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RESUSPENSION OF PARTICULATE MATTER

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Executive Summary

Over the past several years, various studies have been conducted in numerous cities to investigate the urban total suspended particulate matter problem. These studies have generally come to one basic conclusion; that is, in addition to other various sources of particulate matter, vehicular traffic activity, including resuspension of street dust by wind or traffic, is an underlying source which significantly contributes to the TSP problem within the urban area.

These studies have concluded that:

(a) Vehicular traffic activities (i.e., direct tailpipe emissions, rubber tire wear, and resuspension of street dust) contribute approximately 50% (Philadelphia) to 90% (Chicago) of the TSP collected on certain high-volume air samplers in close proximity to the roadway.*

(b) Resuspension of material caused by vehicular movement alone accounts for approximately 15% of the annual TSP average in Chicago (averaged for 20 monitoring locations throughout the city). Resuspension due to wind action, generally greater than 13 miles per hour, may contribute an additional 5% to the annual TSP average in Chicago.

(c) Resuspension is generally a localized problem similar to CO in that TSP levels vary depending upon distance from the roadway.

(d) Resuspension of anti-skid materials (e.g., sand or salt for snow control) may be significant on certain days of the year but generally have a minimal effect on annual air quality levels. In Detroit, ambient sodium chloride levels increased the total TSP loading by 15% to 20% on days after salting for snow control.

*Some have questioned the results of these studies, however, there has been no data to substantiate their claims to date.

(e) Sources of material found on street surfaces vary greatly depending on such factors as land use, geographic location, season, weather, traffic activity, and the length of time which has elapsed since the site was last cleared.

(f) The major sources of street dust include:

(1) Erosion of the street surface itself,

(2) Motor vehicle emissions from both tailpipe and tire wear, etc.,

(3) Atmospheric fall-out of both natural and man-made materials,

(4) Run-off and carryout of materials from adjacent lands,

(5) Spills of material from vehicular transport, and

(6) Use of anti-skid materials, such as salt and sand during periods of snow cover.

(g) One study indicated that half of the mineral material on the roadway is derived from aggregate limestone (i.e., erosion of the pavement), and the remainder of the material is from adjacent soil.

(h) On the average for all types of streets (commercial, industrial, and residential), 350 lbs. of material, less than 100 microns, is found along a curb mile of roadway at a given point in time.

(i) Within 3 or 4 days, dust loadings on a street approach a maximum and begin to level off.

(j) Emission factors available in the literature to estimate the amount of material that becomes airborne due to traffic along a "dirty" street range from 0.8 to 77 grams VMT. Based upon available information, it is believed that 1 to 5 grams VMT is a reasonable estimate of the amount of material less than 40 microns that becomes suspended.

(k) Street cleaning technology consists of sweeping and flushing. Flushing is conducted mainly for aesthetics to displace dirt and debris from the center of the street to the curb area. Traditional brush-type sweepers have an overall removal efficiency of 50% and only a 15% to 20% efficiency for particles less than 100 microns.

However, the results from some tests have indicated an actual increase of particles less than 100 microns after the test site had been swept with a brush-type sweeper. Vacuum sweepers are more efficient and are used quite extensively in Europe but have not been used in this country.

Though one could question the accuracy of the various semi-quantitative techniques used in some of the studies, the findings seem clear - resuspension has been and still is being identified as a common source of TSP in many areas. While the results of each individual study taken alone may not be conclusive, when looked at collectively the preponderence of evidence leaves little doubt that resuspension is a significant problem for attainment of the TSP standards within urban areas. In summary it is difficult with the information available to say quantitatively (without question) how much of an ambient impact resuspension has, however, because of the confirming results from city to city, it is difficult to deny that resuspension is a contributing factor to high ambient levels in urban areas.

Presently there are several ongoing projects and some additional work planned which is associated with the resuspension problem.

(a) 14 Cities Study conducted by GCA on the National Assessment of the Particulate problem, scheduled for completion in the Spring of 1976.

(b) Emission Factor Study, conducted by MRI to determine an emission factor for resuspended dust from paved roads to be completed in Spring of 1976.

(c) American Public Works Association study with the National Science Foundation to design an environmentally desirable street sweeper.

(d) Contract Study by Region III to assess the particulate problem for Philadelphia.

(e) Contract Study to review and update the siting criteria for particulate monitors.

(f) Control technology assessment study to evaluate the available control techniques associated with resuspension. This work is presently in the planning stages.

As the above studies are completed, the results will be forwarded to the Regional Offices and States for their use in the development of revised implementation plans for total suspended particulates in non-attainment areas.

CHAPTER I

DOCUMENTATION OF RESUSPENSION ISSUE

I. Background & Definition

Wipespread failure to attain the national ambient air quality standards for particulate matter in many urban areas has spurred a reexamination of the nature of the urban particulate problem. Routinely the control strategy development for these areas included an analysis of the contribution of conventional point and area sources without consideration of other less conventional sources of particulate. One of these non-conventional sources is vehicular traffic-related particulate, including resuspended particulate matter commonly referred to as just "resuspension" or reentrainment. For the purposes of this discussion, resuspended particulate matter (RPM) is defined as that particulate matter which becomes airborne through the action of the wind across a paved surface or by traffic upon the roadway.

II. Urban Studies

Several studies have been conducted over the past few years to investigate the urban total suspended particulate matter problem. Many of these studies were concerned with the identification of suspended particulate particles and the source of such particles. Some of the studies have indicated that vehicular traffic related activities in general are the key sources while other studies have more specifically identified resuspension of roadway material as the problem.

(a) Vehicular traffic-related studies

One of the first studies was by Scott Research Laboratories in

Philadelphia in 1972. Suspended particulate samples were collected from four sampling sites which were part of the existing air monitoring network for the City of Philadelphia. The site locations ranged from 12 to 75 feet above the ground and 25 to 90 feet from the nearest roadway. The data were analyzed by two semi-quantitative techniques, microscopic and elemental analysis. Based on a combination of microscopic and chemical analyses, the Philadelphia samples show that 30 to 40% of the airborne particulates come from stationary sources and approximately 50% of the particulate is traffic related with a bulk of the particulate large enough to settle quickly. However, some are fine exhaust particles which can be potentially hazardous.[1] Resuspended material was estimated at approximately 30%.

Another study in Chicago, Illinois, by IIT Research Institute[2] identified the types and sources of suspended particles in Chicago via microscopic analysis and examined the relationship between sampling height and TSP. Historical samples from existing sites in various portions of the city with varying heights and distances from the roadway, as well as new samples from temporary sampling locations, were analyzed. The results of the study indicated that calcite and auto tailpipe emissions were the major particles found in every sample analyzed. Their combined mass accounted for more than 90% of the filter weight in many cases.

With regard to sampling height, the study concluded that:

(1) Hi Vol samplers close to street level show higher mass loading due to collection of entrained mineral particulate matter.

(2) Two sites almost identical in all respects except for differences in height above ground were found to have identical type particles but differed in TSP values solely due to differences in height.

In a study in Denver[3], microscopic analysis of particles revealed that an estimated 80% of the mass collected on the hi-volume filter consisted of road dusts (e.g., quartz, limestone and mica). These minerals are common to (1) the soils of Denver, (2) the dust on its street pavement, and (3) the pavement itself (monitoring site located 10 - 20 miles NE of Denver). Because of the relatively low wind speeds observed during the sampling period of the study, it seemed quite probable that auto traffic entrained most of the minerals collected, although no specific estimate of the amount entrained was given. In addition, rubber tire dust and auto exhaust particles were also found on the filters which provides some additional support that the particulates in Denver are highly related to vehicular traffic.[3]

(b) Resuspension Studies

In an investigation of Chicago ambient air quality data, Abel and Neuman[4] analyzed the TSP levels from January 1966 to March 1974 to determine the impact of resuspension (or refloatation) due both to wind-induced and traffic-induced causes on Chicago's total suspended particulate levels. The results indicated that resuspension below wind speeds of 13 mph is generally regarded as vehicular suspended particles and accounts for a time weighed average (on annual basis) of 10 ug/m^3 or 15% of of Chicago's annual average. Wind speeds in excess of 13 mph cause refloata tion of surface dust such that the total annual TSP average is increased nearly 5%. In conclusion, "the total amount of TSP due to resuspension may be 18 to 20 ug/m^3 in Chicago no matter what the yearly average TSP value is because resuspension is a function of traffic volume, precipitation and high wind velocities, rather than a function of industrial emission sources."

