)} \qquad (1)$$

$$E = k(5.9) \left(\frac{s}{12}\right) \left(\frac{S}{30}\right) \left(\frac{W}{3}\right)^{0.7} \left(\frac{w}{4}\right)^{0.5} \left(\frac{365-p}{365}\right) \quad \text{(lb/VMT)}$$

TABLE 11.2.1-1. TYPICAL SILT CONTENT VALUES OF SURFACE MATERIALS ON INDUSTRIAL AND RURAL UNPAVED ROADS[a]

Industry	Road Use Or Surface Material	Plant Sites	Test Samples	Silt (%, w/w) Range	Silt (%, w/w) Mean
Copper smelting	Plant road	1	3	[15.9 - 19.1]	[17.0]
Iron and steel production	Plant road	9	20	4.0 - 16.0	8.0
Sand and gravel processing	Plant road	1	3	[4.1 - 6.0]	[4.8]
Stone quarrying and processing	Plant road	1	5	[10.5 - 15.6]	[14.1]
Taconite mining and processing	Haul road	1	12	[3.7 - 9.7]	[5.8]
	Service road	1	8	[2.4 - 7.1]	[4.3]
Western surface coal mining	Access road	2	2	4.9 - 5.3	5.1
	Haul road	3	21	2.8 - 18	8.4
	Scraper road	3	10	7.2 - 25	17
	Haul road (freshly graded)	2	5	18 - 29	24
Rural roads	Gravel	1	1	NA	[5.0]
	Dirt	2	5	5.8 - 68	28.5
	Crushed limestone	2	8	7.7 - 13	9.6

[a]References 4 - 11. Brackets indicate silt values based on samples from only one plant site.
NA = Not available.

where: E = emission factor
k = particle size multiplier (dimensionless)
s = silt content of road surface material (%)
S = mean vehicle speed, km/hr (mph)
W = mean vehicle weight, Mg (ton)
w = mean number of wheels
p = number of days with at least 0.254 mm (0.01 in.) of precipitation per year

The particle size multiplier, k, in Equation 1 varies with aerodynamic particle size range as follows:

Aerodynamic Particle Size Multiplier For Equation 1

$\leq$30 μm	$\leq$15 μm	$\leq$10 μm	$\leq$5 μm	$\leq$2.5 μm
0.80	0.50	0.36	0.20	0.095

The number of wet days per year, p, for the geographical area of interest should be determined from local climatic data. Figure 11.2.1-1 gives the geographical distribution of the mean annual number of wet days per year in the United States.

Equation 1 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 1

Equation	Road silt content (%, w/w)	Mean vehicle weight		Mean vehicle speed		Mean no. of wheels
		Mg	ton	km/hr	mph	
1	4.3 - 20	2.7 - 142	3 - 157	21 - 64	13 - 40	4 - 13

Also, to retain the quality rating of the equation applied to a specific unpaved road, it is necessary that reliable correction parameter values for the specific road in question be determined. The field and laboratory procedures for determining road surface silt content are given in Reference 4. In the event that site specific values for correction parameters cannot be obtained, the appropriate mean values from Table 11.2.1-1 may be used, but the quality rating of the equation is reduced to B.

Equation 1 was developed for calculation of annual average emissions, and thus, is to be multiplied by annual vehicle distance traveled (VDT). Annual average values for each of the correction parameters are to be substituted into

