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Project Summary

Paved Road Particulate Emissions -- Source Category Report

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This study entailed an extensive field testing program to develop emission factors for particulate emissions generated by traffic entrainment of paved road surface particulate matter. The emission sampling procedure used *in this program provided emission* factors for the following particle size ranges: ≤ 30, 15, 10, and 2.5 µm aerodynamic diameter. Testing was performed at sites in the Kansas City* and St. Louis (MO) areas. These sites represented significant urban paved road emission sources in the following land use categories: commercial/industrial, commercial/residential, expressway, and rural town.

The measured inhalable particulate (IP-- ≤ 15 µm aerodynamic diameter) emission factors ranged from 0.06 to 8.8 g/VKT (vehicle km traveled). Lowest emissions were measured for the expressway category: highest emissions were measured for the rural town category. About 90% of the IP emissions consisted of particles ≤ 10 µm in aerodynamic diameter, and about 50% of the IP emissions consisted of particles ≤ 2.5 µm in aerodynamic diameter.

Correlation analysis of particulate emissions with parameters characterizing the source conditions showed the existence of a relatively strong positive relationship between intensity of emissions and roadway surface silt loading. This relationship was used as the basis for deriving predictive emission factors for each particle size range. The equation for IP emissions was found to represent measured IP more accurately over a much larger range of values than does the AP-42* single-valued factor.

To facilitate the use of these particle *size specific equations in developing* emission inventories, a classification system of mean or typical silt loadings as a function of roadway category was derived. These mean silt loadings were then inserted into the respective emission factor equations to derive a matrix of emission factors for specific roadway categories and particle size fractions.

This Project Summary was developed by EPA's Industrial Environmental Research laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

As early as 1976, receptor oriented air quality assessments showed traffic-entrained particulate from paved roads to be a major cause of non-attainment of air quality standards for total suspended particulates (TSP) in urban areas. However, only a few field programs (all completed by 1977) had tried to directly measure dust emissions from urban streets. Moreover, these programs were seriously limited in the measurement of aerodynamic particle size characteristics.

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*In this Summary, failure to specify either Kansas or Missouri after "Kansas City," implies both cities.

*U.S. EPA report AP-42, Compilation of Air Pollutant Emission Factors, Third Edition (NTIS PB 275525), July 1977.

This study was aimed at developing size-specific particulate emission factors for urban paved roads, based on expanded field testing of representative sources. The resulting emission factors would provide for the development of effective strategies for the attainment and maintenance of the TSP standards, as well as the anticipated standard for particles ≤ 10 μm in aerodynamic diameter.

The emission sampling procedure used in this program provided emission factors for the following particle size ranges:

TSP = Total suspended particulate matter (as measured by a standard high-volume sampler) consisting of particles ≤ 30 μm in aerodynamic diameter.

IP = Inhalable particulate matter consisting of particles ≤ 15 μm in aerodynamic diameter.

PM-10 = Particulate matter consisting of particles ≤ 10 μm in aerodynamic diameter.

FP = Fine particulate matter consisting of particles ≤ 2.5 μm in aerodynamic diameter.

Results are presented for winter testing in the Kansas City, MO, area and spring testing in areas of St. Louis, MO, and Granite City, IL.

Sampling Site Selector

Eight candidate sampling areas in Kansas, Missouri, and Illinois were identified by the EPA as likely representative sites for the field study. These areas represented a range of typical road, traffic, geographical, and environmental conditions within residential, commercial, and industrial land uses. Each sampling area contained a TSP monitoring site providing historical air quality data.

Three major criteria were used to determine the suitability of specific sites within the designated areas, for sampling of road dust emissions by the exposure profiling technique:

1. Adequate space for sampling equipment.
2. Sufficient traffic and/or surface loading so that adequate mass would be captured on the lightest loaded collection substrate during a reasonably short sampling time.
3. A wide range of acceptable wind directions, taking into account (a) the street orientation relative to the predominant wind directions for the locality, and (b) upwind obstacles (houses, buildings, or trees) to free wind flow.

Although roads with light traffic were not considered, they probably do not contribute substantially to total emissions of traffic entrained dust in urban areas.