In a study in 1973 by PEDCO Environmental, a resuspension problem was analyzed for Denver.[5] In that city, dust emissions are created by traffic movement over sanded highways and streets resulting from the mechanical grinding of sand which remains after the snow melts. On an annual basis, this has only a minimal effect on air quality, but it has considerable air quality impact on those few days a year when it does occur (average increase of 50 ug/m^3).

In 1972 the Montana Department of Health and Environmental Sciences[6] conducted a sampling program which indicated that a very large portion of the material collected by the high volume air sampling is dust from streets (no estimate of concentration was given). Of this street dust, a large part comes from winter sanding operations. Through the use of questionnaires, it was determined that few communities used any form of dust removal when they treated the sand for use. Further, the sand on the streets is ground into finer dust by the tires of vehicles. Results of a special study indicated that though only about 1 percent of the sand applied was dust (·79u), by the spring because of the traffic activity, 16% of the sand found on the roadway surface had been ground into dust. The dust which has been carried away by rain or melting snow and by the wind was not included in the sample. Therefore, it is quite likely that the actual percentage of dust may well have exceeded 20%. The impact of this dust on ambient levels was not quantified, however.

Another study conducted in Detroit during late 1973 and early 1974[7] indicated a close correlation between local street salting and general ambient levels of aerosol chloride in suspended particulate as measured by the hi-vol. The sampling network was established using high volume air samplers to sample aerosol at urban locations which would be expected to experience various degrees of influence from traffic-related street salting. Actual percentage of sodium chloride measured as chloride at 8 metro stations in Detroit was found to be from 4 to 8% of the total suspended particulate matter for normal winter months to highs of 20 to 30 percent following incidents of street salting. Assuming chloride could be used as a tracer for resuspended materials, the study would indicate that 15 to 20 ug/m^3 results from resuspended salt.

A study was conducted by Pennsylvania State University[8] to determine the original source of reentrained material. In the study, selected samples (grab) from the road and adjacent soil were subjected to emission spectrographic analysis. The dominant particle size for this source is in the range of 10 to 60 microns. While there were slight differences between the road samples, these were within the expected experimental error of the whole procedure. The difference that appears significant is a definite lower silica and higher limestone composition for the road dusts than for the soil sample, showing that roughly half of the dust on the roadway appears to be derived from the aggregate limestone and the remainder from adjacent soil dust.

Similarly, Harrison and Rahn[9] undertook a separate study to determine the chemical composition of Chicago street dust. The study consisted of a survey of the elemental composition of Chicago street dust using nondestructive neutron activation as the analytical tool. The study suggested that the variability of the concentration of enriched elements in the street dust provided evidence that the material was deposited locally and that the street dust was not well mixed. In other words, deposition and resuspension of materials is local in nature.

Mr. G. A. Sehmel of Battelle, Pacific Northwest attempted to quantify the particle suspension caused by auto and truck generated surface stresses by using solid ZnS as a tracer ($<25\mu$ particles).[10]

The results of the study indicate the following: (1) the resuspension rate increases with vehicle speed, (2) the resuspension rates are proportional to car-generated turbulence, (3) resuspension decreased nearly an order of magnitude when the vehicle is driven on a lane adjacent to the tracer as compared to driving through the tracer and (4) particles are less readily resuspended the longer the particles remain in contact with the road surface (due to weathering).

From the data collected during the study on the day the tracer is placed on the road, it is estimated that 1% of the material becomes resuspended at an automotive speed of 50 mph and 0.3% for speeds of 30 mph. However, in just 5 days after placing the tracer on the surface, the resuspension rates have dropped to .1% for 50 mph and .006% for 30 mph. It should be noted that the resuspension rates for trucks are greater than the resuspension rates for cars at the same weathering time by a factor of 10.

Soon after the particles become resuspended, they begin to deposit on the ground immediately adjacent to and downwind of the road. Samplers were located a varying distance up to 30 feet from the roadway. Deposition is a function of weathering time and for a car driving through the tracer at a speed of 30 mph after 30 days, the cumulative deposition fraction (the fraction of particles resuspended and leaving the road during a vehicle pass which is deposited up to the distance of interest) at 30 feet from the road, is .32. That is, 32% of the material that was resuspended would have been deposited between the road and 30 feet from it.

Late in 1972 a study was begun in Seattle's Dumwamish Air Basin[11] to measure the emissions from dusty roads. The study indicated that road dust, from both paved and unpaved (gravel) roads is the largest source of suspended particles in Seattle, 2100 tons/year. Table VIII (Appendix B) provides some estimates of the impact of mud carryout from unpaved roads and parking lots, and dust from paved streets.

Additional Work and Conclusions

In addition to the above auto-related activity and resuspension studies, some additional work has been done by GCA and others, both within the United States and Australia, to determine the variation of TSP levels with height and slant distance (i.e., vertical and horizontal distance of a sampler) from a roadway. In all cases the sites further from the roadway consistently had lower TSP concentrations than those nearer the road when average daily traffic (ADT) was considered. Specific relationships will become available as the GCA study nears completion.

Thus, from the above results one can reasonably conclude that while resuspension is a significant source of TSP, its impact upon receptors will vary, depending upon the receptor's distance from the roadway and height above the ground. Thus from this sense the resuspension problem may be like CO in that it may have more of a localized, rather than a regionwide, effect.

CHAPTER II

AVAILABLE CONTROL TECHNIQUES

The present methods of cleaning streets fall into two categories: sweeping and flushing. Machine sweeping accounts for the great majority of street cleaning in most communities. This may be supplemented by some manual sweeping in a few areas. Rainfall also acts to clean streets in the short term, however, it is responsible for mud carryout in the long term such that overall rainfall may not be an effective "control."

Mechanical street sweepers are designed to loosen dirt, transport it onto a conveyor and deposit it in a hopper. Typically sweepers do have some type of dust control system.

There are three basic types of sweepers in use: (1) pickup broom which uses a rotating gutter broom to move matter into the main pickup broom - water spray is used to control dust, (2) regenerative air which blasts dirt from surface into a hopper with some of the air being recycled - also uses water spray for dust control, (3) vacuum (limited use in U.S. - wide use in Europe) where all material picked up by the vacuum nozzle is saturated with water on entry.

Street flushing is presently conducted to mainly displace dirt and debris from street into the gutter, at which point the material is concentrated for sweeper pickup. Most agencies use flushers for aesthetic purposes and moving material out of travel lanes quickly.

Table I is a summary of cleaning practices in selected cities. All cities surveyed were found to have a comprehensive sweeping program. About half had a flushing program. Several cities relied on manual

TABLE I

CLEANING PRACTICES IN SELECTED CITIES

	MAJOR CLEANING PROGRAMS			EQUIPMENT		EQUIPMENT/1,000-mi. STREET	
	SWEEPER	FLUSHER	MANUAL	SWEEPER	FLUSHER	SWEEPER	FLUSHER
San Jose	x	0	0	15	0	12.9	-
Phoenix	x	M	M	21	1	14.5	0.7
Milwaukee	x	M	x	22	2	12.9	1.2
Baltimore	x	x	x	26	11	13.0	5.5
Atlanta	x	M	x	24	3	13.7	1.7
Seattle	x	x	x	18	8	14.1	6.3
Minneapolis	x	M	M	18	3	18.0	3.0
St. Paul	x	x	M	14	7	15.6	7.8
San Francisco	x	x	x	14	10	16.5	11.8
Lawrence	x	x	M	3	2	20.0	13.3

NOTE:

• Manual cleaning normally used in business districts only.

x = major use.

0 = none

M = minor use.

Source: Reference 12

cleaning programs, mainly in downtown areas. The study[12] also surveyed the sweeping frequency, sweeper utilization factor, pickup per sweeper, and pickup rate. This data is summarized in Figure I.

Three general types of tests have been conducted to determine sweeping effectiveness: (1) in situ street tests, (2) controlled tests in which paved areas are artificially given a variable or uniform loading, and (3) strip test in which a narrow path of material is laid down to be removed. Since the last test is easily run and readily reproducible, most of the data available is for strip tests. Since strip tests provide nearly ideal operating conditions, it is not surprising that results from such tests result in very high removal efficiency (90%). Controlled tests have reported less efficient results and in situ street tests even lower. It should be noted, however, that the in situ street tests represent actual real world conditions. A summary of these tests results is shown in Figure II.

In an in situ test conducted for the 1972 study, the contractor found that there was an overall removal effectiveness of 50% for sweeping operations. However, when considering the removal effectiveness in terms of particle size, the results are quite different. Larger particles are picked up very effectively (70 - 80%), however, the smaller fraction range (43 - 104u) in some cases showed an increase (See Table II).

Since approximately 80 - 90% of the material found on the road accumulates within 12 inches of the curb, most of the street cleaning operations concentrate on this area. Thus, since the smaller particles are not effectively picked up, they may be actually redistributed across the entire street, due to the action of the brushes near the curb.