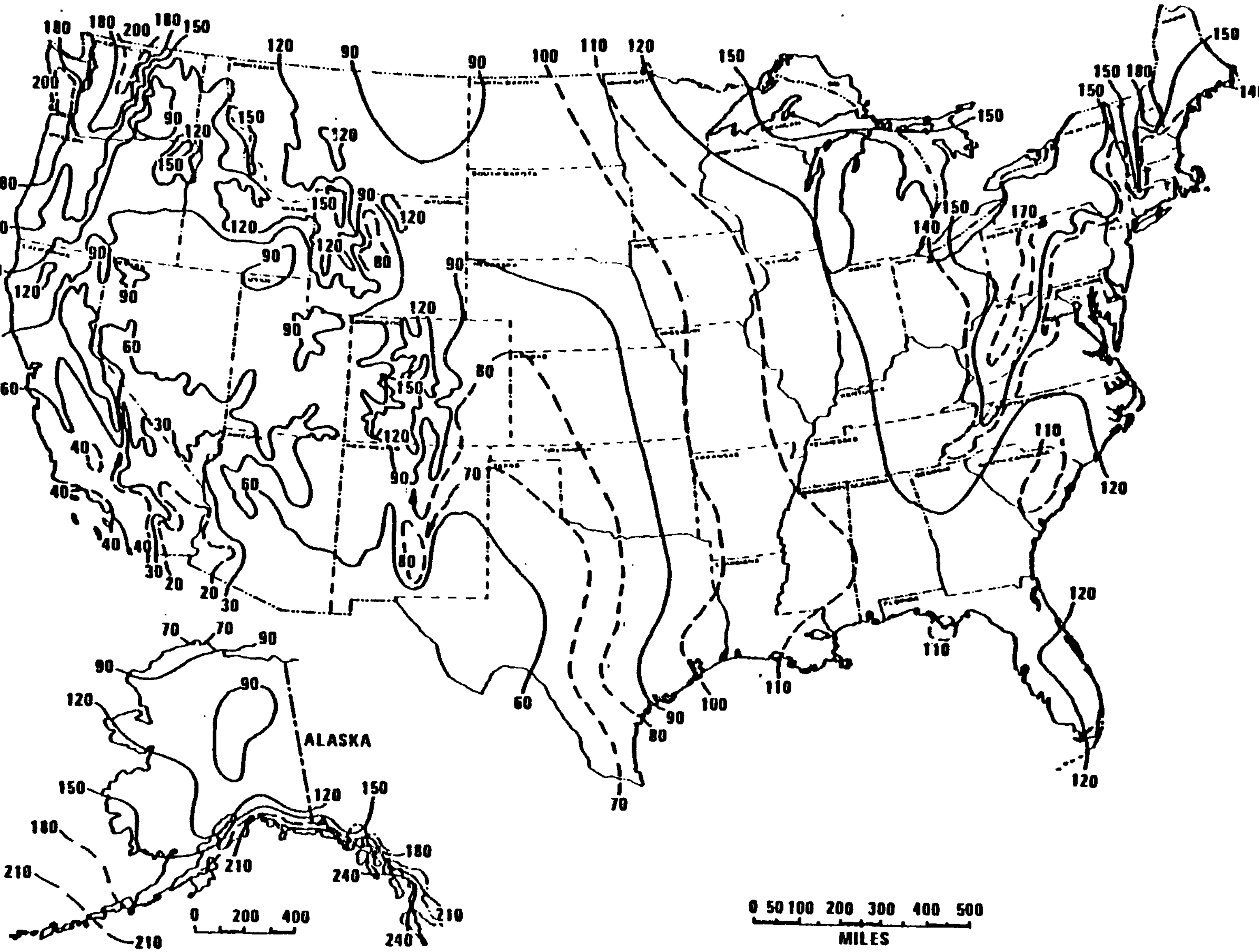

Figure 11.2.1-1. Mean number of days with 0.01 inch or more of precipitation in United States.[10]

the equation. Worst case emissions, corresponding to dry road conditions, may be calculated by setting p = 0 in the equation (which is 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 averaging period (usually 24 hours). Similarly, to calculate emissions for a 91 day season of the year using Equation 1, 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. Also, use appropriate seasonal values for the nonclimatic correction parameters and for VDT.

11.2.1.3 Control Methods

Common control techniques for unpaved roads are paving, surface treating with penetration chemicals, working into the roadbed of chemical stabilization chemicals, watering, and traffic control regulations. 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 with moderate to low costs, but frequent retreatments 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 11.2.6, 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 which determine control efficiency include dilution ratio, application intensity (mass of diluted chemical per road area) and application frequency. Between applications, the control efficiency is usually found to decay at a rate which is proportional to the traffic count. Therefore, for a specific chemical application program, the average efficiency is inversely proportional to the average daily traffic count. Other factors that affect the performance of chemical stabilizers include vehicle characteristics (e. g., average weight) and road characteristics (e. g., bearing strength).

Water acts as a road dust suppressant by forming cohesive moisture films among the discrete grains of road surface material. The average moisture level in the road surface material depends on the moisture added by watering and natural precipitation and on the moisture removed by evaporation. The natural evaporative forces, which vary with geographic location, are enhanced by the movement of traffic over the road surface. Watering, because of the frequency of treatments required, is generally not feasible for public roads and is used effectively only where water and watering equipment are available and where roads are confined to a single site, such as a construction location.