Based on the above criteria, seven sites were selected for this testing program:

Kansas City Area - three sites

7th Street in Kansas City, KS (commercial/industrial)

Volker Boulevard/Rockhill Road in Kansas City, MO (commercial/residential)

4th Street in Tonganoxie, KS (rural town)

St. Louis, MO - two sites

I-44 (expressway)

Kingshighway (commercial/residential)

Granite City, IL - two sites

Madison Street (commercial/residential)

Benton Road (commercial/residential)

Sampling Equipment

A variety of sampling equipment was utilized in this study to measure particulate emissions, roadway surface particulate loadings, and traffic characteristics.

The basic emission sampling equipment included an isokinetic exposure profiling system with four sampling heads positioned at 1- to 4-m heights. In addition, high-volume samplers, each fitted with a size selective inlet (SSI) and a parallel-slot cascade impactor (CI), were placed at 1- and 3-m heights to determine the respective IP mass fractions of the total particulate emissions and the corresponding particle size distributions. The five-stage cascade impactors had, at a flow rate of 40 scfm (1133 L/min), 50% efficiency cutpoints at 7.2, 3.0, 1.5, 0.95, and 0.49 μm aerodynamic diameter. The impactor substrates were greased to reduce particle bounce. A standard high-volume air sampler was operated at a height of 2 m. Normally, these sampling devices were positioned 5 m from the downwind edge of the road.

The basic upwind equipment included SSIs and a standard high-volume air sampler. In the Kansas City testing, two SSIs at heights of 2 and 4 m were used to obtain the IP concentration of upwind particulate matter. In the St. Louis testing, the primary upwind equipment included a high-volume air sampler and an SSI/CI with greased substrates.

Samples of the dust on the roadway surface were collected during the source tests. To collect this surface dust, it was necessary to close each traffic lane for about 15 min. Normally, an area that was 3 m by the width of a lane was sampled. For each test, collection of material from all travel lanes and curb areas (extending to about 25 to 30 cm from the curbing) was attempted. A hand-held portable vacuum cleaner was used to collect the roadway dust. The attached brush on the collection inlet was used to abrade surface-compacted dust and to remove dust from the crevices of the road surface. Vacuuming was preceded by broom sweeping if large aggregate was present.

Characteristics of the vehicular traffic during the source testing were determined both automatically and manually. The characteristics included: (a) total traffic count, (b) mean traffic speed, and (c) vehicle mix.

Total vehicle count was determined using pneumatic-tube counters. To convert the axle counts to total vehicles, vehicle mix was determined visually over 1-min intervals every 15 min during the source testing. The vehicle mix summaries recorded vehicle type, number of vehicle axles, and number of vehicle wheels. From this information, the total axle counts were corrected to the total number of vehicles by type.

The speed of the freely flowing traffic was taken to be the posted speed limit of the roadway test section. As a check, speeds of the vehicles were determined occasionally using a hand-held radar gun. The weights of the vehicle types were estimated by consulting automobile literature and distributors of medium-duty and semi-trailer trucks.

Sampling and Analysis Procedures

The sampling and analysis procedures used in this study were subject to quality control (QC) guidelines which met or exceeded the requirements specified by EPA. As part of the QC program for this study, sampling and analysis procedures were audited routinely, to demonstrate that measurements were made within acceptable control conditions for particulate source sampling and to assess the source testing data for precision and accuracy. Audit items included gravimetric analysis, flowrate calibration, data processing, and emission factor calculation.

Prior to equipment deployment, a number of decisions were made as to the potential for acceptable source testing conditions. These decisions were based on forecast information obtained from the local U.S. Weather Service office. A specific sampling location was identified based on the anticipated wind direction. Sampling would be initiated only if the wind speed was forecast between 4 and 20 miles per hour (6 and 32 km/hr). Sampling was not planned if there was a high probability of measurable precipitation (normally > 20%) or if the road surface was damp.

Sampling usually lasted 4 to 6 hr. Occasionally sampling was interrupted because of unacceptable meteorological conditions and then restarted when conditions were suitable. The unacceptable meteorological conditions most frequently encountered consisted of light winds (below 4 mph or 6 km/hr) and insufficient angle (< 45 degrees) between mean (15-min average) wind direction and road direction.