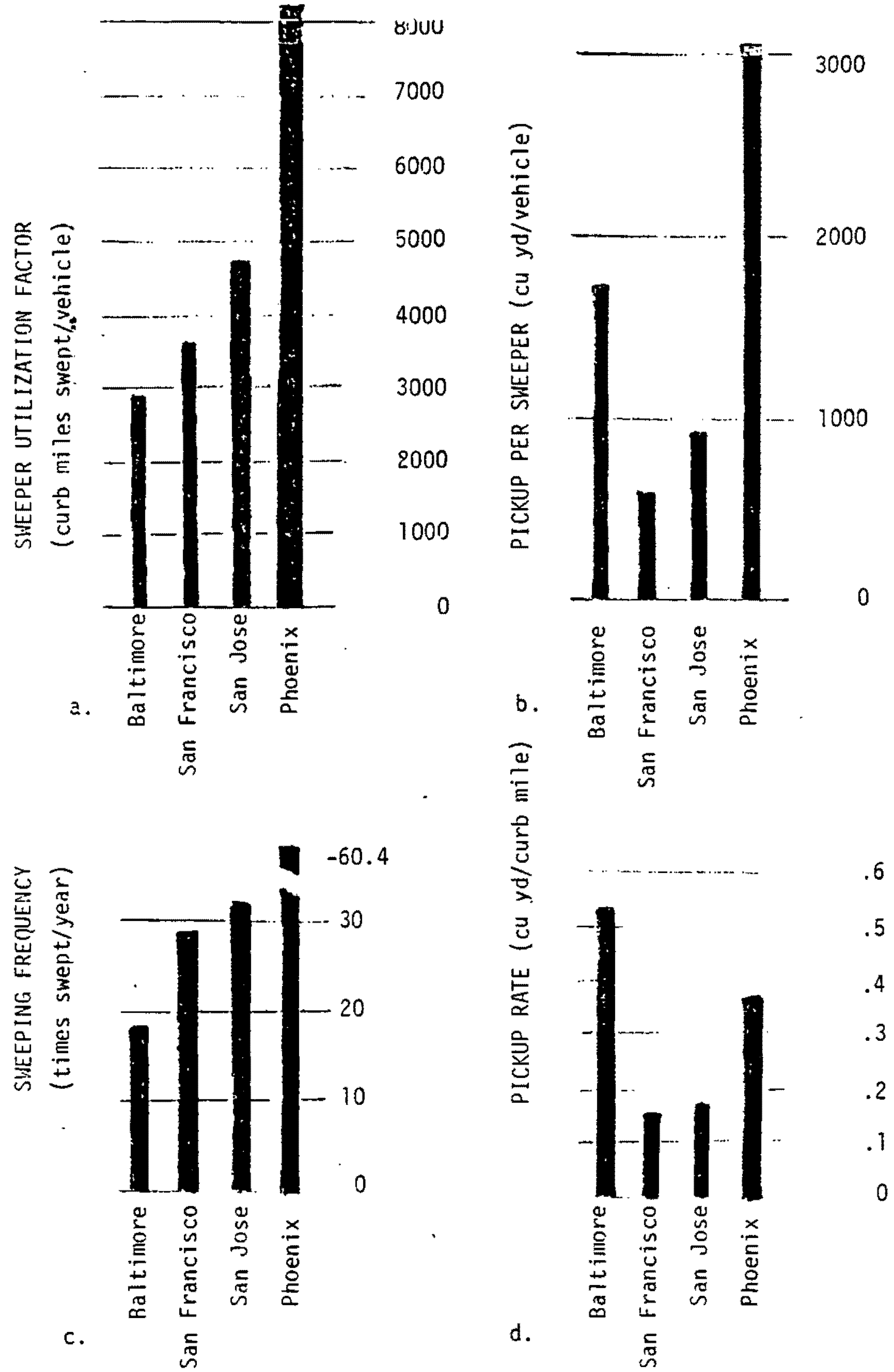


FIG. I. Comparison of Sweeper Performance in Four Cities

Source - Reference 12.

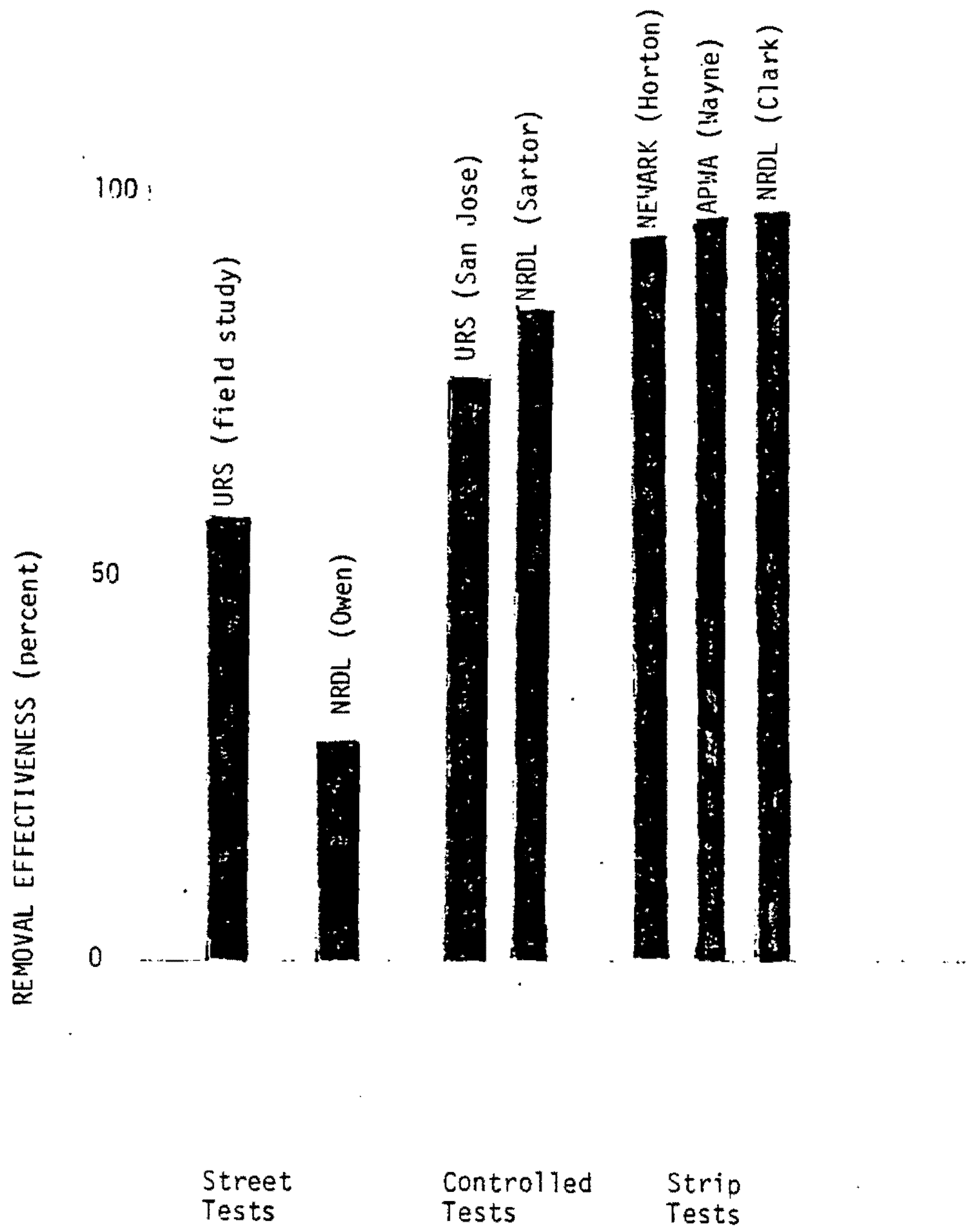


FIG. II. Comparison of Results from Sweeping Effectiveness Tests Conducted Under Various Conditions: For Dirt/Dust Fraction

Source - Reference 12.

