13.2.1 Paved Roads

13.2.1.1 General

Particulate emissions occur whenever vehicles travel over a paved surface such as a road or parking lot. Particulate emissions from paved roads are due to direct emissions from vehicles in the form of exhaust, brake wear and tire wear emissions and resuspension of loose material on the road surface. In general terms, resuspended particulate emissions from paved roads originate from, and result in the depletion of, the loose material present on the surface (i.e., the surface loading). In turn, that surface loading is continuously replenished by other sources. At industrial sites, surface loading is replenished by spillage of material and trackout from unpaved roads and staging areas. Figure 13.2.1-1 illustrates several transfer processes occurring on public streets.

Various field studies have found that public streets and highways, as well as roadways at industrial facilities, can be major sources of the atmospheric particulate matter within an area.[1-9] Of particular interest in many parts of the United States are the increased levels of emissions from public paved roads when the equilibrium between deposition and removal processes is upset. This situation can occur for various reasons, including application of granular materials for snow and ice control, mud/dirt carryout from construction activities in the area, and deposition from wind and/or water erosion of surrounding unstabilized areas. In the absence of continuous addition of fresh material (through localized trackout or application of antiskid material), paved road surface loading should reach an equilibrium value in which the amount of material resuspended matches the amount replenished. The equilibrium surface loading value depends upon numerous factors. It is believed that the most important factors are: mean speed of vehicles traveling the road; the average daily traffic (ADT); the number of lanes and ADT per lane; the fraction of heavy vehicles (buses and trucks); and the presence/absence of curbs, storm sewers and parking lanes.[10]

EPA's Office of Transportation and Air Quality plans to release the MOBILE6.1 model soon. This model will calculate particulate emissions from on road mobile sources from the engine exhaust, brake wear and tire wear. The emission factors in this section of AP-42 implicitly include the emissions of exhaust, brake wear, and tire wear that occurred in the field testing that produced the data used to develop the emission factor equation, in addition to resuspended particulate matter from the road surface. Therefore, adding the emission factors in this section to those calculated by MOBILE6.1 poses the problem of double counting. The double counting problem is of most concern when estimating the emissions on high traffic volume roads with low surface silt loadings. The following modifications should be made if double counting is a substantial issue for a particular application of this section. Where MOBILE6.1 predicts higher emissions of particulate matter than the equations in this section for a given combination of road and traffic variables, then only the MOBILE6.1 results should be used and resuspended particulate matter should be considered negligible. Where MOBILE6.1 predictions are less than the emissions that would be predicted from the equation in this section, then the emissions calculated with the equation in this section can be taken as a reasonable representation of total particulate emissions. If in such a case it is desired to separate emissions into resuspended particulate matter versus exhaust, brake and tire wear matter, then the MOBILE6.1 estimates can be subtracted from the estimates made using the equation in this section with the remainder taken as the resuspended portion of the emissions.

13.2.1.2 Emissions And Correction Parameters

Dust emissions from paved roads have been found to vary with what is termed the "silt loading" present on the road surface as well as the average weight of vehicles traveling the road. The term silt loading (sL) refers to the mass of silt-size material (equal to or less than 75 micrometers [µm] in physical diameter) per unit area of the travel surface. The total road surface dust loading consists of loose material that can be collected by broom sweeping and vacuuming of the traveled portion of the paved road. The silt fraction is determined by measuring the proportion of the loose dry surface dust that passes through a 200-mesh screen, using the ASTM-C-136 method. Silt loading is the product of the silt fraction and the total loading, and is abbreviated "sL". Additional details on the sampling and analysis of such material are provided in AP-42 Appendices C.1 and C.2.

The surface sL provides a reasonable means of characterizing seasonal variability in a paved road emission inventory. In many areas of the country, road surface loadings [11-21] are heaviest during the late winter and early spring months when the residual loading from snow/ice controls is greatest. As noted earlier, once replenishment of fresh material is eliminated, the road surface loading can be expected to reach an equilibrium value, which is substantially lower than the late winter/early spring values.