The vertical distributions of exposure (i.e., the product of plume concentration and mean wind speed) were numerically integrated to calculate emission factors. The size selective inlet/cascade impactor sampler combinations provided reliable point concentrations for IP and finer particle size fractions. Plume height was determined by extrapolation of the vertical profile of total particulate concentration as measured by the MRI exposure profiler.

Test Results

Table 1 summarizes, by land use category, the emission factor data and the corresponding source characteristics. As can be seen, the smallest emission factors were measured in the freeway category, which also had the lowest surface silt loadings. The highest emission factor was measured in the rural town category which showed a correspondingly high surface silt loading.

Table 1. Mean Emission Factors and Source Characterization Parameters

Land Use Category	No. of Tests	Emission Factor (g/VKT) ≤15 μm	≤10 μm	≤2.5 μm	Silt Loading (g/m²)	Vehicle Speed (km/hr)	Vehicle Weight (Mg)
Commercial/Industrial	4	2.43	2.07	1.31	0.29	48	4.1
Commercial/Residential	10	0.94	0.80	0.46	0.54	53	2.1
Expressway	4	0.14	0.13	0.066	0.022	89	4.0
Rural Town	1	8.77	6.96	1.42	2.5	32	2.0

Multiple Regression Analysis

The source tests were evaluated according to established QA criteria for exposure profiling. Seven of the nine Kansas City tests met all of the QA criteria, while only three of the ten tests conducted in the St. Louis/ Granite City area met the QA criteria. The spring testing in particular, was hampered by unseasonably light winds. Wind speed for four of the ten spring tests did not meet the minimum wind speed criterion of 4 mph (6 km/hr).

Stepwise multiple linear regression (MLR) was used to evaluate independent variables for possible use as correction factors in a predictive emission factor equation. Because it was desirable to have multiplicative rather than additive correction factors in the emission factor equations, all independent and dependent variable data were transformed to natural logarithms before being entered in the MLR program.

The independent variables evaluated initially as possible correction factors were silt loading (g/m²), total loading (g/m²), average vehicle speed (km/hr), and average vehicle weight (Mg). The rationale for including measures of roadway particulate loading stems from findings of an earlier program that indicated that the magnitude of roadway emissions was directly related to variations in surface loadings. The vehicle parameters--mean weight and speed--were included largely by analogy to a predictive emission factor equation for unpaved roads, although it was recognized that the dust generation mechanism for paved roads may differ from that for unpaved roads. The moisture content of the road surface particulate was not included as a correction parameter because of the difficulty of collecting a sample without altering its moisture content.

The resulting MLR equation after normalization to a typical value for silt loading was:

$$e_{IP} = 2.54 \left(\frac{sL}{0.5}\right)^{0.8} \quad (1)$$

where:

eIP = IP emission factor, g/VKT

sL = Silt loading of road surface particulate matter, g/m².

This equation explained 73% of the variation on the emission factors. The MLR data set did contain data from all the land use categories sampled during the field program.

The emission factor equation was found to predict the MLR series test data with a precision factor of 2.0. The precision factor (f) for an emission 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 observed emission factors.

The precision factor may be interpreted as a measure of "average" error in predicting IP emissions from the regression equation. Assuming that the actual IP emission factors are normally distributed about the regression line, about 68% of the predictions are within a factor of 2. The effective outer bounds of predictability are determined by exponentiating twice the standard error of the estimate. The resultant estimate of predictive accuracy, in this case 4.0, then encompasses about 95% of the predictions.

To put the precision factor of the IP predictive emission factor equation emission factor into perspective, two comparisons were undertaken utilizing the single-valued emission factor found in EPA's AP-42. However, before valid comparisons could be made, it was necessary to convert the AP-42 single-valued factor (which represents TSP emissions) to an approximate IP emission factor. This was done by multiplying the AP-42 value by 0.4, which is the mean ratio of net IP (downwind minus upwind) to net TSP concentrations as determined from the data collected in this study.