TABLE II

REMOVAL EFFECTIVENESS VERSUS PARTICLE SIZE DISTRIBUTION

PARTICLE SIZE RANGE (micron)	ATLANTA INITIAL LOADING (g)	ATLANTA RESIDUAL LOADING (g)	TULSA INITIAL LOADING (g)	TULSA RESIDUAL LOADING (g)	PHOENIX INITIAL LOADING (g)	PHOENIX RESIDUAL LOADING (g)	SCOTTSDALE INITIAL LOADING (g)	SCOTTSDALE RESIDUAL LOADING (g)
> 2,000	175	76	1,438	142	535	240	217	43
840-2,000	103	14	418	181	308	107	439	124
246-890	375	56	690	588	2,190	224	915	115
104-246	231	29	544	595	1,273	381	421	287
43-104	66	136	415	549	425	614	213	134
< 43	43	187	324	431	175	498	87	44
Total (g)	993	498	3,829	2,486	4,906	2,064	2,292	1,017
Overall Eff. (%)		50		35		62		56

Source: Reference 12

These results were corroborated by another study which indicates the particles that are most important as far as air and water pollution is concerned are the most poorly reduced by conventional street sweeping procedures. Table III provides a summary by particle size of the results of the two studies mentioned above. The second study utilized an equation to determine the removal efficiencies.

The efficiency of street sweepers can be increased by (1) operating the sweeper at a slower rate, (2) increasing the number of passes on a given street, and (3) increasing the frequency of cleaning. In fact, it was shown that by decreasing the speed from 5 to 2½ mph almost as much dirt could be picked up in one pass as with two at the higher speed. Also, it was found that vacuum sweeping was more effective than motorized sweeping.

Two studies are currently underway to obtain more information about street cleaning operations. The first is a study by the National Science Foundation (NSF) under contract with the American Public Works Association to develop performance specifications for street cleaning as it pertains to air and water pollution requirements. The study has four major activities: (1) literature search relating to street sweeping, (2) survey of street cleaning equipment maintenance and costs, (3) survey of street cleaning practice and costs, and (4) develop performance specifications for existing technology and prescriptive specifications for environment-oriented technology.

The second study is being done as part of the EPA's New York City demonstration grant to the Interstate Sanitation Commission. As part of the study, Brooklyn Polytechnical Institute is evaluating the resuspension of dust from paved streets in New York City. Further information

Table III.

ESTIMATED STREET SWEEPER EFFICIENCY

PARTICLE SIZE (μ)	REMOVAL EFFICIENCY, (%)		
	IN SITU TEST	EQUATION	COMPOSITE (estimate)
> 2,000	78.8	-	79
840 - 2,000	66.4	-	66
246 - 840	69.5	49.2	60
104 - 246	47.7	48.7	48
43 - 104	< 0	22.2	20
< 43	< 0	15.8	15

Source - Reference 12.

on this project will be forthcoming as no specific date has been set for its completion.

In the past, the major concern of the Agency in regard to street cleaning, etc., has been with respect to the water oolution and solid waste aspects associated with these activities.[12, 13] Thus, up to now little emphasis has been placed upon street sweeping and cleaning for air pollution considerations. The major studies therefore that have been completed in the past and a majority of those going on presently, except for the above work, have been mainly associated with the solid waste and water pollution aspects of the problem.

Little information is available in the literature on the cost of street sweeping. What information is available has shown wide variations between cities of comparable size. One study[14] reported in the literature was done by The American City magazine in 1970 - 1971. In this survey only about one third of the survey-reporting cities supplied data on their unit street-sweeping costs, though sweeping is a major budget item. What information was available indicated that the average curb mile sweeping costs vary from $8.42 in the surveyed cities of 500,000 population and above to $2.18 per curb mile among those cities of 25,000 to 50,000 population. Some relatively old total expenditure data (1955) indicates the costs for street cleaning varies from 500,000 to 3 or 4 million dollars per year per city.

Summary

Since most of the work on street cleaning practices has been done in regard to the water pollution aspects, there is no real information available which indicates how effective these practices might be in controlling resuspension. To our knowledge, no work has been done to date in which ambient air quality samples have been collected before and after various street cleaning procedures have been used. In fact, we are unsure if the actual sweeping operation using brush-type sweepers does not in fact create more of a resuspension problem than it solves.[15] A good ambient study to further quantify the impact of these measures is needed before we recommend that they be used as part of the control strategy alternatives for resuspension.

In addition to the above control techniques, steps can be taken to minimize the amount of dust which can get onto the street in the first place. This concept in the past has generally been associated with abating of local nuisances. However, recently some have looked to these regulations as a source of control of resuspended particulate matter in that one could minimize the amount of material upon the roadway that has the potential of being resuspended. These regulations take many different forms or approaches. The first is the so called "mud-carryout" regulations. This regulation basically requires those involved in construction type operations, etc., to wash down the surrounding streets at the end of every day or so to minimize the amount of mud or soil carryout upon the surrounding streets.

The second type of control involves the watering or chemically stabilizing construction haul roads and other areas on the construction site to control wind induced or vehicle induced particulate emissions from construction activities.

The third type of regulation is the limitation of the number of acres that may be disturbed at any one time prior to stabilization. This greatly reduces the potential for vast areas of the construction site to be subjected to potential wind erosion.

The fourth type of control regulation deals with the issuance of a permit to construct or excavate. In this type of regulation the agency places stipulations on the permit that requires that the owner or operator take all reasonable precautions to minimize the dust emissions from this activity.

The fifth type of regulation deals with the requirement that all trucks carrying aggregate type material must be covered to minimize the emissions from transport and reduce losses due to spills.

While these type of regulations have been part of the air program in many cities for several years, there is no information available at present to indicate how actively these regulations are enforced if they are enforced at all. In addition, there have not been any studies done to indicate how effective these measures may be if they are properly used and actively enforced in reducing the TSP levels due to resuspended particulate matter. It is believed however that these types of minimizing regulations do have considerable promise in reducing the amount of material that can get onto the roadway and have the potential for resuspension.

APPENDIX

The following appendices contain information on the more technical aspects of the resuspension problem. They are included to provide a more thorough understanding of what is on the street and how does it get there? (Appendix A) and the range of emission factors associated with the resuspended problem (Appendix B).

Appendix A provides some insight into the nature and amount of material that is found on urban streets as a result of studies done to identify and quantify street surface contaminants.

Appendix B attempts to calculate some theoretical emission factors using all the available information found in the literature to date. It should not be interpreted to be the last word on emission factors for resuspension but should act as a guide to determine if the more empirical numbers are reasonable and in line with the ranges proposed in this paper.

APPENDIX A

WHAT IS ON THE STREET AND HOW DOES IT GET THERE?

A. Suspension Process

While particulate emissions from paved surfaces are primarily generated by vehicle motion, particulate emissions may also be generated when the wind velocity across a surface exceeds the threshhold velocity value at which dust becomes airborne from streets (i.e., erosion threshhold velocity). In Chicago, this threshhold velocity has been estimated to be 13 mph and is responsible for approximately 5% of the annual TSP concentration.

A threshhold value of air caused surface stress on a particle must be exceeded before a particle is suspended. "The threshhold stress is a function of particle properties as well as surface properties."[10] Particles for a given set of physical properties are resuspended more easily from a smooth surface than from one of irregular shape, such as an asphalt surfaced road. However, in some cases, the particles may become attached to the surface. This attachment of the particles to the surface or particles of the surface is referred to as weathering. Particles weather as a function of time and become more firmly attached to the surface, thus making them less susceptible to resuspension.[10]

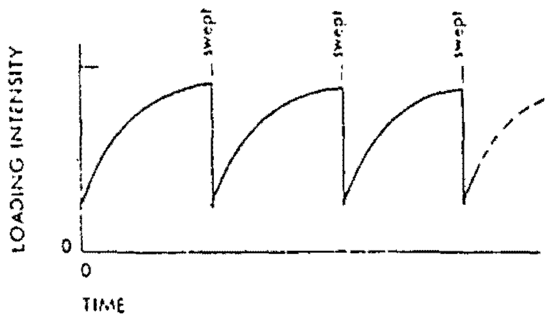
Basically, there are three types of movements associated with the action of the wind across a surface (usually soil, although it has an application to paved surface): surface creep, saltation and suspension. Surface creep is associated with particles in the size range of 500 to 1000 u. As the wind exerts its force on these large particles (500 to 1000 u) they are rolled along the ground, being pushed instead of lifted.