References for Section 11.2.1

1. C. Cowherd, Jr., et al., Development of Emission Factors for Fugitive Dust Sources, EPA-450/3-74-037, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

2. R. J. Dyck and J. J. Stukel, "Fugitive Dust Emissions from Trucks on Unpaved Roads", Environmental Science and Technology, 10(10):1046-1048, October 1976.

3. R. O. McCaldin and K. J. Heidel, "Particulate Emissions from Vehicle Travel over Unpaved Roads", Presented at the 71st Annual Meeting of the Air Pollution Control Association, Houston, TX, June 1978.

4. C. Cowherd, Jr., et al., Iron and Steel Plant Open Dust Source Fugitive Emission Evaluation, EPA-600/2-79-103, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1979.

5. R. Bohn, et al., Fugitive Emissions from Integrated Iron and Steel Plants, EPA-600/2-78-050, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1978.

6. R. Bohn, Evaluation of Open Dust Sources in the Vicinity of Buffalo, New York, U. S. Environmental Protection Agency, New York, NY, March 1979.

7. C. Cowherd, Jr., and T. Cuscino, Jr., Fugitive Emissions Evaluation, Equitable Environmental Health, Inc., Elmhurst, IL, February 1977.

8. T. Cuscino, Jr., et al., Taconite Mining Fugitive Emissions Study, Minnesota Pollution Control Agency, Roseville, MN, June 1979.

9. K. Axetell and C. Cowherd, Jr., Improved Emission Factors for Fugitive Dust from Western Surface Coal Mining Sources, 2 Volumes, EPA Contract No. 68-03-2924, PEDCo Environmental, Inc., Kansas City, MO, July 1981.

10. 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, NC, October 1983.

11. J. Patrick Reider, Size Specific Emission Factors for Uncontrolled Industrial and Rural Roads, EPA Contract No. 68-02-3158, Midwest Research Institute, Kansas City, MO, September 1983.

12. C. Cowherd, Jr., and P. Englehart, Size Specific Particulate Emission Factors for Industrial and Rural Roads, EPA-600/7-85-038, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1985.

13. Climatic Atlas of the United States, U. S. Department of Commerce, Washington, DC, June 1968.

APPENDIX C

RECOMMENDED UPDATE OF AP-42 SECTION 11.2.6

11.2.6 INDUSTRIAL PAVED ROADS

11.2.6.1 General

Various field studies have indicated that dust emissions from industrial paved roads are a major component of atmospheric particulate matter in the vicinity of industrial operations. Industrial traffic dust has been found to consist primarily of mineral matter, mostly tracked or deposited onto the roadway by vehicle traffic itself when vehicles enter from an unpaved area or travel on the shoulder of the road, or when material is spilled onto the paved surface from haul truck traffic.

11.2.6.2 Emissions And Correction Parameters

The quantity of dust emissions from a given segment of paved road varies linearly with the volume of traffic. In addition, field investigations have shown that emissions depend on correction parameters (road surface silt content, surface dust loading and average vehicle weight) of a particular road and associated vehicle traffic.[1-2]

Dust emissions from industrial paved roads have been found to vary in direct proportion to the fraction of silt (particles $\leq$75 µm in diameter) in the road surface material.[1-2] 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. In addition, it has also been found that emissions vary in direct proportion to the surface dust loading.[1-2] The road surface dust loading is that loose material which can be collected by broom sweeping and vacuuming of the traveled portion of the paved road. Table 11.2.6-1 summarizes measured silt and loading values for industrial paved roads.

11.2.6.3 Predictive Emission Factor Equations

The quantity of total suspended particulate emissions generated by vehicle traffic on dry industrial paved roads, per vehicle kilometer traveled (VKT) or vehicle mile traveled (VMT) may be estimated, with a rating of B or D (see below), using the following empirical expression[2]:

$$E = 0.022\ I\left(\frac{4}{n}\right)\left(\frac{s}{10}\right)\left(\frac{L}{280}\right)\left(\frac{W}{2.7}\right)^{0.7} \quad \text{(kg/VKT)} \qquad (1)$$

$$E = 0.077\ I\left(\frac{4}{n}\right)\left(\frac{s}{10}\right)\left(\frac{L}{1,000}\right)\left(\frac{W}{3}\right)^{0.7} \quad \text{(lb/VMT)}$$

where: E = emission factor
I = industrial augmentation factor (dimensionless) (see below)
n = number of traffic lanes
s = surface material silt content (%)
L = surface dust loading, kg/km (lb/mile) (see below)
W = average vehicle weight, Mg (ton)

