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DEVELOPMENT OF A METHODOLOGY AND EMISSION INVENTORY FOR FUGITIVE DUST FOR THE REGIONAL AIR POLLUTION STUDY

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

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DEVELOPMENT OF A METHODOLOGY AND EMISSION INVENTORY FOR FUGITIVE DUST FOR THE REGIONAL AIR POLLUTION STUDY

by

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Prepared for

ENVIROMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Air Quality Planning and Standards
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Approved for:

MIDWEST RESEARCH INSTITUTE

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Physical Sciences Division

March 22, 1976

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SUMMARY

This report outlines the methodology that was used in developing an hourly fugitive dust emissions inventory for the Metropolitan St. Louis Air Quality Control Region as part of the Regional Air Pollution Study (RAPS). The inventory encompassed the following source categories: (a) unpaved roads, (b) agricultural land tilling, (c) wind erosion of agricultural land, (d) construction sites, (e) aggregate storage piles, and (f) unpaved airstrips.

For each of approximately 2,000 RAPS grid areas, data were compiled on annual emissions of fugitive dust. This required, in addition to basic emission factors adjusted for local climatic and surface conditions, annual measures of source extent (vehicle-miles traveled on unpaved roads, acres of land tilled, etc.) for each grid area. Finally, hourly apportioning factors were derived to account for emissions variations by hour of the day, day of the week, and season of the year.

Results presented in this report include temporal apportioning factors, county totals of annual source extent and annual emissions for each source category. Fine particle emissions from fugitive dust sources in the St. Louis area are found to comprise 39% of the total emissions of suspended particulates.

INTRODUCTION

Analysis of the physical relationships between air pollutant source emissions and ambient air quality is essential to the rational development and implementation of pollution abatement and control strategies. These relationships are predictable through the use of mathematical models which simulate the processes of atmospheric transport, dispersion, transformation, and removal of pollutant emissions.

The Environmental Protection Agency (EPA) is currently sponsoring a comprehensive regional air pollution study (RAPS) in the St. Louis Air Quality Control Region (AQCR 70). The primary purpose of the RAPS program is the development and validation of improved air quality models. To accomplish this purpose, a major portion of the program effort is being directed to the preparation of a comprehensive regional data base.

Inputs required for model verification include an emissions inventory, meteorological data (wind velocity and temperature) and air quality data. The spatial and temporal resolution of the RAPS data base will be far more precise than any previously compiled in an undertaking of this type. This will permit verification of sophisticated models which predict air quality distributions on a short term (hourly) basis.

Recently it has become evident that fugitive dust sources contribute substantially to atmospheric concentrations of total suspended particulates (TSP) in both urban and rural areas. Failure to incorporate fugitive source emissions into model-based control strategies has resulted in widespread overestimation of TSP reductions resulting from the control of conventional point and area sources. Therefore, the need to include fugitive dust sources in the RAPS emissions inventory is evident.

This report presents the results of an investigative program directed to (a) development of a methodology for reporting fugitive dust emissions in the RAPS region and (b) compilation of an hourly emissions inventory of fugitive dust sources for the nearly 2,000 RAPS grid areas.

The following six categories of fugitive dust sources were addressed in this study:

1. Unpaved roads;

2. Agricultural land tilling;

3. Wind erosion of agricultural land;

4. Construction sites;

5. Aggregate storage piles; and

6. Unpaved airstrips.

Appendix B presents an assessment of factors affecting atmospheric transport of fugitive dust.

TECHNICAL APPROACH

Figure 1 traces the methodology that was developed to compile hourly emissions of fugitive dust by grid. The key data elements in this scheme are:

1. Appropriate annual measures of the extent of each source type within each grid area.

2. Emission factors adjusted to climatic conditions and surface properties characteristic of the St. Louis area.

3. Temporal apportioning factors to account for emissions variations by hour of the day, day of the week, and season of the year.

The basic emission factors and associated correction terms used in this study, as shown in Figure 1, were developed by Midwest Research Institute (MRI) under EPA Contract No. 68-02-0619.[1/] These factors refer to dust particles smaller than 30 µm in diameter, the approximate effective cutoff diameter of a standard high-volume particulate sampler (based on a particle density of 2 to 2.5 g/cm^3).

The initial work objective was to prepare a base map of the RAPS grid system which incorporated county outlines and river outlines. United States Geological Survey (USGS) maps with a scale of 1:250,000 were used to locate the RAPS grid system based on Universal Transverse Mercator (UTM) coordinates designated for Zone 15.

A reduction of the resulting overlay map is shown in Figure 2. The overlay was photographically scaled to fit appropriate land use and street maps of the St. Louis area. A computer-generated plot of the grid system, supplied by the EPA project officer, was also reduced to the size of the MRI overlay for comparative purposes.

The following sections of this report document, for each source category, the methodology used to obtain annual grid source extent, corrected emission factors, and temporal apportioning factors. Also presented are key computational results summarized by county, including extent of fugitive dust sources, temporal apportioning factors, and annual totals of fugitive dust emissions.