Saltation consists of individual particles jumping and bouncing within a few centimeters of the surface. The particles that are acted upon by saltation are those within the 100 to 500 u range. The third type of movement caused by the action of the wind consists of particles below 100 u being lifted off the surface and becoming completely airborne. These particles will stay suspended as long as the upward vertical velocities of the wind are greater than the terminal settling velocities of the particles. However, the mechanism whereby fine particles are suspended is slightly different than that described above. Some work by Dr. Chepil[16] has shown that soil or dust composed only of small particles lie in a somewhat laminar layer next to the surface and therefore do not protrude as much as larger particles do into the turbulent air layers. Therefore, if the dust contains larger particles, they are the first to be affected by surface creep which in turn causes saltation and finally suspension of the finer particles. It should be noted, however, that the fine dust is susceptible to suspension by means other than wind, such as the action of moving vehicles, people, etc.[4]

B. Accumulation Process

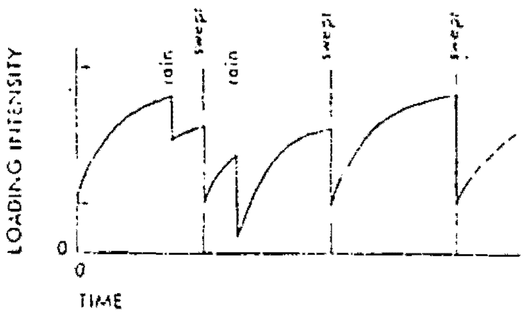
Before discussing the sources and amount of contaminants on a street, it is important to understand the basic principles involved with the accumulation of contaminants on a street surface. "Consider a hypothetical area of street surface which is (for the purposes of discussion) subjected to a continual and uniform loading of contaminants (uniform with respect to both time and spatial distribution). If there were no other activities to disturb the contaminants, the loading intensity would increase linearly with respect to time."[12]

Where periodic cleaning is practiced, the plot looks like below. Note that this represents a case of uniform, continuous loading and a regular cleaning (with the same degree of efficiency each time and a uniform frequency).



Accumulation of Contaminants - Hypothetical Case
(natural buildup with periodic sweeping but no rainfall)

Intermittent rains would also have an effect on accumulation. Large storms would remove more than sweepers; small storms, less.



Accumulation of Contaminants -
Typical Case (natural buildup
with periodic sweeping and
intermittent rainfall)

The main purpose for the above discussion is to place into context the meaning of the "observed loading intensities" to be discussed and provide a general understanding of the accumulation process. Streets were sampled to determine their contaminent loading intensities. At each sampling location, historical information was obtained as to when the street had last been swept and when the last rain occurred. While these data are of value, they can by no means be used to describe the shape of the overall curve. "Observed loading intensities" provide an answer to the question, how much material resides on a typical street at any point in time?[12]

C. Sources of Material Found on the Urban Roadway

Figure 3 is a block diagram depicting a qualitative mass balance for urban resuspension problems. Two studies have been done by Municipal Pollution Control Division (MPCD) of the Office of Research and Development, EPA,[12, 13] on the composition of materials on roadways in relation to the water pollution aspects of street surfaces and urban roadways which are applicable to air pollution problems.

The materials found on street surfaces vary greatly. Obviously, the material observed at any given location will be a composite of several sources depending on such factors as land use, geographical location, season, weather, traffic activity, etc. There are 6 major sources of materials found on the street:

(a) Erosion of street surface material itself. ("On a weight basis, aggregate materials account for the largest contribution from this source.")

(b) Motor vehicle related particles (broad range of materials, such as tire wear, particulate exhaust emissions and dirt from undercarriages).

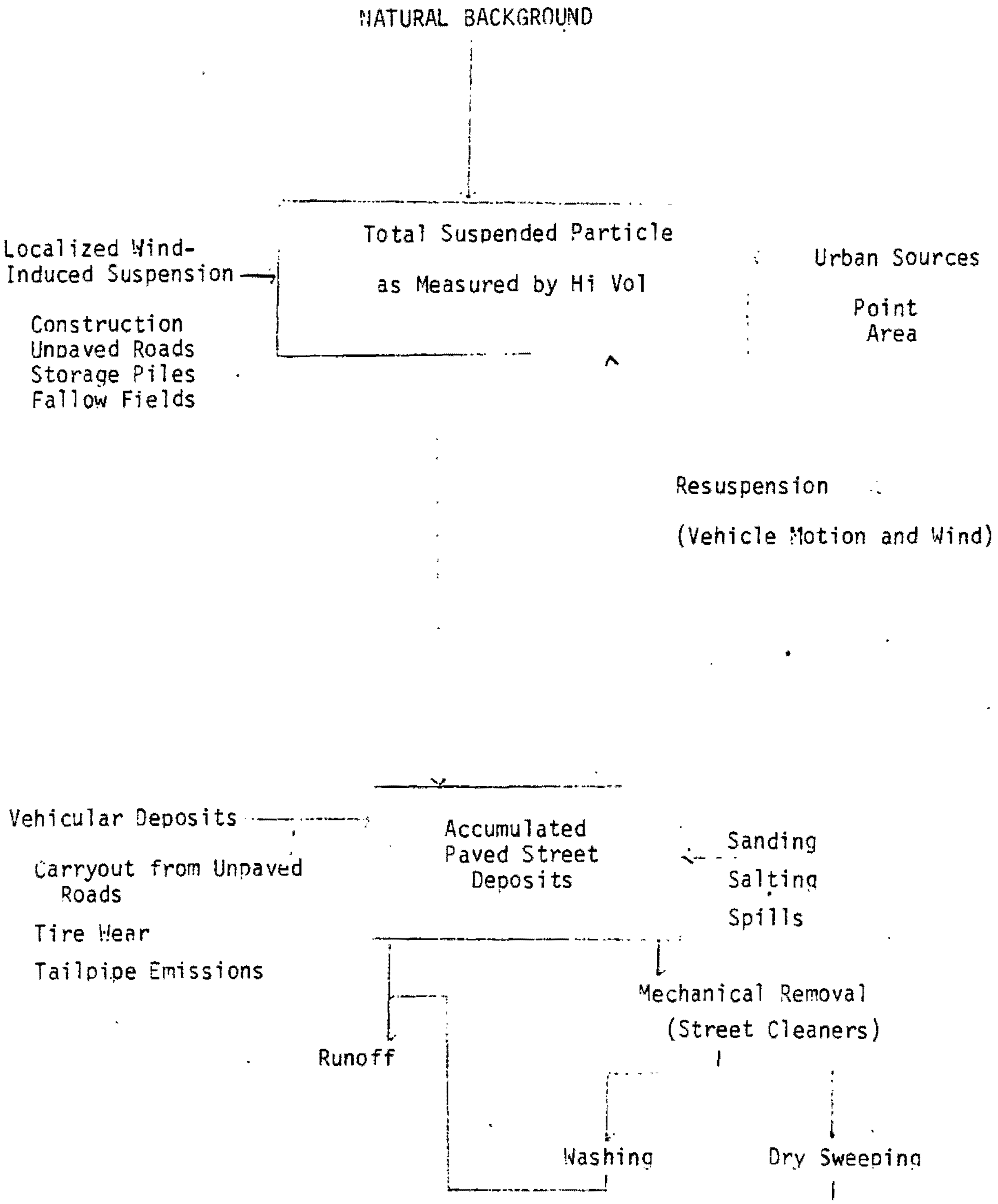


Figure 3. Urban Resuspension.

(c) Atmospheric fallout. (This material may be of a size fine enough that it could have been transported by air currents prior to being deposited on the street surface. Major sources of such materials would be industrial stacks, construction projects, agricultural operations and exposed vacant land.)

(d) Runoff from adjacent land areas. (Areas where soil is exposed rather than protected by vegetative cover, paving or other means.)

(e) Spills from vehicular transport. (While this source is well-known, it is virtually impossible to quantify. The types of material that may be included are dirt, sand, gravel, cement, etc.)

(f) Anti-skid compounds. (Sand, salt, ashes which are applied with the intent of melting ice or providing better traction during the winter months.)

It should be noted that the amount of material residing on a street surface will vary considerably from place to place and from time to time depending on several factors:

--time since last cleaning or rainfall

--season of year

--land use activity for a particular location

"Microscopic examination of the bulk of the materials found on street surfaces consists of inert minerals of various types which effect the components of street paving compounds and local geology." This inert or inorganic material is probably blown, washed, or tracked in from surrounding land areas. [12]

The quantity and character of contaminants found on streets is summarized in Table I. These data are weighted averages for the 12 cities samples (San Jose, Phoenix, Milwaukee, Bucyrus, Baltimore, Atlanta, Tulsa, Seattle, Decatur, Scottsdale, Mercer Island and Owasso). Table II contains the values for each land use category where samples were collected. These values are the average loadings one would find if the material were spread uniformly across the full width of the street. However, some studies have been done which indicate that some 80 - 90% of the material found on a street is within 12 inches of the curb. Therefore, the numbers in Tables IV and V should be used with caution.

The quantity of contaminant material existing at a given test site was found to depend upon the length of time which had elapsed since the site was last cleaned; intentionally (by sweeping or flushing) or by rainfall. The field sampling program focused on collecting materials from street surfaces at single points in time. However, information was collected for each site to define the elapsed time since the last substantial rain storm and/or cleaning. Accumulation patterns as calculated here are shown in Figure IV.