TABLE 11.2.6-1. TYPICAL SILT CONTENT AND LOADING VALUES FOR PAVED ROADS AT INDUSTRIAL FACILITIES[a]

Industry	No. of Plant Sites	No. of Samples	Silt (%, w/w) Range	Mean	No. of Travel Lanes	Total loading x 10 Range	Mean	Units[b]	Silt loading (g/m^2) Range	Mean
Copper smelting	1	3	[15.4-21.7]	[19.0]	2	[12.9-19.5] [45.8-69.2]	[15.9] [55.4]	kg/km lb/mi	[188-400]	[292]
Iron and steel production	6	20	1.1-35.7	12.5	2 2	0.006-4.77 0.020-16.9	0.495 1.75	kg/km lb/mi	<1.0-2.3	7
Asphalt batching	1	4	[2.6-4.6]	[3.6]	1	[12.1-18.0] [43.0-64.0]	[15.7] [55.7]	kg/km lb/mi	[76-193]	[138]
Concrete batching	1	3	[5.2-6.0]	[5.5]	2	[1.4-1.8] [5.0-6.4]	[1.7] [5.9]	kg/km lb/mi	[11-12]	[12]
Sand and gravel processing	1	3	[6.4-7.9]	[7.1]	1	[2.8-5.5] [9.9-19.4]	[3.8] [13.3]	kg/km lb/mi	[53-95]	[70]

[a]References 1-5. Brackets indicate values based on samples obtained at only one plant site.
[b]Multiply entries by 1,000 to obtain stated units.

The industrial road augmentation factor (I) in the Equation 1 takes into account higher emissions from industrial roads than from urban roads. I = 7.0 for an industrial roadway which traffic enters from unpaved areas. I = 3.5 for an industrial roadway with unpaved shoulders where 20 percent of the vehicles are forced to travel temporarily with one set of wheels on the shoulder. I = 1.0 for cases in which traffic does not travel on unpaved areas. A value between 1.0 and 7.0 which best represents conditions for paved roads at a certain industrial facility should be used for I in the equation.

The equation retains the quality rating of B if applied to vehicles traveling entirely on paved surfaces (I = 1.0) and if applied within the range of source conditions that were tested in developing the equation as follows:

Silt content (%)	Surface loading kg/km	Surface loading lb/mile	No. of lanes	Vehicle weight Mg	Vehicle weight tons
5.1 - 92	42.0 - 2,000	149 - 7,100	2 - 4	2.7 - 12	3 - 13

If I is >1.0, the rating of the equation drops to D because of the subjectivity in the guidelines for estimating I.

The quantity of fine particle emissions generated by traffic consisting predominately of medium and heavy duty vehicles on dry industrial paved roads, per vehicle unit of travel, may be estimated, with a rating of A, using the following empirical expression[6]:

$$E = k \left(\frac{sL}{12}\right)^{0.3} \quad \text{(kg/VKT)} \qquad (2)$$

$$E = k(3.5) \left(\frac{sL}{0.35}\right)^{0.3} \quad \text{(lb/VMT)}$$

where: E = emission factor
sL = road surface silt loading, g/m^2 (oz/yd^2)

The particle size multiplier (k) above varies with aerodynamic size range as follows:

Aerodynamic Particle Size Multiplier (k) For Equation 2 (Dimensionless)

$\leq$15 µm	$\leq$10 µm	$\leq$2.5 µm
0.28	0.22	0.081

To determine particulate emissions for a specific particle size range, use the appropriate value of k above.