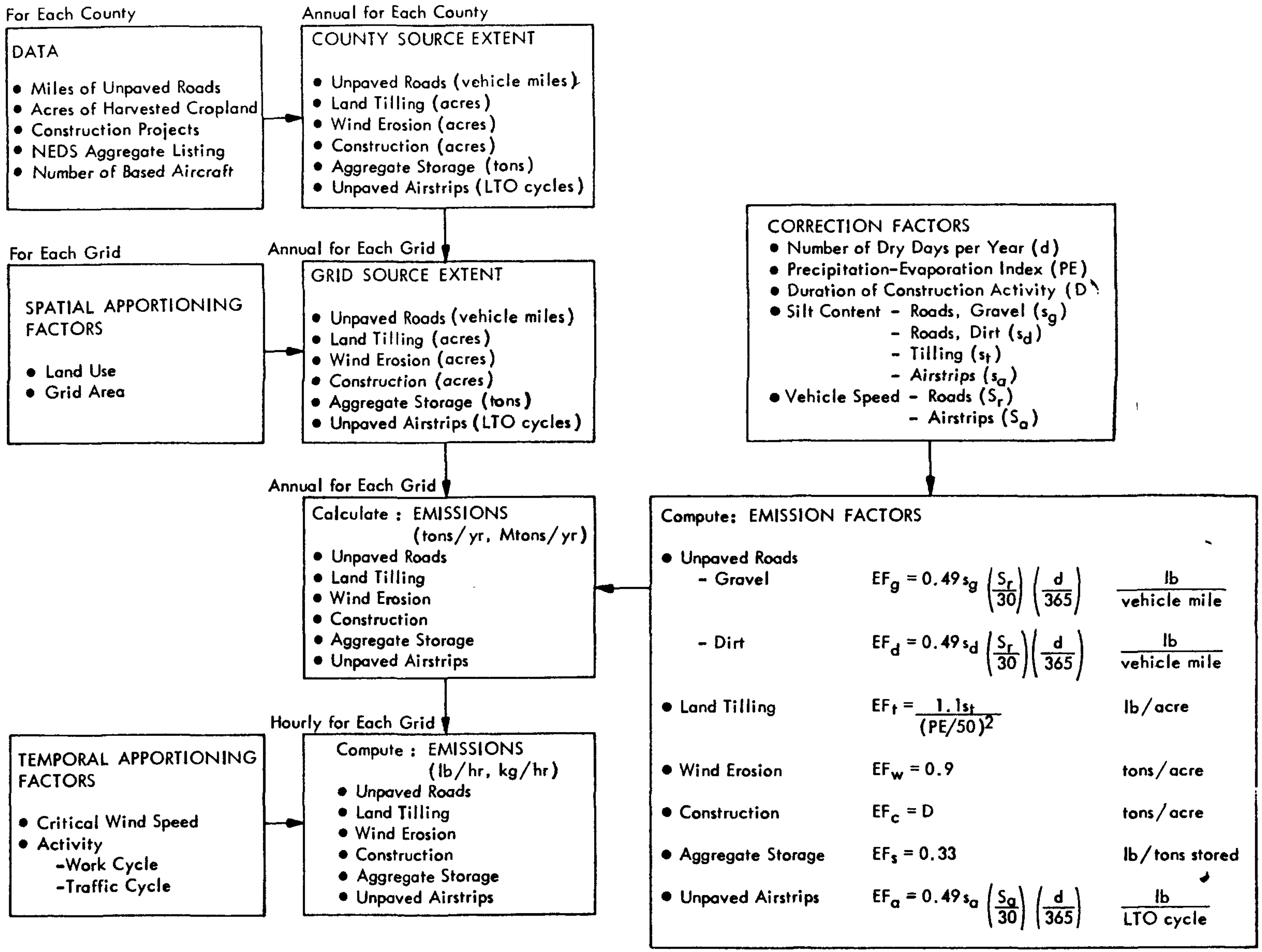

Figure 1. Project data flow diagram

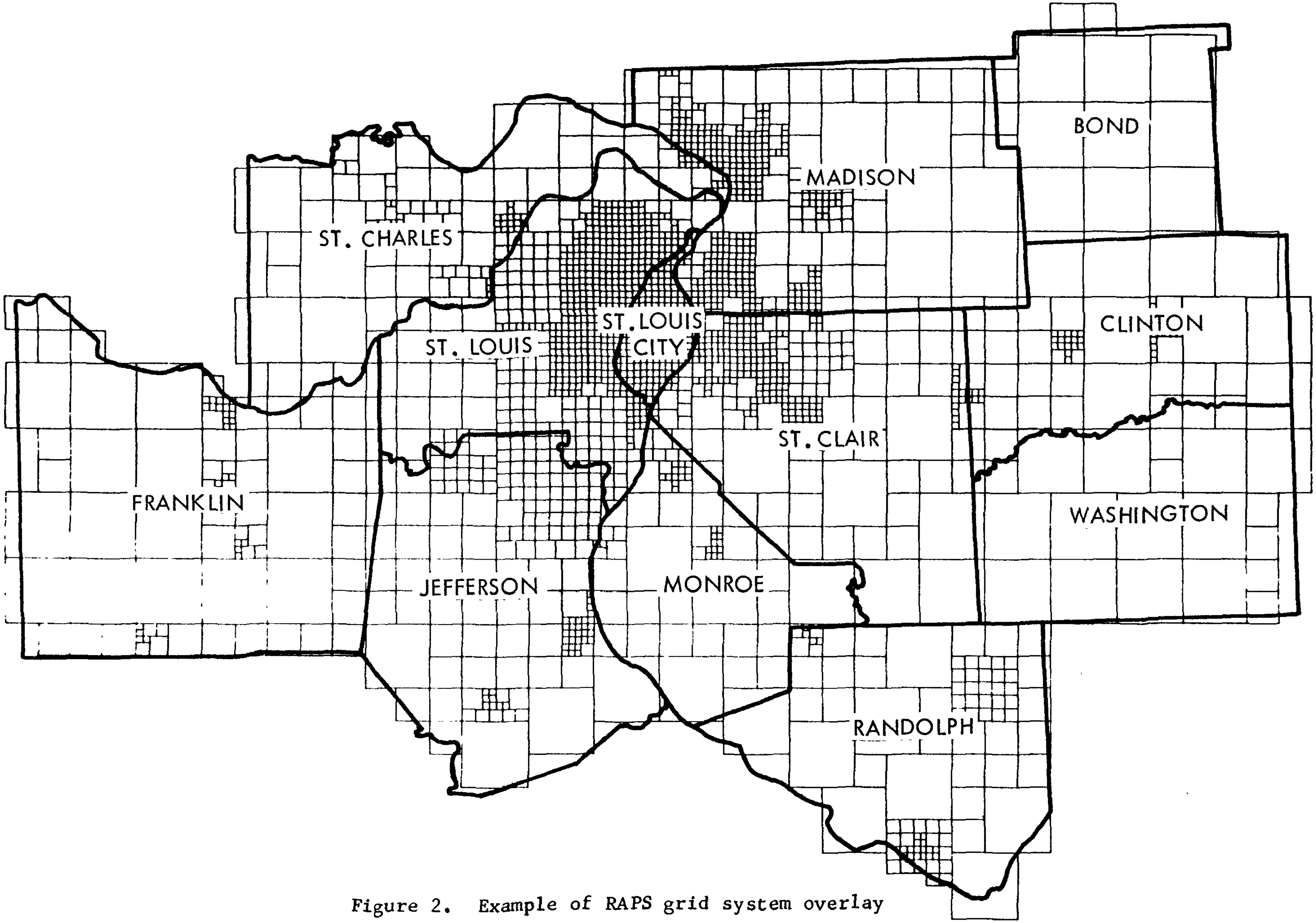

Figure 2. Example of RAPS grid system overlay

UNPAVED ROADS

GRID SOURCE EXTENT

The measure of source extent for fugitive dust emissions from unpaved roads is vehicle miles traveled (VMT). The basic equation for calculation of annual VMT on unpaved roads in a specified grid area is given by:

$$VMT = 365 \sum_{i=1}^{4} (ADT_i) m_i$$

where ADT_i is average daily traffic on unpaved roads with surface type i, and m_i is the mileage of unpaved roads with surface type i within the grid area. Road surface types considered in this study were: (a) gravel/stone surfaced, (b) soil surfaced, (c) graded and drained, and (d) unimproved. The procedure used to determine ADT_i and m_i for each grid is depicted in Figure 3.

Traffic volume on unpaved roads within each grid was derived from appropriate county maps. Traffic flow and road surface-type maps were obtained from the Illinois Department of Transportation[2/] for each of the seven Illinois counties in the St. Louis AQCR. Highway maps, designating road surface type, were obtained from the Missouri State Highway Commission[3/] for the counties of Franklin, Jefferson, St. Charles, and St. Louis in Missouri. Communications with officials of St. Louis City and County[4/] indicated that there are no unpaved roads in the city and only a few municipal or private unpaved roads in the St. Louis County.

The RAPS grid system was scaled to each county map, and mileage and average ADT for each of the four road surface types were manually obtained for each grid. Table 1 presents a county summary of the mileage and ADT for each road type. As indicated, values for ADT on unpaved roads in the Missouri counties were estimated based on reported ADT values for Illinois roads differentiated by road surface type.