As can be seen, contaminant loading intensities were found to vary with respect to land-use activities. In general, industrial areas have substantially heavier than average loadings. This is probably due to the fact that these areas are swept less often and because "fallout", spills, unpaved roads, etc., tend to be high in these areas. However, commercial areas have substantially lighter loading. This may be due in part to the fact that they are swept more often than other

TABLE IV

MEASURED CONSTITUENTS	WEIGHTED MEANS FOR ALL SAMPLES (lb/curb mile)
Total Solids	1400
Oxygen Demand	
BOD_5	13.5
COD	95
Volatile Solids	100
Algal Nutrients	
Phosphates	1.1
Nitrates	.094
Kjeldahl Nitrogen	2.2
Bacteriological	
Total Coliforms (org/curb mile)	99×10^9
Fecal Coliforms (org/curb mile)	5.6×10^9
Heavy Metals	
Zinc	.65
Copper	.20
Lead	.57
Nickel	.05
Mercury	.073
Chromium	.11
Pesticides	
p,p-DDD	67×10^{-6}
p,p-DDT	61×10^{-6}
Dieldrin	24×10^{-6}
Polychlorinated Biphenyls	1100×10^{-6}

Source: Reference 12

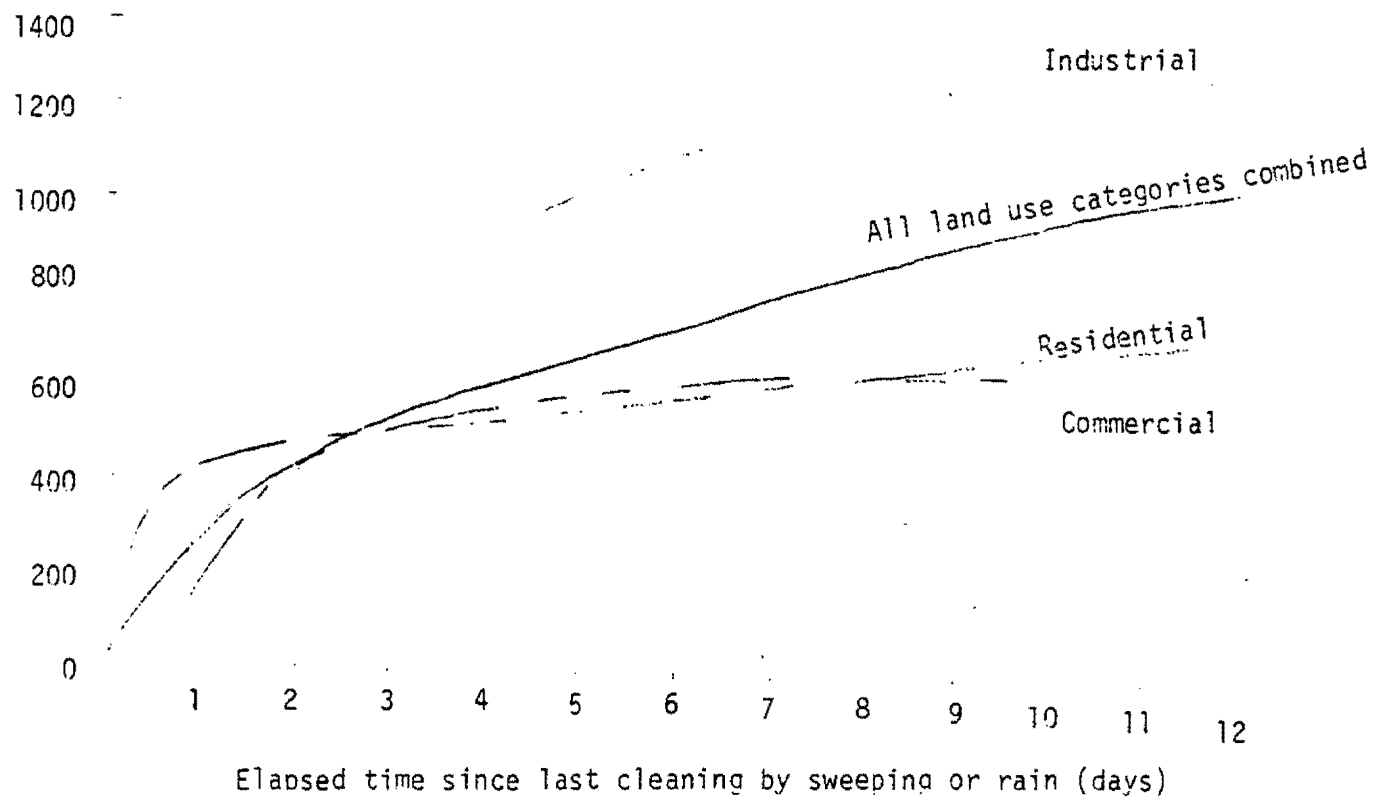
Note: The term "org" refers to "number of coliform organisms observed."

TABLE V

LAND USE	NUMERICAL MEAN (lb/curb mi)	WEIGHTED MEAN (lb/curb mi)
Residential		1,200
low/old/single	850	
low old/multi	800	
med/new single	430	
med/old/single	1,200	
med/old/multi	1,400	
Industrial		2,800
light	2,600	
medium	800	
heavy	3,500	
Commercial		290
central		
business district	290	
shopping center	290	
Overall		1,100

Source - Reference 12.

Figure IV



Source: Appendix I Reference 12

areas. Finally, residential areas were found to have an average loading intensity comparable to the average for all land use of all cities. However, the loading varied widely from site to site. One possible explanation that the more affluent neighborhoods tended to be cleaner possibly because they are better maintained by residents.

In order for the above information on loadings to be useful to air pollution work, one must know what percent of this material may become suspended and collected by the high volume air sampler. In theory particles less than 100u can readily become suspended and be measured as total suspended particles by the high volume air sampler technique.

Particle size distributions were determined from composite samples collected from 5 representative cities. The data were determined by summing values obtained by dry sieving, wet sieving and sedimentation pipette analysis. The results are given in Table IV. The average percent composition of particles less than 100u was approximately 25%.

Thus, in order to obtain the amount of material which has the potential for resuspension, one must multiply the value for a given land use category by 25% (That percent of material which is less than 100u). If the overall weighted mean average of 1400 lb/curb mile is used, then (.25 x 1400 lb/curb mi = 350 lb/curb mile) is in the potential size range for resuspension, and collection by the high volume air sampler.

In a second study by MPCD[13] work was done to analyze roadway dust and dirt. (See Table VII.) Street surface contaminants are deposited on the roadway from many sources as stated above. Metropolitan Washington, D.C., with its low background of industrial emissions was chosen for a study to determine the contribution of motor vehicle usage to urban roadway loading. Specific sites were selected to provide minimal interference from non-traffic related land use activites and thus isolate traffic-related depositions.

Less than 5% by weight of the material on the streets originates directly from motor vehicles, however, these pollutants are important because of their potential toxicity (lead, zinc, other metals, asbestos from clutch and brake linings), the bulk of the traffic-related material is representative of local geology and to lesser extent, products of abraded roadway surfaces.

An examination of the street surface contaminants found that they consisted largely of roadway surfacing materials and various mineral forms representative of the local geology. The results of the study showed that dust and dirt is composed of over 95% inorganic material, most of which is insoluable. Close examination of the particles under the microscope revealed many individual particles appeared to be fractured mineral crystals. A semiquantitative emission spectrographic analysis of eight samples were performed to determine the major metallic constituents. The results are summarized in Table VII.