The first comparison involved calculating a precision factor for the AP-42 data set. The resulting value of 2.1 is a measure of the ability of the single-valued factor to represent the 40 pieces of data which were averaged originally to produce the AP-42 factor. The second comparison involved calculating a precision factor using the single-valued AP-42 factor to represent the MLR data set, as collected in this study. This comparison yielded a precision factor of 4.4.

The most important conclusion that can be drawn from these comparisons is that the emission factor equation, though far from ideal, does predict IP emissions more accurately over a much greater range of values than does the AP-42 single-valued factor over a considerably smaller range of data values corresponding to the AP-42 data set. Furthermore, applying the single-value AP-42 factor (to represent the wide range of IP emissions from paved roads as measured during this program) yields a precision factor that is more than double (4.4 versus 2.0) that associated with the predictive equation. This ability of the predictive equation to more accurately represent variations in IP emissions is directly attributable to the relatively strong relationship between roadway surface silt loading and IP emissions.

Predictive emission factor equations for the PM-10 and FP particle size fractions were developed using the same procedure as that applied in developing the equation for IP. Derivation of TSP emission factors for use in developing a predictive equation required different initial calculations, since only two TSP samplers (one upwind, one downwind) were operated during the measurement phase of the program. In essence, the initial calculation involved multiplying the IP emission factor for each run in the MLR data set by the corresponding net ratio of TSP to IP concentration as measured by appropriate samplers. This procedure assumed that the TSP/IP ratio was constant over the vertical extent of the plume.

The general form of the emission factor equations, applicable to the additional particle size fractions, was the same as Equation 1:

$$e = k\left(\frac{sL}{0.5}\right)^P \qquad (2)$$

The base emission factor coefficient (k), exponent (P), and precision factor for each size fraction are listed in Table 2.

Note that the tendency for the power term in the equation to increase witn larger particle size fraction is generally consistent with the previous paved road equation in which silt loading to the 1.0 power was employed to account for variations in TSP emissions.

Table 2. Paved Road Emission Factor Equation Parameters (by particle size fraction)

Particle Size Fraction	k (g/VKT)	P	Precision Factor[a]
TSP	5.87	0.9	2.4
IP	2.54	0.8	2.0
10 μm	2.28	0.8	2.2
FP	1.02	0.6	2.2

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

Emissions Inventory Applications

For most emissions inventory applications involving urban paved roads, silt loading will probably not actually be measured. Therefore, to facilitate the use of the previously described equations, it was necessary to characterize silt loadings according to a parameter(s) more readily available to developers of emissions inventories. After examination and analysis of silt loading and traffic data collected during relevant MRI sampling programs, as well as surface loading data gathered in connection with an extensive study of urban water pollution, the decision was made to characterize variations in silt loading based on the roadway classification system shown in Table 3. This system generally corresponds to the functional classification systems employed by transportation agency personnel; and thus the data necessary for emissions inventory--number of road miles per road category and traffic counts-- should be easily obtainable.

Table 3. Paved Roadway Classification

Roadway Type	Average Daily Traffic (ADT)	No. of Lanes
Freeways/Expressways	> 50,000	≥ 4
Major streets/highways	> 10,000	≥ 4
Collector streets	500-10,000	2[a]
Local streets	< 500	2[b]

[a] Total roadway width ≥ 32 ft (9.75 m).
[b] Total roadway width < 32 ft (9.75 m).

The data base made up of 44 samples collected and analyzed according to the procedures outlined above, may be used to characterize the silt loadings for each roadway category. These samples, obtained during field sampling programs over the past 3 years, represent a broad range of urban land use and roadway conditions. Geometric means for this data set are broken out by sampling location (i.e., city) and roadway category in Table 4.

Table 5 presents the emission factors broken out by roadway category and particle size. These were obtained by inserting the above mean silt loadings into the emission factor equations with parameters defined in Table 2. These emission factors can be utilized directly for emission inventory purposes. It is important to note that the current AP-42 paved road emission factors for TSP agree quite well with those developed in this study. For example, those cited in connection with previous testing were conducted at two roadway sites in the major street and highway category. Those tests yielded a mean TSP emission factor of 4.3 g/VKT versus 4.4 g/VKT as determined from the data presented here.