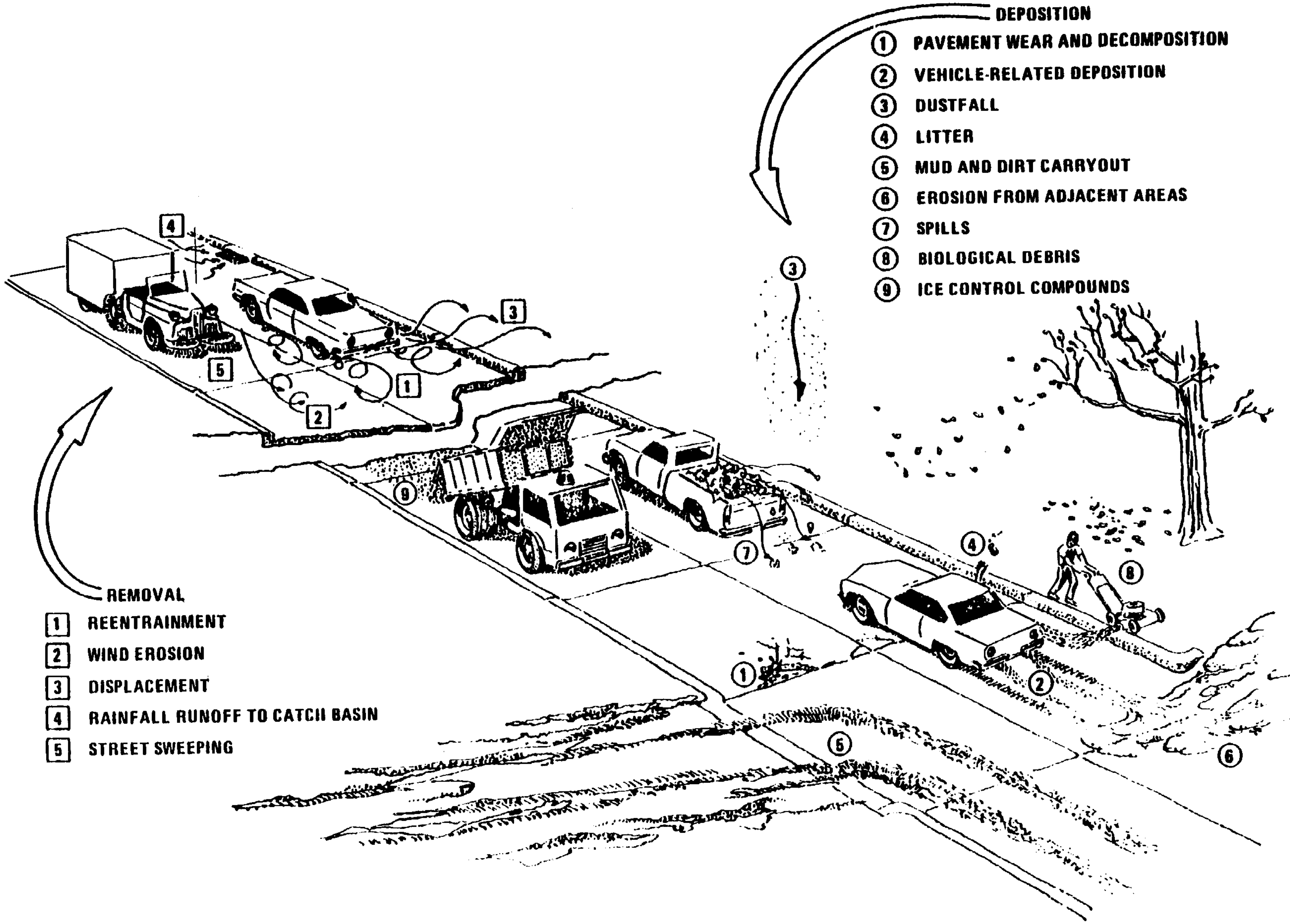

Figure 13.2.1-1. Deposition and removal processes.

13.2.1.3 Predictive Emission Factor Equations[10]

The quantity of particulate emissions from vehicle traffic on a dry paved road may be estimated using the following empirical expression:

$$E = k\ (sL/2)^{0.65}\ (W/3)^{1.5} \qquad (1)$$

where:

E = particulate emission factor (having units matching the units of k)
k = particle size multiplier for particle size range and units of interest (see below)
sL = road surface silt loading (grams per square meter) (g/m^2)
W = average weight (tons) of the vehicles traveling the road

It is important to note that Equation 1 calls for the average weight of all vehicles traveling the road. For example, if 99 percent of traffic on the road are 2 ton cars/trucks while the remaining 1 percent consists of 20 ton trucks, then the mean weight "W" is 2.2 tons. More specifically, Equation 1 is *not* intended to be used to calculate a separate emission factor for each vehicle weight class. Instead, only one emission factor should be calculated to represent the "fleet" average weight of all vehicles traveling the road.