Loadings intensities of street surface contaminants measured during a 12-month field study were examined and observed loadings were plotted as the dependent variable against total traffic and least square equation of the linear relationships were calculated. For example, the equation of the least squares line obtained upon plotting total dust and dirt by weight in pounds per mile against traffic in axles is:

$$\text{lb/mile} = 96 + .00238 \text{ tires axles}$$

Table VI

PARTICLE SIZE DISTRIBUTION OF SOLIDS
SELECTED CITY COMPOSITES

SIZE RANGES	MILWAUKEE	BUCYRUS	BALTIMORE	ATLANTA	TULSA
> 4,800 μ	12.0%	- %	17.4%	- %	- %
2,000-4,800 μ	12.1	10.1	4.6	14.8	37.1
840-2,000 μ	40.8	7.3	6.0	6.6	9.4
216-840 μ	20.4	20.9	22.3	30.9	16.7
104-216 μ	5.5	15.5	20.3	29.5	17.1
43-104 μ	1.3	20.3	11.5	10.1	12.0
30-43 μ	4.2	13.3	10.1	5.1	3.7
14-30 μ	2.0	7.9	4.4	1.8	3.0
4-14 μ	1.2	4.7	2.6	0.9	0.9
< 4 μ	0.5	-	0.9	0.3	0.1
Sand %, 43-4,800 μ	92.1	74.1	82.1	91.9	92.3
Silt %, 4-43 μ	7.4	25.9	17.1	7.8	7.6
Clay %, < 4 μ	0.5	-	0.9	0.3	0.1
Lb Sand/curb mi	2,480	1,020	815	394	300
Lb Silt/curb mi	200	356	176	33.5	30
Lb Clay/curb mi	13.5	-	9.3	1.3	0.3

Note: μ = microns.
Source: Reference 12

TABLE VII

SEMIQUANTITATIVE EMISSION SPECTROGRAPHIC ANALYSES
OF ROADWAY DUST AND DIRT SAMPLES
(WASHINGTON, D.C. METROPOLITAN AREA)

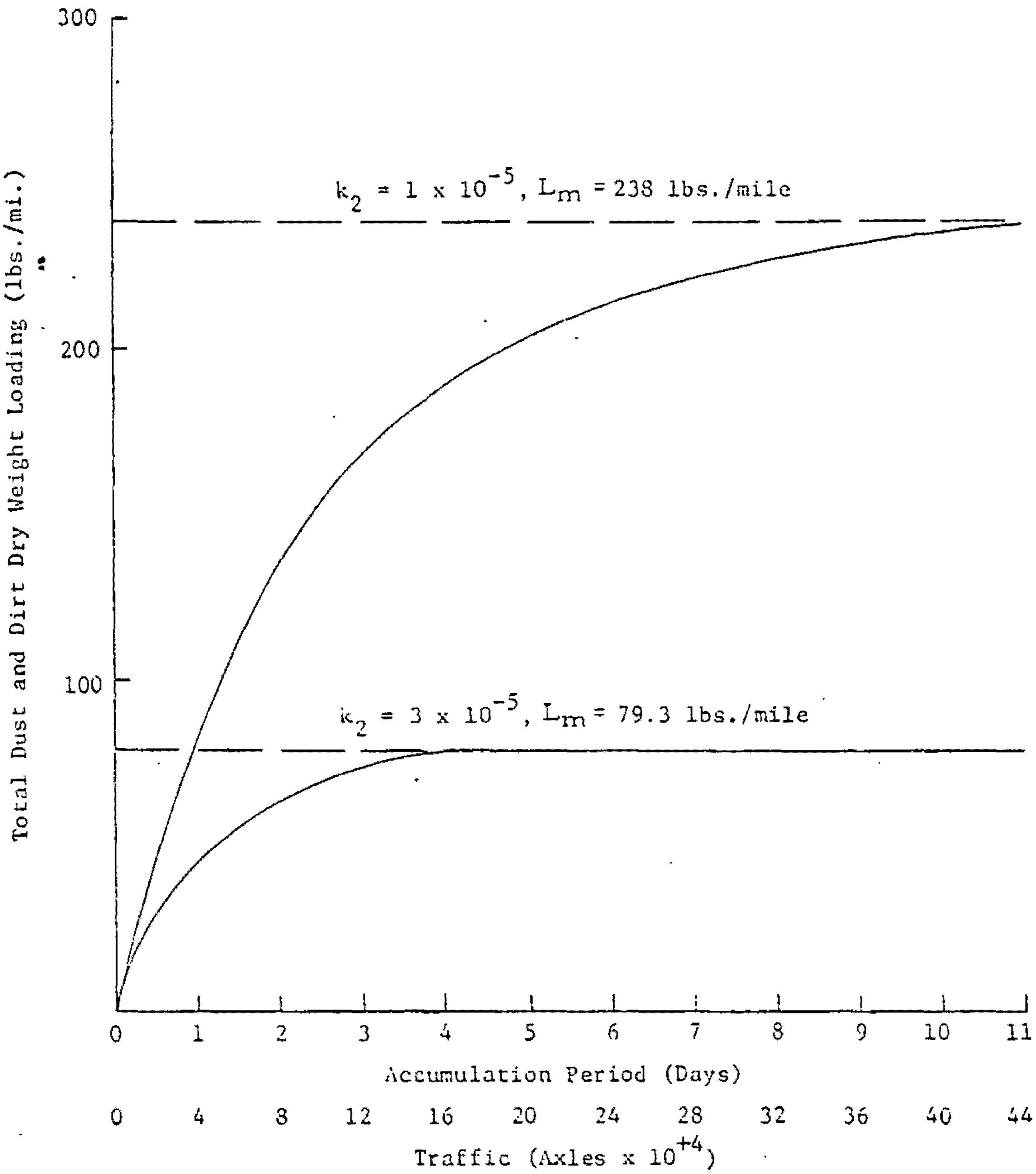
Concentration range	Element
High	Silicon
	Iron
	Aluminum
Med-high	Calcium
	Magnesium
Low	Titanium
	Zinc
Low-med	Lead
Trace	Boron
	Barium
	Cobalt
	Strontium
	Chromium
	Copper
	Vanadium
	Nickel
Trace-med	Sodium
Trace-low	Zirconium
	Manganese
n.d.-trace	Molybdenum
	Tin

Reference 13

Although the deposition of traffic-related materials occurs at a constant rate, the accumulation of material along the roadway tends to level off after some period of time due to traffic-related removal mechanisms. The y intercept, 96 lb/roadway mile, is the amount of total dust which appears as a result of phenomena not related to actual traffic. This is dependent upon geographic location and the intensity of the local particulate air pollution problem. Only a very small portion of the 96 lb/roadway mile is due to materials abraded from the roadway during sample collection. Therefore, in any event a majority of the y intercept results from the transport of particulate pollutants from air currents from some distance. Since the rate at which airborne material is deposited is more nearly time dependent than traffic related, the y-intercept is no doubt a function of time.

As mentioned previously, the deposition of the pollutants on a street through traffic-related mechanisms appears to occur at a relatively constant rate and is independent of loadings already present. However, the accumulation of surface contaminants is not linear and levels off due to a combination of factors, other than cleaning or rainfall.

One hundred twenty-seven (127) roadway samples were collected during the study, 94 of which samples were taken to be used in calculation of traffic-related deposition rates. Of the 94, 75 were collected after a one-day accumulation. The remaining 19 samples were gathered after either 3 or 4 days accumulation. Comparisons of the loading samples for one day accumulation with those of multiday accumulation revealed that within 3 or 4 days, the loading began to level off and approach a maximum value. This occurs as particles of the material are picked up by passing traffic and by other mechanisms and displaced onto areas adjacent to the roadways. Mechanical fracture to smaller particle size, as well as physical transport, is postulated as the mechanism responsible for this leveling off. The relationship between total dust and dirt dry-weight loading and accumulation period are shown in Figure II for one street in Washington, D.C. using above estimates of K_2 (removal rate) and K_1 (deposition rate) = 2.38×10^{-3} lb/axle-mile and average daily traffic (ADT) of 40,000 axles. The speed limit on this street is 30 mph. Thus, given the proper information to calculate K_2 and ADT, one can calculate the maximum pollutant loading on any given street for traffic-related sources of street dust. However, as mentioned above, motor vehicle or traffic-related sources of contaminants are only one source of dust and dirt found on the street surface, therefore, in order to calculate the amount of total material that is susceptible to resuspension (<100u), one should use the total loading intensities approach from the first MPCD study for particles less than 100u.[12]



(k_1 = 2.38 x 10^{-3} lbs./axle-mile, ADT = 40,000 axles)

Figure V Total dust and dirt dry weight accumulation

Source: Reference 13

APPENDIX B

THEORETICAL EMISSION FACTOR ESTIMATES FOR RESUSPENSION

The previous information in Appendix A on loading intensities coupled with the information on the fraction resuspended from Chapter I allows one to calculate a resuspension factor in lb/veh-mile.

I. Loading Intensity Approach (MDCD/Sehmel Data)

Since the accumulated loading begins to level off after the third or fourth day, the resuspension rate which utilized the 5-day weathering factor (from Sehmel's work, see Chapter I) is used to calculate a resuspension factor. This factor would estimate the amount of material generated (<100u) which would be suspended beyond 30 feet from the roadway and theoretically would be measured by a high volume air sampler.