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

silt loading, 2 - 240 g/m^2 (0.06 - 7.1 oz/yd^2)

mean vehicle weight, 6 - 42 Mg (7 - 46 tons)

The following single valued emission factors[6] may be used in lieu of Equation 2 to estimate fine particle emissions generated by light duty vehicles on dry, heavily loaded industrial roads, with a rating of C:

Emission Factors For Light Duty Vehicles On Heavily Loaded Roads

$\leq$15 µm	$\leq$10 µm
0.12 kg/VKT (0.41 lb/VMT)	0.093 kg/VKT (0.33 lb/VMT)

These emission factors retain the assigned quality rating, if applied within the range of source conditions that were tested in developing the factors, as follows:

silt loading, 15 - 400 g/m^2 (0.44 - 12 oz/yd^2)

mean vehicle weight, $\leq$4 Mg ($\leq$4 tons)

Also, to retain the quality ratings of Equations 1 and 2 when applied to a specific industrial paved road, it is necessary that reliable correction parameter values for the specific road in question be determined. The field and laboratory procedures for determining surface material silt content and surface dust loading are given in Reference 2. In the event that site specific values for correction parameters cannot be obtained, the appropriate mean values from Table 11.2.6-1 may be used, but the quality ratings of the equations should be reduced by one level.

11.2.6.4 Control Methods

Common control techniques for industrial paved roads are broom sweeping, vacuum sweeping and water flushing, used alone or in combination. All of these techniques work by reducing the silt loading on the traveled portions of the road. As indicated by a comparison of Equations 1 and 2, fine particle emissions are less sensitive than total suspended particulate emissions to the value of silt loading. Consistent with this, control techniques are generally less effective for the finer particle sizes.[4] The exception is water flushing, which appears preferentially to remove (or agglomerate) fine particles from the paved road surface. Broom sweeping is generally regarded as the least effective of the common control techniques, because the mechanical sweeping process is inefficient in removing silt from the road surface.

To achieve control efficiencies on the order of 50 percent on a paved road with moderate traffic (500 vehicles per day) requires cleaning of the surface at least twice per week.[4] This is because of the characteristically rapid buildup of road surface material from spillage and the tracking and deposition of material from adjacent unpaved surfaces, including the shoulders (berms) of the paved road. Because industrial paved roads usually do not have curbs, it is important that the width of the paved road surface be sufficient for vehicles to pass without excursion onto unpaved shoulders. Equation 1 indicates that elimination of vehicle travel on unpaved or untreated shoulders would effect a major reduction in particulate emissions. An even greater effect, by a factor of 7, would result from preventing travel from unpaved roads or parking lots onto the paved road of interest.

References for Section 11.2.6

1. R. Bohn, et al., Fugitive Emissions from Integrated Iron and Steel Plants, EPA-600/2-78-050, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1978.

2. C. Cowherd, Jr., et al., Iron and Steel Plant Open Dust Source Fugitive Emission Evaluation, EPA-600/2-79-103, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1979.

3. R. Bohn, Evaluation of Open Dust Sources in the Vicinity of Buffalo, New York, U. S. Environmental Protection Agency, New York, NY, March 1979.

4. 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, NC, October 1983.

5. J. Patrick Reider, Size Specific Particulate Emission Factors for Uncontrolled Industrial and Rural Roads, EPA Contract No. 68-02-3158, Midwest Research Institute, Kansas City, MO, September 1983.

6. C. Cowherd, Jr., and P. Englehart, Size Specific Particulate Emission Factors for Industrial and Rural Roads, EPA-600/7-85-038, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1985.

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16. ABSTRACT The report gives results of a study to derive size-specific particulate emission factors for industrial paved and unpaved roads and for rural unpaved roads from an existing field testing data base. Regression analysis was used to develop predictive emission factor equations which relate emission quantities to road and traffic parameters. Separate equations were developed for each road type and for three aerodynamic particle size fractions: < or = 15, < or = 10, and < or = 2.5 micrometers. Recommendations are made for including the resulting emission factors in EPA document AP-42. Over the past few years, traffic-generated dust emissions from unpaved and paved industrial roads have become recognized as a significant source of atmospheric particulate emissions, especially within industries involved in mining and processing mineral aggregates. Although a considerable amount of field testing of industrial roads has been performed, most studies have focused on total suspended particulate (TSP) emissions, because the current national ambient air quality standards (NAAQS) for particulate matter are based on TSP. Only recently, in anticipation of a NAAQS for particulate matter based on particle size, has the emphasis shifted to the development of size-specific emission factors.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Size Separation	Pollution Control	13B 07A, 13H
Roads	Regression Analysis	Stationary Sources	12A
Industries		Industrial Roads	05C
Rural Areas		Rural Roads	05K
Dust		Particulate	11G
Emission		Emission Factors	14G

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