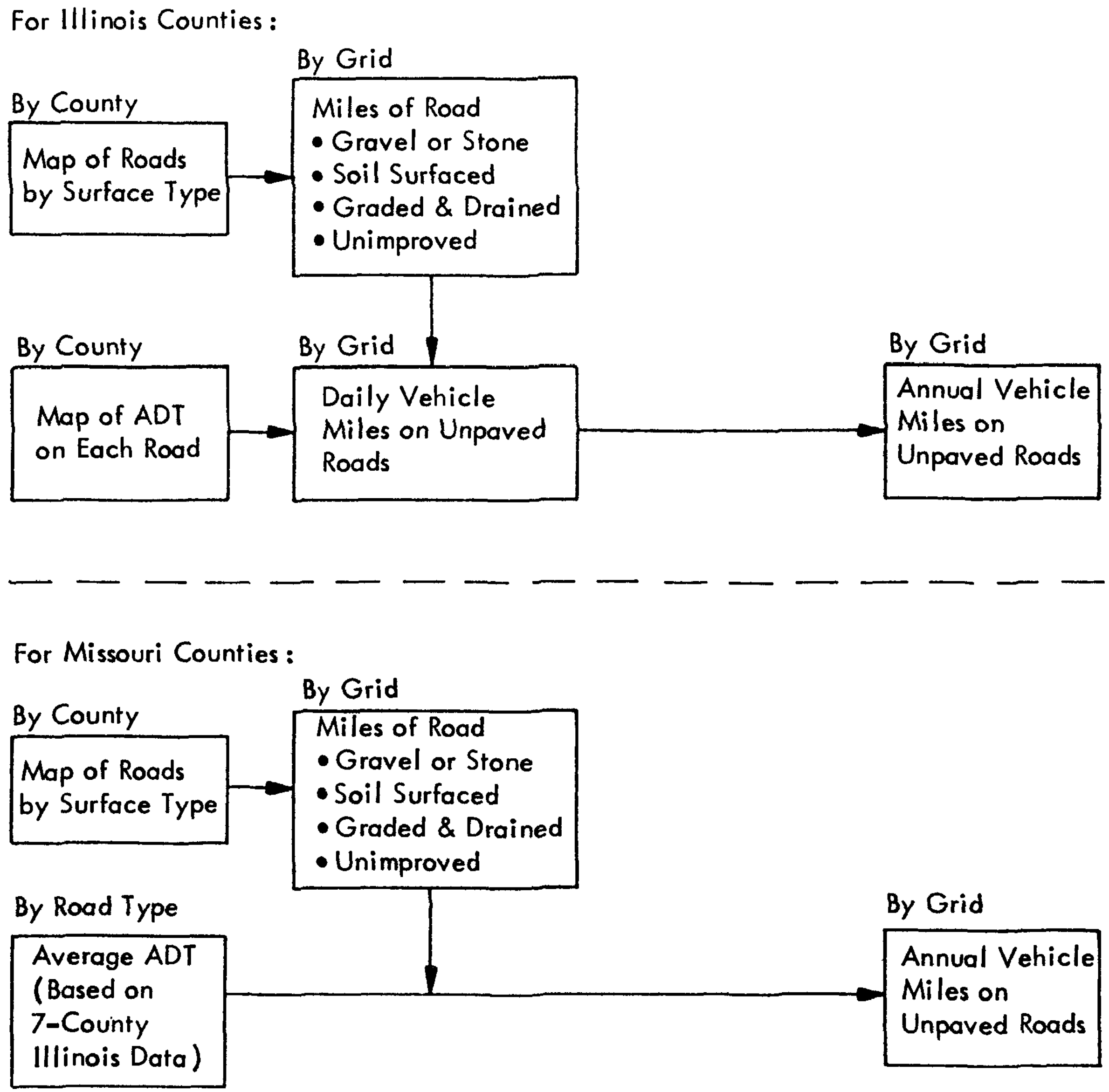

Figure 3. Procedure for determination of annual vehicle-miles on unpaved roads

Table 1. COUNTY STATISTICS FOR UNPAVED ROADS

		Map date		Mileage					ADT				Annual VMT (thousands)	
State	County	Road surface	Traffic	Gravel/ stone	Soil surfaced	Graded and drained	Unimproved	Total	Gravel/ stone	Soil surfaced	Graded and drained	Unimproved	Gravel	Dirt
Illinois	Bond	1972	1969	351.1	39.5	41.7	1.5	433.8	81	57	51	25	10,321	1,607
	Clinton	1972	1968	504.7	11.0	36.0	1.5	553.2	83	58	72	25	15,226	1,361
	Madison	1973	1971	20.0	285.0	11.0	0.2	316.2	92	63	50	25	675	6,736
	Monroe	1973	1973	234.2	0.0	32.5	1.7	268.4	64	--	64	25	5,548	591
	Randolph	1973	1973	284.5	13.7	42.2	9.0	449.5	65	280	50	25	9,429	2,304
	St. Clair	1973	1972	209.0	42.2	15.0	0.2	266.5	--	--	--	25	13,500	2,284
	Washington	1971	1973	339.5	24.0	107.5	3.5	474.5	73	85	51	25	9,079	2,821
Missouri	Franklin	1973	--	606.1	0.0	1.2	3.0	610.3	71[a/]	73[a/]	53[a/]	25	16,563	33
	Jefferson	1975	--	260.7	0.0	0.0	0.0	260.7	71[a/]	73[a/]	53[a/]	25	6,882	0
	St. Charles	1971	--	282.7	0.0	0.0	0.0	282.7	71[a/]	73[a/]	53[a/]	25	6,967	190
	St. Louis	1969	--	0.0	0.0	0.0	0.0	0.0	--	--	--	--	0	0
	St. Louis City	--	--	0.0	0.0	0.0	0.0	0.0	--	--	--	--	0	0

a/ Average value based on Illinois counties in the St. Louis AQCR weighted by miles of each road surface type.

EMISSION FACTOR

The emission factor for dust emissions from unpaved roads (pounds per VMT) is given by:

$$EF_r = 0.49\ s_r \left(\frac{S_r}{30}\right)\left(\frac{d}{365}\right)$$

where s_r = silt content of road surface material, gravel (s_g) and dirt (s_d) (percent), i.e., particles smaller than 75 μm in diameter, S_r = average vehicle speed (miles per hour), and d = number of dry days per year, i.e., days with less than 0.01 in. of precipitation. Based on driver interviews, the average vehicle speed on unpaved roads in the St. Louis area was taken to be 30 mph. On the average, there are 250 dry days per year in the RAPS study region.[5/]

The silt content of gravel roads was estimated to be 16%,[6/] and the silt content of dirt roads (i.e., soil-surfaced, graded and drained, and unimproved) was assumed to be the same as the soil silt content determined for agricultural sources (see Section Agricultural Tilling, Emission Factors). Composite road silt content by grid was found to vary from 10 to 70% with corresponding emission factors ranging from 3.36 to 23.5 lb/vehicle mile.

TEMPORAL APPORTIONING FACTORS

Little data are available describing temporal variations in traffic on unpaved roads. Figure 4 illustrates hourly, daily, and seasonal variations of VMT on unpaved roads for a farming area in California.[7/] These data were assumed to approximate temporal variations in the St. Louis area.