The particle size multiplier (k) above varies with aerodynamic size range as shown in Table 13.2.1-1. To determine particulate emissions for a specific particle size range, use the appropriate value of k shown in Table 13.2.1-1.

Table 13.2-1.1. PARTICLE SIZE MULTIPLIERS FOR PAVED ROAD EQUATION

Size range[a]	Particle Size Multiplier k[b]		
	g/VKT	g/VMT	lb/VMT
PM-2.5[c]	1.1	1.8	0.0040
PM-10	4.6	7.3	0.016
PM-15	5.5	9.0	0.020
PM-30[d]	24	38	0.082

[a] Refers to airborne particulate matter (PM-x) with an aerodynamic diameter equal to or less than x micrometers.

[b] Units shown are grams per vehicle kilometer traveled (g/VKT), grams per vehicle mile traveled (g/VMT), and pounds per vehicle mile traveled (lb/VMT). The multiplier k includes unit conversions to produce emission factors in the units shown for the indicated size range from the mixed units required in Equation 1.

[c] Ratio of PM-2.5 to PM-10 taken from Reference 22**.**

[d] PM-30 is sometimes termed "suspendable particulate" (SP) and is often used as a surrogate for TSP.

The above equation is based on a regression analysis of numerous emission tests, including 65 tests for PM-10.[10] Sources tested include public paved roads, as well as controlled and uncontrolled industrial paved roads. All sources tested were of freely flowing vehicles traveling at constant speed on relatively level roads . No tests of "stop-and-go" traffic or vehicles under load were available for inclusion in the data base. The equations retain the quality rating of A (B for PM-2.5), if applied within the range of source conditions that were tested in developing the equation as follows:

Silt loading:	0.02 - 400 g/m^2
	0.03 - 570 grains/square foot (ft^2)
Mean vehicle weight:	1.8 - 38 megagrams (Mg)
	2.0 - 42 tons
Mean vehicle speed:	16 - 88 kilometers per hour (kph)
	10 - 55 miles per hour (mph)

To retain the quality rating for the emission factor equation when it is applied to a specific paved road, it is necessary that reliable correction parameter values for the specific road in question be determined. With the exception of limited access roadways, which are difficult to sample, the collection and use of site-specific silt loading (sL) data for public paved road emission inventories are strongly recommended. The field and laboratory procedures for determining surface material silt content and surface dust loading are summarized in Appendices C.1 and C.2. In the event that site-specific values cannot be obtained, an appropriate value for a paved public road may be selected from the values given in Table 13.2.1-2, but the quality rating of the equation should be reduced by 2 levels. Also, recall that Equation 1 refers to emissions due to freely flowing (not stop-and-go) traffic at constant speed on level roads.

Equation 1 may be extrapolated to average uncontrolled conditions (but including natural mitigation) under the simplifying assumption that annual (or other long-term) average emissions are inversely proportional to the frequency of measurable (> 0.254 mm [0.01 inch]) precipitation by application of a precipitation correction term. The precipitation correction term can be applied on a daily or an hourly basis. For the daily basis, equation 1 becomes:

$$E_{ext} = k\,(sL/2)^{0.65}\,(W/3)^{1.5}\,(1-P/4N) \qquad (2)$$

where k, sL, and W are as defined in Equation 1 and

E_{ext} = annual or other long-term average emission factor in the same units as k
P = number of “wet” days with at least 0.254 mm (0.01 in) of precipitation during the averaging period
N = number of days in the averaging period (e.g., 365 for annual, 91 for seasonal, 30 for monthly)

Note that the assumption leading to Equation 2 is based on analogy with the approach used to develop long-term average unpaved road emission factors in Section 13.2.2. However, Equation 2 above incorporates an additional factor of "4" in the denominator to account for the fact that paved roads dry more quickly than unpaved roads and that the precipitation may not occur over the complete 24-hour day.

For the hourly basis, equation 1 becomes:

$$E_{ext} = k\,(sL/2)^{0.65}\,(W/3)^{1.5}\,(1-1.2P/N) \qquad (3)$$

where k, sL, and W are as defined in Equation 1 and

E_{ext} = annual or other long-term average emission factor in the same units as k
P = number of hours with at least 0.254 mm (0.01 in) of precipitation during the averaging period
N = number of hours in the averaging period (e.g., 8760 for annual, 2124 for seasonal, 720 for monthly)

Note: In the hourly moisture correction term (1-1.2P/N) for equation 3, the 1.2 multiplier is applied to account for the residual mitigative effect of moisture. For most applications, this equation will produce satisfactory results. However, if the time interval for which the equation is applied is short, e.g., for one hour or one day, the application of this multiplier makes it possible for the moisture correction term to become negative. This will result in calculated negative emissions which is not realistic. Users should expand the time interval to include sufficient "dry" hours such that negative emissions are not calculated. For the special case where this equation is used to calculate emissions on an hour by hour basis, such as would be done in some emissions modeling situations, the moisture correction term should be modified so that the moisture correction "credit" is applied to the first hours following cessation of precipitation. In this special case, it is suggested that this 20% "credit" be applied on a basis of one hour credit for each hour of precipitation up to a maximum of 12 hours.