Overall $$\frac{(4.44 X 10^{-5})(350\ lb)}{\text{vehicle}\quad \text{mile}} = \frac{.015\ lb}{\text{veh-mile}} = \frac{7.05g}{\text{veh-mile}}$$

Residual Street $$(4.44 X 10^{-5})(300) = \frac{.013 lb}{\text{veh-mile}} = \frac{6.05g}{\text{veh-mile}}$$

Industrial Street $$(4.44 X 10^{-5})(700) = \frac{.031 lb}{\text{veh-mile}} = \frac{14.11g}{\text{veh-mile}}$$

Commercial Street $$(4.44 X 10^{-5})(72.5) = \frac{.003\ lb}{\text{veh-mile}} = \frac{1.46g}{\text{veh-mile}}$$

It should be noted that these factors represent averages based upon loadings which were highly variable from site to site and city to city. Also no ambient measurements were made in the vicinity of the roads in the water pollution studies to provide any cross-check on the validity of using the values obtained by Sehmel in his tracer work. Sehmel also was only concerned with asphalt roads and the streets used in the water pollution studies were constructed of various materials not just asphalt. In fact, the first study by MPCH states that pavement composition and coordination

$.05 \text{ TMVEF} = .34$

$\text{TMVEF} = 6.8$

$$\begin{aligned} \text{Road dust} &= \text{TMVEF} - \text{exhaust} - \text{tire wear} - \text{brake wear} \\ &= 6.8 - .34 - .2 - .02 \\ &= 6.24 \text{ grams/vmt} \end{aligned}$$

III. Lead Tracer Approach

Another approach for estimating the impact of resuspension via an emission factor is to utilize the lead tracer concept.[18] From previous work on auto exhaust particles, lead is believed to comprise 26% of the suspended particle emissions from automobiles.[19] Thus, if one has ambient lead data, he can obtain the associated auto tailpipe emissions by multiplying by 3.8 (3.8 x 26% = 100% TSP auto). In the case of Denver, Colorado, the annual arithmetic mean for TSP at the one site with lead data is 139 ug/m^3. The average lead concentration at that site is 1.61 ug/m^3.

$$\begin{array}{rl} 139 \text{ ug/m}^3 & \\ - \underline{35 \text{ ug/m}^3} & \text{background} \\ 109 \text{ ug/m}^3 & \text{from man-made sources} \end{array}$$

$1.61 \times 3.8 = 6.12 \text{ ug/m}^3$ from auto TSP tailpipe

Thus if the site were solely traffic-originated, then the worst case situation would assume that all the remaining TSP were from resuspension alone.

Thus if all the remaining TSP were from resuspension then

$$\frac{\text{AQ auto}}{\text{AQ resup}} = \frac{\text{EF auto}}{\text{EF resup}}$$

$$\frac{6.12 \text{ ug/m}^3}{109 - 6.12 \text{ ug/m}^3} = \frac{.34 \text{ g/vmt}}{X}$$

EF = 5.72 g/vmt (Probable worst case number)

However, if the site is not strictly influenced by traffic-related activities, then one might assume that only 15% of the annual TSP is auto-related resuspension as estimated in Abel's work in Chicago as referenced above:

$$\frac{6.12\ ug/m^3}{20.85\ ug/m^3} = \frac{.34}{X}$$

$$\therefore \quad X = 1.16\ g/vmt$$

IV. Air Quality Impact Approach

Another approach is to attempt to define an air quality impact type factor rather than just an emission source type. This was attempted by using the line source model and air quality data from a site in Philadelphia which is located very near a heavily traveled paved road and which is believed to record TSP values which are highly related to traffic activity.

The line source equation when the wind direction is normal to the line is as follows:

$$X = \frac{2 \exp -\frac{1}{2} \left(\frac{H}{\sigma_z}\right)^2 q}{\sqrt{2\pi}\ \sigma_z\ U} \qquad 20$$

X = conc. mg/m^3

q = source strength g/sec-meter

σ_z = vertical dispersion coefficient

H = source or receptor height (m)

U = average wind speed (m/sec)

Now solving for source strength line source equation becomes

$$q = \frac{X\ \sqrt{2\pi}\ \sigma_z\ U}{2 \exp -\frac{1}{2} \left(\frac{H}{\sigma_z}\right)^2}$$

For the particular situation in Philadelphia the following values were used:

$X = AQ - Bkg = 115-35 = 80\ mg/m^3$

$\sigma_z = 4.6$ m (Figure 3-3 Turner[18]) for x = .006 km

$U = 4.47$ m/sec

$H = 3.96$ m

$$q = \frac{.08\ \sqrt{2(3.14)}\ (4.6)\ (4.47)}{2\ \exp\ -\frac{1}{2}\left(\frac{3.96}{4.6}\right)^2} \qquad \frac{4.12}{1.38}$$

$$q = 2.9855\ mg/m/sec$$

The street near where the monitor is located has an average weekday traffic count of 30,000 vehicle/day. Thus, in order to develop a factor in grams/vmt, one must use the ADT data coupled with the calculated source strength asfollows:

$$q = \frac{2.9855 \times 10^{-3}}{m - sec} \times \frac{3600\ sec}{hr} \times \frac{8760\ hr}{yr} \times \frac{M}{6.21 \times 10^{-4}\ miles} \times \frac{yr}{26/wkday} \times \frac{wkday}{30,000}$$

$$q = 19.44\ grams/vmt$$

The above estimate is simply used as a rough estimate of how the approach would be used; however, it does attempt to provide a "ball park estimate" of resuspension influence as related to existing air quality levels. Certainly such things as particle size and density of the material a hi-vol might collect at 6 m from the road at a height of 13 feet off the ground is a factor along with the particle size and density of the material on the roadway. More accurate estimates of wind speed and direction along with a better estimate of ADT and daily air quality levels would provide a better estimate of the source strength from the road as calculated via its impact on existing hi-volume air samplers. The number above again would probably be a worst case estimate. Also, if there were other hi-vols at varying distances from the roadway, one could use this technique to calculate the source strength from the road based on each hi-vol measurement and average these to provide an estimate of what had to be the calculated source strength to have the TSP levels at varying distances from the roadway as measured by the hi-vol.

V. Summary and Status of Current Work on Emission Factors

Thus with the exception of the Seattle data, all the values for vehicle resuspension are in the range of 1 to 20 g/vmt. (See Table VIII.) The most reasonable values appear to be somewhere between 1-5 g/vmt as the number generated using the MPCD values for loading could be reduced substantially if one assumes that only particles of 30-40u or less instead of 100u or less would actually be picked up and deposited beyond the immediate vicinity of the street. If one does make this assumption, (i.e., only particles less than 40u), then the overall factor from the Sehmel/MPCD data would become

$$(4.44 \times 10^{-5})(1400)(.135) = \frac{.01 \text{ lb}}{\text{veh mi}} = \frac{4.54 \text{ g}}{\text{veh mi}}$$

Recently another approach has been used by RTI under contract with EPA in their efforts to identify problems associated with non-attainment in North Carolina. In this approach RTI modeled two cities in North Carolina, and in both cases the model calibrated quite poorly. As a result of this poor calibration, RTI found that they had overlooked resuspended particulate emissions from paved streets. By a trial-and-error method, they used various emission factors for resuspensed particulate matter from paved streets until they obtained a good correlation between predicted and measured air quality. They found their best correlation when 6.1 g/vmt was used as an emission factor. They tried their same approach in another city and found the value to be 4.2 g/vmt. While the factors are relatively close considering two different cities were involved, further investigation found that the city with the lower emission factor had some vacuum sweeping as part of its street cleaning program, which is more effective than brush-type sweepers used in

TABLE VIII

Study	Road Surface	Particulate Emission Factor
Dumawish Valley	Dusty paved road--no curb	376 g/vmt (77 g/vmt $<10\mu$)
	Paved streets--washed regularly	63 g/vmt
	Mud carryout from gravel roads	3174 g/vmt
	Carryout from unpaved parking lots	336 g/vmt
Nashville Work	Dust from paved streets	.8 g/vmt
Nashvile Work Modified	Dust from paved streets	6.24 g/vmt
Lead Tracer Approach	Dust from paved streets	5.72 g/vmt
Lead Tracer Approach Modified	Dust from paved streets	1.16 g/vmt
Air Quality Impact Modified	Dust from paved streets	19.44 g/vmt
Sehmel/MPCD	Dust from paved streets	7.05 g/vmt
Sehmel/MPCD Modified	Dust from paved streets	4.54 g/vmt
RTI Approach	Dust from paved streets	4-6 g/vmt
MRI Preliminary	Dust from paved streets	10 g/vmt (6.1 g/vmt $<30\mu$)

the other city. More work is proceeding on this study and the final report should be available shortly.

Preliminary indications from some emission factor work currently being done by MRI under contract with EPA indicate that the emission factor may be approximately 10 g/vmt(6.1 g/vmt<30μ). The final report on this study is due in March of 1976.

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