TEMPORAL APPORTIONING FACTORS

Source Type: Unpaved Roads

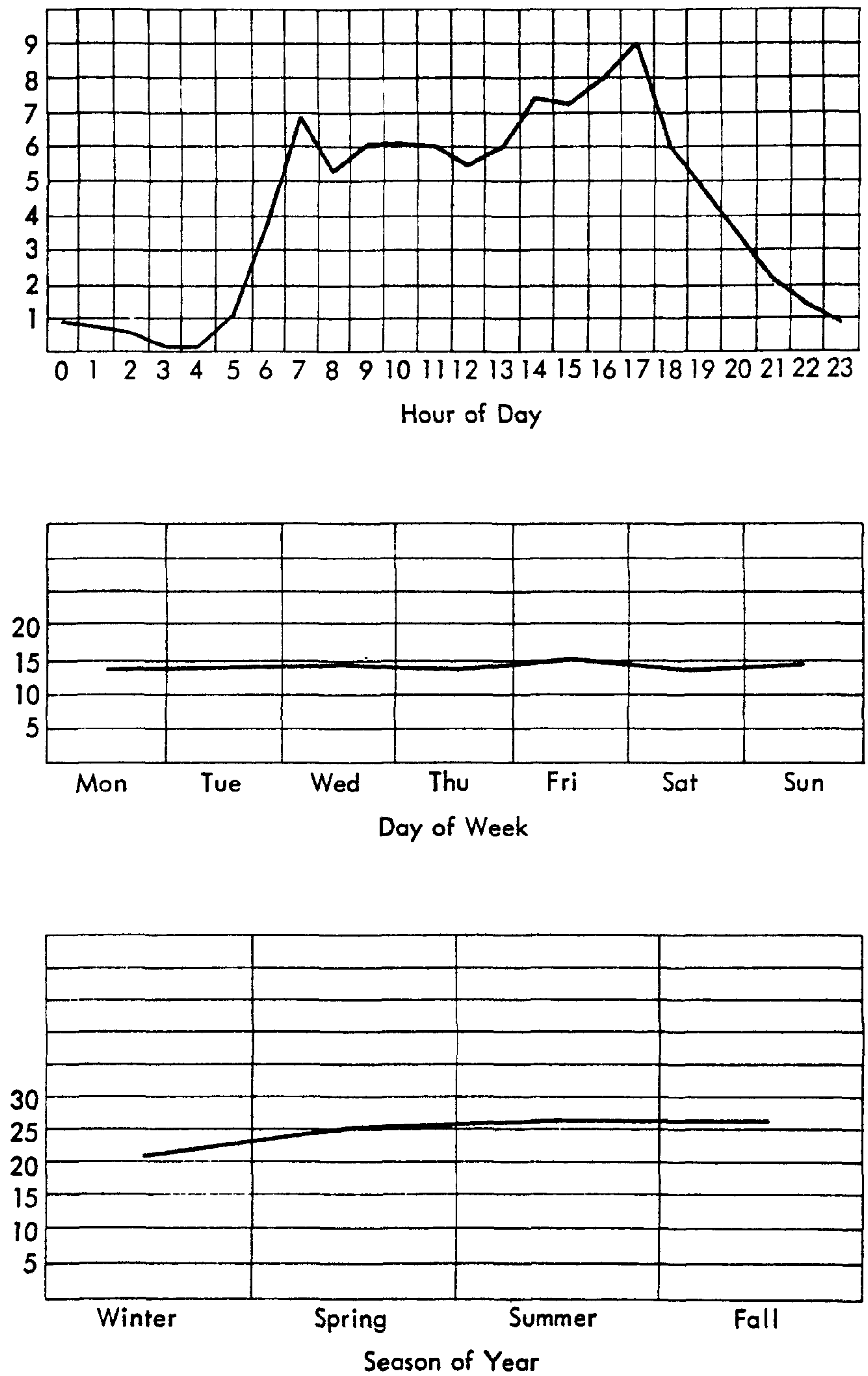

Figure 4. Percentage of total daily, weekly, and annual vehicle-miles on unpaved roads

AGRICULTURAL TILLING

GRID SOURCE EXTENT

Dust emissions from agricultural tilling can be quantified in terms of annual acres of cropland tilled. Data used for this determination (see Figure 5) were:

1. Acreage of harvested cropland by grid, for five major crops (corn, soybeans, wheat, milo and hay).

2. Number of yearly agricultural operations by crop, including tilling, planting, and harvesting.

The acres of harvested cropland for all farms on a county basis, as presented in Table 2, were obtained from the 1969 Census of Agriculture.[8/] The number of yearly agricultural operations for the five major crops (see Table 3) were estimated by knowledgeable MRI personnel. This information was used to determine the equivalent acres of land tilled per year by county, based on the following equation:

$$\text{Equivalent acres of land tilled annually by county} = \sum_{i=1}^{5} \left[\text{Number of equivalent tilling operations by crop, } i \times \text{Acres of harvested cropland, by crop } i, \right]_{\text{by county}}$$

Planting and harvesting operations were estimated to have half of the fugitive dust potential of tilling, based on visual observations made by MRI personnel.

Annual acreage of land tilled by grid was determined by spatial apportioning of county totals on the basis of grid area and land use, according to the following equation:

$$\text{Annual acres of land tilled by grid} = \text{Annual acres of land tilled by county} \times \frac{\text{Agricultural acreage within grid} \times \text{Fraction of grid in county}}{\text{Agricultural acreage within county}}$$