Summary and Conclusions

The purpose of this study was to quantify size-specific particulate emissions generated by traffic entrainment of paved road surface particulate matter. Paved road source testing was performed at sites representing significant emission sources within a broad range of urban land-use categories.

The measured inhalable particulate emission factors spanned two orders of magnitude (0.06 to 8.8 g/VKT). Lowest mean emissions were measured for the expressway category; highest mean emissions were measured for the rural town category. About 90% of the IP emissions consisted of particles ≤ 10 μm in aerodynamic diameter, and about 50% of the IP emission consisted of particles ≤ 2.5 μm in aerodynamic diameter.

Correlation analysis of IP emissions with parameters characterizing the source conditions showed the existence of a relatively strong positive relationship between intensity of emissions and roadway surface silt loading. This confirms the findings of earlier testing. Regression analysis of a subset of acceptable (MLR) test runs was used to derive a predictive IP emission factor equation which explained 73% of the variation in the emission factors.

This predictive equation has an associated precision factor of 2.0 in relation to the MLR data set. By way of comparison, the AP-42 single-value factor (corrected to represent IP emissions) has a precision factor of 2.1 for its data set and a precision factor of 4.4 for the MLR data set, which spans a much larger range of values than the AP-42 data set. Therefore, the predictive equation, though far

Table 4. *Summary of Silt Loadings for Urban Paved Roadways (g/m²)[a]*

City	Roadway Category: Local $\bar{X}g$[b]	n	Collector $\bar{X}g$	n	Major $\bar{X}g$	n	Overall $\bar{X}g$	n
Baltimore	1.42	2	0.72	4	0.39	3	0.68	9
Buffalo	1.41	5	0.29	2	0.24	4	0.56	11
Granite City (IL)	---	---	---	---	0.82	3	0.82	3
Kansas City	---	---	2.11	4	0.41	13	0.60	17
St. Louis	---	---	---	---	0.16	3	0.16	3
Overall	1.41	7	0.92	10	0.36	26	---	---

[a]Freeway/expressway data not included; only one value (0.022 g/m²) obtained.
[b]$\bar{X}g$'s are geometric means based on the corresponding n sample size.

Table 5. *Recommended Emission Factors for Specific Roadway Categories and Particle Size Fractions*

Category	TSP g/VKT	TSP lb/VMT	≤ 15 μm g/VKT	≤ 15 μm lb/VMT	≤ 10 μm g/VKT	≤ 10 μm lb/VMT	≤ 2.5 μm g/VKT	≤ 2.5 μm lb/VMT
Local	15	0.053	5.8	0.021	5.2	0.018	1.9	0.0067
Collector	10	0.035	4.1	0.015	3.7	0.013	1.5	0.0053
Major street and highway	4.4	0.016	2.0	0.0071	1.8	0.0064	0.84	0.0030
Expressway	0.35	0.0012	0.21	0.00074	0.19	0.00067	0.16	0.00057

from ideal, does represent IP emissions more accurately over a much larger range of values than does the AP-42 single-valued factor. This fact is directly attributable to the relationship of IP emissions to silt loading.

Extending the regression analysis to include emission factor equations for other particle size fractions--FP, PM-10, and TSP--yielded a set of equations in which the power term for silt loading increased with larger particle size fraction. This result is generally consistent with the previous paved road equation in which silt loading to the 1.0 power was employed to account for variations in TSP emissions.

To facilitate the use of these particle-size-specific equations in developing emission inventories, a classification system was derived of mean or typical silt loadings as a function of roadway category. These mean silt loadings were then inserted into the respective emission factor equations. The resultant emission factors for specific roadway category and particle size fractions can be utilized directly for emissions inventory purposes. By accounting for variations in silt loading, these emission factors are significantly more reliable than an overall average emission factor in developing components of an urban paved road emission inventory.

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The complete report, entitled "Paved Road Particulate Emissions: Source Category Report," (Order No. PB 84-223 734; Cost: $11.50, subject to change) will be available only from:
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