Note that the assumption leading to Equation 3 is based on analogy with the approach used to develop long-term average unpaved road emission factors in Section 13.2.2.

Figure 13.2.1-2 presents the geographical distribution of "wet" days on an annual basis for the United States. Maps showing this information on a monthly basis are available in the *Climatic Atlas of the United States*[23]. Alternative sources include other Department of Commerce publications (such as local climatological data summaries). The National Climatic Data Center (NCDC) offers several products that provide hourly precipitation data. In particular, NCDC offers *Solar and Meteorological Surface Observation Network 1961-1990* (SAMSON) CD-ROM, which contains 30 years worth of hourly meteorological data for first-order National Weather Service locations. Whatever meteorological data are used, the source of that data and the averaging period should be clearly specified.

It is emphasized that the simple assumption underlying Equations 2 and 3 has not been verified in any rigorous manner. For that reason, the quality ratings for Equations 2 and 3 should be downgraded one letter from the rating that would be applied to Equation 1.

During the preparation of the background document (Reference 10), public road silt loading values from 1992 and earlier were assembled into a data base. This data base is available in the file named "r13s03-1b.zip" located at the Internet URL "http://www.epa.gov/ttn/chief/ap42/ch13/related/c13s02-1.html" on the World Wide Web. Although hundreds of public paved road silt loading measurements had been collected, there was no uniformity in sampling equipment and analysis techniques, in roadway classification schemes, and in the types of data reported. Not surprisingly, the data set did not yield a coherent relationship between silt loading and road class, average daily traffic (ADT), etc., even though an inverse relationship between silt loading and ADT has been found for a subclass of curbed paved roads in urban areas. Further complicating the analysis is the fact that, in many parts of the country, paved road silt loading varies greatly over the course of the year, probably because of cyclic variations in mud/dirt carryout and in use of anti-skid materials. Although there were strong reasons to suspect that the assembled data base was skewed towards high values, independent data were not available to confirm the suspicions.