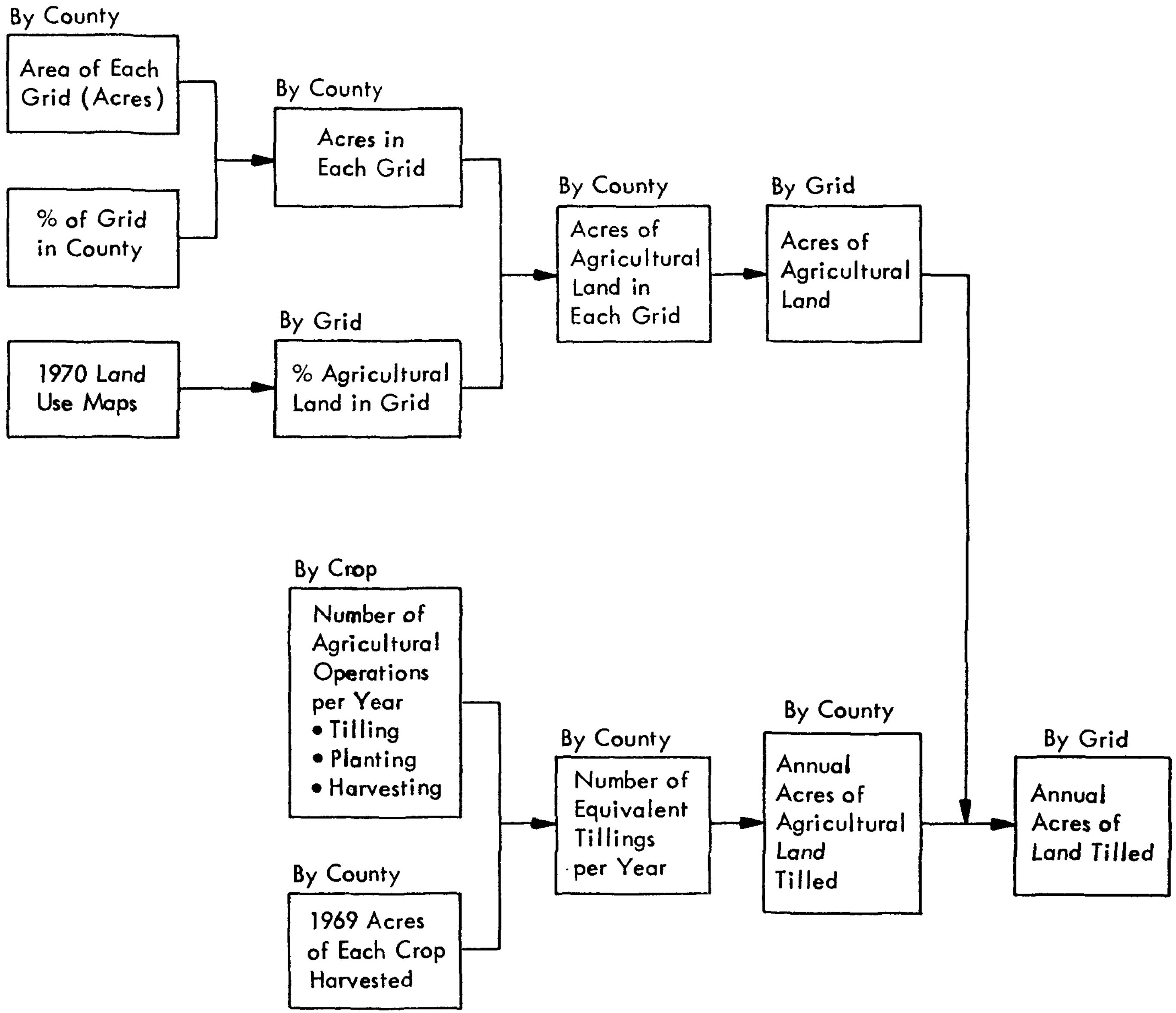

Figure 5. Procedure for determination of annual acres of land tilled

Table 2. COUNTY BREAKDOWN OF HARVESTED ACRES BY CROP AND EQUIVALENT TILLINGS

State	County[a]	Harvested cropland (acres)	Percentage of acres by crop[b]						Equivalent tillings per year
			Corn (5)	Wheat (4)	Soybeans (4)	Milo (5)	Hay (2.5)	Other (0)	
Illinois	Bond	122,755	32.9	16.3	39.6	0.4	8.6	2.2	4.1
	Clinton	170,718	39.7	16.7	29.1	0.4	12.0	2.1	4.1
	Madison	224,634	32.0	18.1	38.7	0.9	8.0	2.3	4.1
	Monroe	114,343	36.9	25.3	27.1	0.1	6.9	3.7	4.1
	Randolph	148,136	32.9	19.4	29.6	0.1	13.4	4.6	4.0
	St. Clair	214,750	31.5	20.9	38.6	0.2	5.0	3.8	4.1
	Washington	204,371	28.3	20.5	38.1	0.5	9.4	3.2	4.0
Missouri	Franklin	74,974	32.7	17.4	3.9	0.9	39.8	5.3	3.5
	Jefferson	27,506	18.0	13.8	7.0	1.8	52.6	6.8	3.1
	St. Charles	108,909	37.9	22.8	25.5	0.2	10.7	2.9	4.1
	St. Louis	35,460	29.1	29.1	22.2	0.5	10.5	8.6	3.8

a/ St. Louis City not included; harvested cropland (acres) = 0.

b/ Numbers in parentheses are equivalent tillings per year for each crop.

Table 3. AGRICULTURAL OPERATIONS BY CROP

Crop	Number of equivalent tillings per year[a] Primary tilling	Secondary tilling	Planting	Harvesting	Total
Corn	1 (F)	3 (Sp)	1/2 (Sp)	1/2 (F)	5
Wheat	1 (Su)	2 (Su, F)	1/2 (F)	1/2 (Su)	4
Soybeans	1 (W, Sp)	2 (Sp)	1/2 (Sp)	1/2 (F)	4
Milo	1 (F, W, Sp)	3 (Sp)	1/2 (Sp)	1/2 (F)	5
Hay	1/2 (Su)	1 (Su, F)	1/2 (F)	1/2 (Su)	2.5

a/ Season of operation is abbreviated by W = winter, Sp = spring, Su = summer, and F = fall.

Agricultural acreage within each grid and within each county was determined by analysis of land use maps supplied by the East-West Gateway Coordinating Council.[9,10] The area of a grid lying within a particular county was determined from the base map of the RAPS grid system (Figure 2). Results for grids which cross county lines were summed.

EMISSION FACTOR

The emission factor for dust emissions from agricultural tilling operations (pounds per acre tilled) is given by:

$$EF_t = 1.1 \frac{s_t}{(PE/50)^2}$$

where s_t = silt content of soil (percent), i.e., particles between 2 and 50 μm in diameter, and PE = Thornthwaite's Precipitation-Evaporation Index.[11]

Soil silt content for each grid was determined from an analysis of soils maps, obtained from Soil Conservation Service offices for the counties of Bond, Clinton, Madison, St. Clair, and Washington in Illinois[12] and St. Charles County in Missouri.[13] A map of the soils of the North Central United States[14] was used for the remaining counties and to provide data comparisons.

The soil classification system for each map was converted to soil families (the second most specific classification of soils, indicating the soil texture), and a soil texture triangle[15] was used to estimate silt content for each family designation. Areas of uniform soil family were superimposed on a grid map (see Figure 6) and appropriate silt content values were assigned to each grid.

A map of the PE-index by state climatic division, generated in an earlier MRI study,[1] indicates a PE-index of 93 for both state climatic divisions which comprise the Metropolitan St. Louis AQCR.

TEMPORAL APPORTIONING FACTORS

Agricultural land tilling, planting, and harvesting follow a regular yearly cycle dependent on the type of crop. Within these yearly cycles, agricultural operations are performed mainly during the hours from dawn to dusk and uniformly through the week, with only a slight reduction on Sundays. The temporal apportioning factors derived for agricultural operations are shown in Figure 7.

Based on seasonal performance of primary and secondary tilling, planting, cultivation, and harvesting for the main crops in the St. Louis AQCR, as determined by MRI personnel (see Table 3), seasonal apportioning factors were determined for each county, taking into account the respective crop mixes. Separate average seasonal factors were calculated for Missouri and Illinois to reflect wide differences in types of crops in the two states.