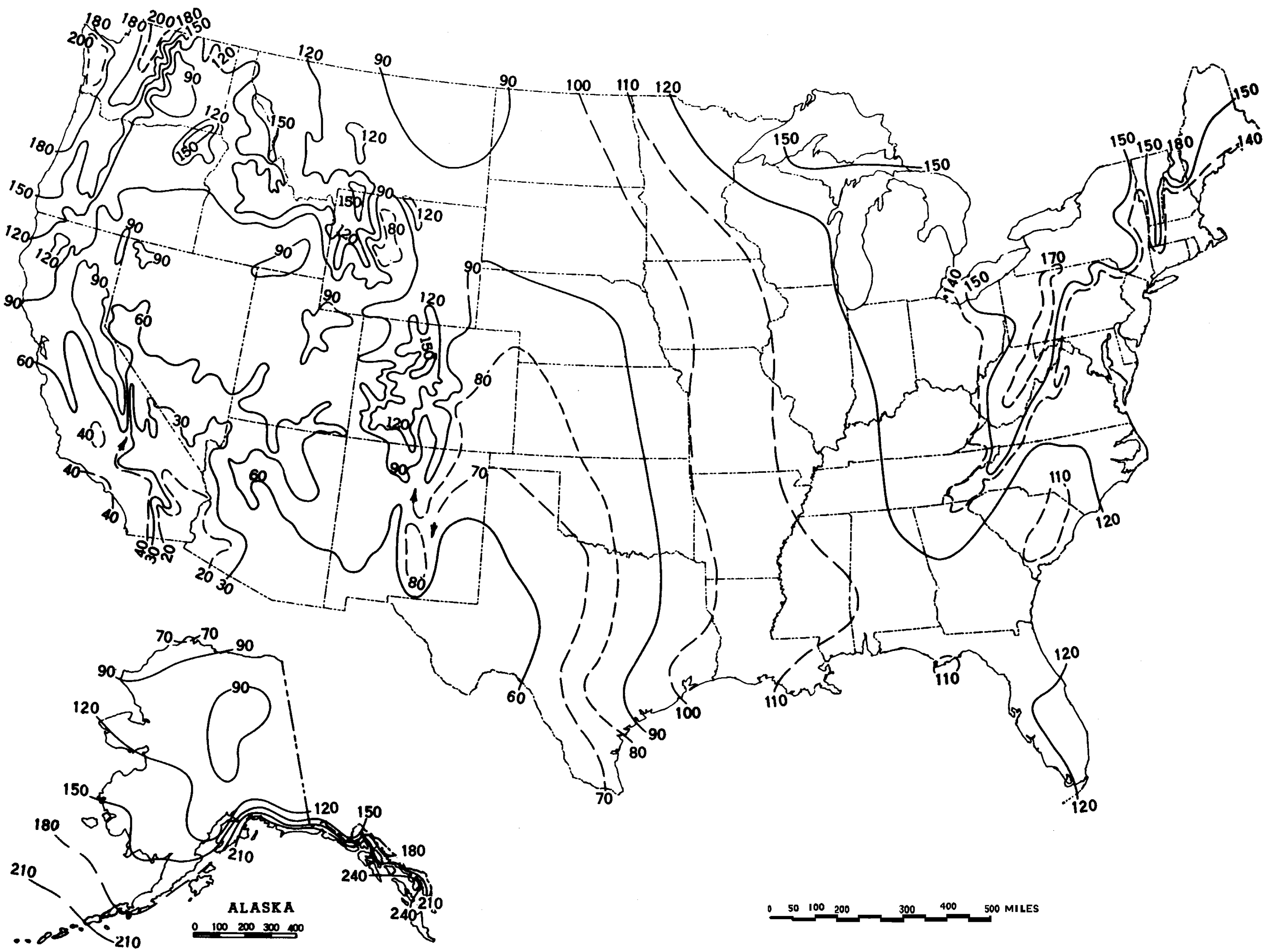

Figure 13.2.1-2. Mean number of days with 0.01 inch or more of precipitation in the United States.

Since the time that the background document was prepared, new field sampling programs have shown that the assembled silt loading data set is biased high for “normal” situations.[24] Just as importantly, however, the newer programs confirm that substantially higher than “normal” silt loadings can occur on public paved roads. As a result, two sets of default values are provided in Table 13.2.1-2, one for “normal” conditions and another for worst-case conditions (such as after winter storm seasons or in areas with substantial mud/dirt trackout). The “normal” silt loading data base is available in the file “r13s03-1a.zip” located at the Internet URL “http://www.epa.gov/ttn/chief/ap42/ch13/related/c13s02-1.html” on the World Wide Web.

Table 13.2.1-2 (Metric Units). RECOMMENDED DEFAULT SILT LOADING (g/m^2) VALUES FOR PUBLIC PAVED ROADS[a]

	High ADT roads[b]	Low ADT roads
Normal conditions	0.1	0.4
Worst-case conditions[c]	0.5	3

[a] Excluding limited access roads. See discussion in text. 1 g/m^2 is equal to 1.43 $grains/ft^2$

[b] High ADT refers to roads with at least 5,000 vehicles per day.

[c] For conditions such as post-winter-storm or areas with substantial mud/dirt carryout.

The range of silt loading values in the data base for normal conditions is 0.01 to 1.0 for high-ADT roads and 0.054 to 6.8 for low-ADT roads. Consequently the use of a default value from Table 13.2.1-2 should be expected to yield only an order-of-magnitude estimate of the emission factor. Public paved road silt loadings are dependent upon: traffic characteristics (speed, ADT, and fraction of heavy vehicles); road characteristics (curbs, number of lanes, parking lanes); local land use (agriculture, new residential construction) and regional/seasonal factors (snow/ice controls, wind blown dust). As a result, the collection and use of site-specific silt loading data is highly recommended. In the event that default silt loading values are used, the quality ratings for the equation should be downgraded 2 levels.

Limited access roadways pose severe logistical difficulties in terms of surface sampling, and few silt loading data are available for such roads. Nevertheless, the available data do not suggest great variation in silt loading for limited access roadways from one part of the country to another. For annual conditions, a default value of 0.015 g/m^2 is recommended for limited access roadways.[9,22] Even fewer of the available data correspond to worst-case situations, and elevated loadings are observed to be quickly depleted because of high traffic speeds and high ADT rates. A default value of 0.2 g/m^2 is recommended for short periods of time following application of snow/ice controls to limited access roads.[22]

The limited data on silt loading values for industrial roads have shown as much variability as public roads. Because of the variations of traffic conditions and the use of preventive mitigative controls, the data probably do not reflect the full extent of the potential variation in silt loading on industrial roads. However, the collection of site specific silt loading data from industrial roads is easier and safer than for public roads. Therefore, the collection and use of site-specific silt loading data is preferred and is highly recommended. In the event that site-specific values cannot be obtained, an appropriate value for an industrial road may be selected from the mean values given in Table 13.2.1-3, but the quality rating of the equation should be reduced by 2 levels.

Table 13.2.1-3 (Metric And English Units). TYPICAL SILT CONTENT AND LOADING VALUES FOR PAVED ROADS AT INDUSTRIAL FACILITIES[a]

Industry	No. Of Sites	No. Of Samples	Silt Content (%)		No. Of Travel Lanes	Total Loading x 10^{-3}			Silt Loading (g/m^2)	
			Range	Mean		Range	Mean	Units[b]	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	9	48	1.1-35.7	12.5	2	0.006-4.77 0.020-16.9	0.495 1.75	kg/km lb/mi	0.09-79	9.7
Asphalt batching	1	3	2.6-4.6	3.3	1	12.1-18.0 43.0-64.0	14.9 52.8	kg/km lb/mi	76-193	120
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
Municipal solid waste landfill	2	7	—	—	2	—	—	—	1.1-32.0	7.4
Quarry	1	6	—	—	2	—	—	—	2.4-14	8.2

[a] References 1-2,5-6,11-13. Values represent samples collected from *industrial* roads. Public road silt loading values are presented in Table-13.2.1-2. Dashes indicate information not available.

[b] Multiply entries by 1000 to obtain stated units; kilograms per kilometer (kg/km) and pounds per mile (lb/mi).

13.2.1.4 Controls[6,25]

Because of the importance of the silt loading, control techniques for paved roads attempt either to prevent material from being deposited onto the surface (preventive controls) or to remove from the travel lanes any material that has been deposited (mitigative controls). Covering of loads in trucks, and the paving of access areas to unpaved lots or construction sites, are examples of preventive measures. Examples of mitigative controls include vacuum sweeping, water flushing, and broom sweeping and flushing. Actual control efficiencies for any of these techniques can be highly variable. Locally measured silt loadings before and after the application of controls is the preferred method to evaluate controls. It is particularly important to note that street sweeping of gutters and curb areas may actually increase the silt loading on the traveled portion of the road. Redistribution of loose material onto the travel lanes will actually produce a short-term increase in the emissions.

In general, preventive controls are usually more cost effective than mitigative controls. The cost-effectiveness of mitigative controls falls off dramatically as the size of an area to be treated increases. The cost-effectiveness of mitigative measures is also unfavorable if only a short period of time is required for the road to return to equilibrium silt loading condition. That is to say, the number and length of public roads within most areas of interest preclude any widespread and routine use of mitigative controls. On the other hand, because of the more limited scope of roads at an industrial site, mitigative measures may be used quite successfully (especially in situations where truck spillage occurs). Note, however, that public agencies could make effective use of mitigative controls to remove sand/salt from roads after the winter ends.

Because available controls will affect the silt loading, controlled emission factors may be obtained by substituting controlled silt loading values into the equation. (Emission factors from controlled industrial roads were used in the development of the equation.) The collection of surface loading samples from treated, as well as baseline (untreated), roads provides a means to track effectiveness of the controls over time.

13.2.1.5 Changes since Fifth Edition

The following changes were made since the publication of the Fifth Edition of AP-42:

1) The particle size multiplier was reduced by approximately 55% as a result of emission testing specifically to evaluate the PM-2.5 component of the emissions.

2) Default silt loading values were included in Table 13.2.1-2 replacing the Tables and Figures containing silt loading statistical information.

3) Editorial changes within the text were made indicating the possible causes of variations in the silt loading between roads within and among different locations. The uncertainty of using the default silt loading value was discussed.

4) Section 13.2.1.1 was revised to clarify the role of dust loading in resuspension. Additional minor text changes were made.

5) Equations 2 and 3, Figure 13.2.1-2, and text were added to incorporate natural mitigation into annual or other long-term average emission factors.

6) Discussion was added to the text on the application of the MOBILE6.1 model and this section of AP-42.

7) References were rearranged and renumbered.

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