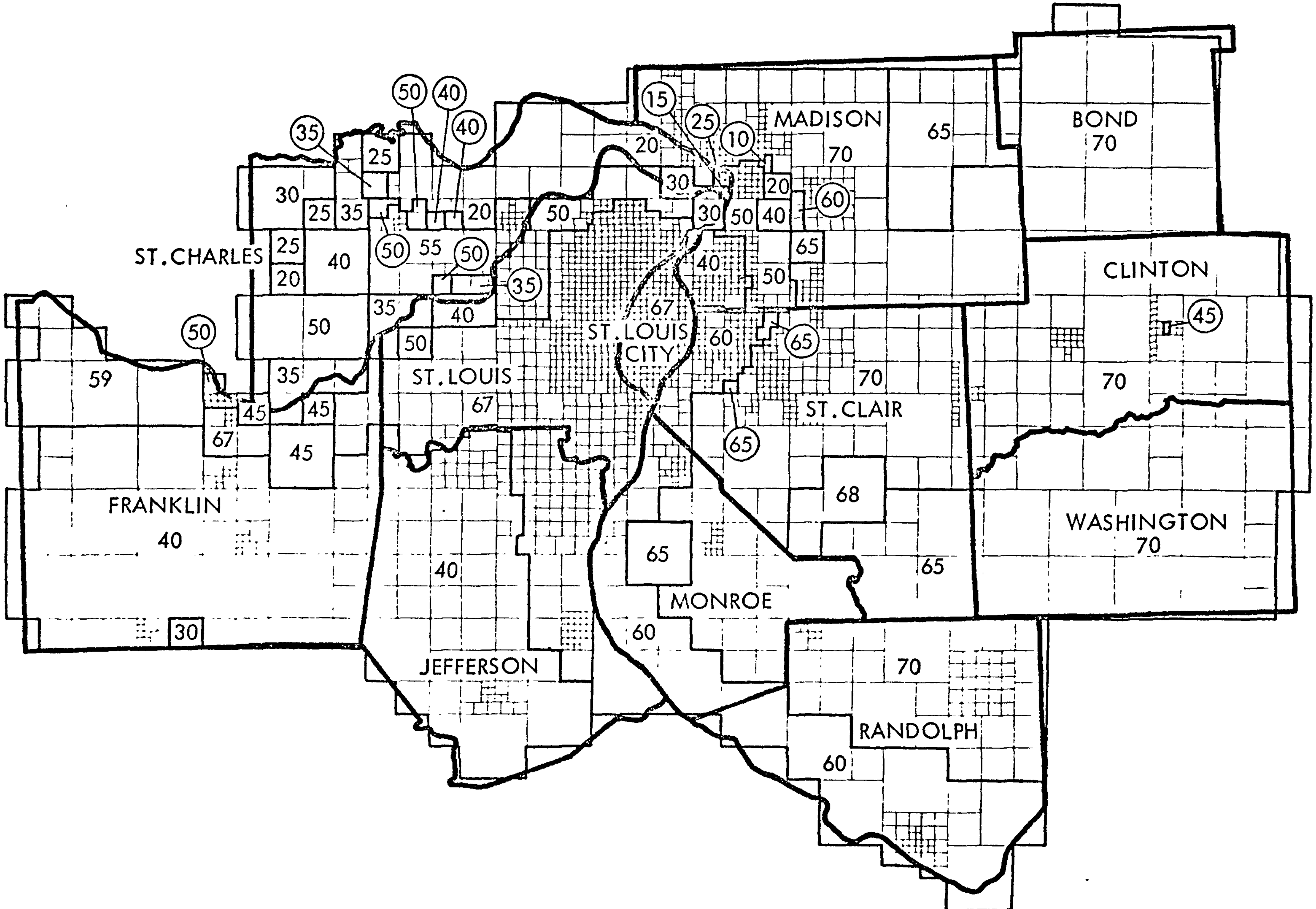

Figure 6. Soil silt content (%) for RAPS Grid system

TEMPORAL APPORTIONING FACTORS

Source Type: Agricultural Tilling

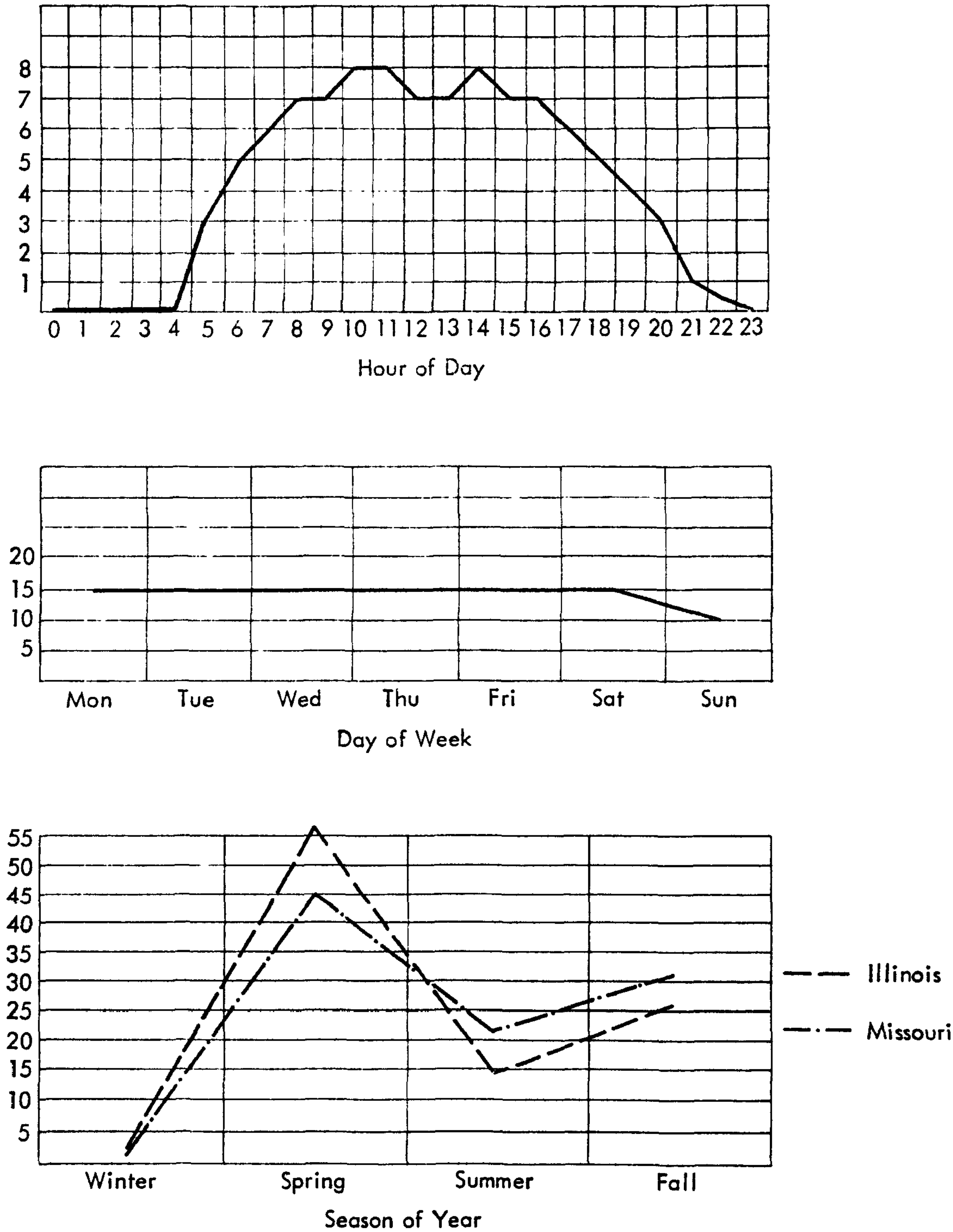

Figure 7. Percentage of total daily, weekly, and annual agricultural tilling

WIND EROSION FROM TILLED LAND

GRID SOURCE EXTENT

The measure of source extent for wind erosion from tilled agricultural land is average exposed (unvegetated) acreage. Agricultural land is assumed to remain vulnerable to wind erosion from the time of primary tilling to about 1 month after planting. The procedure used to determine average area of erodible agricultural land within each grid is depicted in Figure 8.

Annual average exposed acreage for each county was determined from seasonal values (see Table 4) which were calculated from the acreage planted in each crop and the corresponding months of exposure. Erodible acreage for each grid was determined by apportioning county totals on the basis of the proportion of county agricultural acreage which lies within the grid.

EMISSION FACTOR

An emission factor for wind erosion from agriculturally tilled land was derived from data on atmospheric loadings of suspended dust measured by Gillette[16/] during dust storms in West Texas. The threshold rate of wind erosion was adjusted to apply to values of soil silt content and climatic factor which are representative of the St. Louis area.

The threshold value for the St. Louis area was calculated to be: 3.5 tons/acre/year. Based on meteorological data for 3-hr time increments, winds in the St. Louis region exceed 12 mph approximately 26% of the time.[17/] Thus, the annual average emission factor for wind erosion becomes:

$$3.5 \text{ tons/acre} \times 0.26 = 0.9 \text{ tons/acre}$$

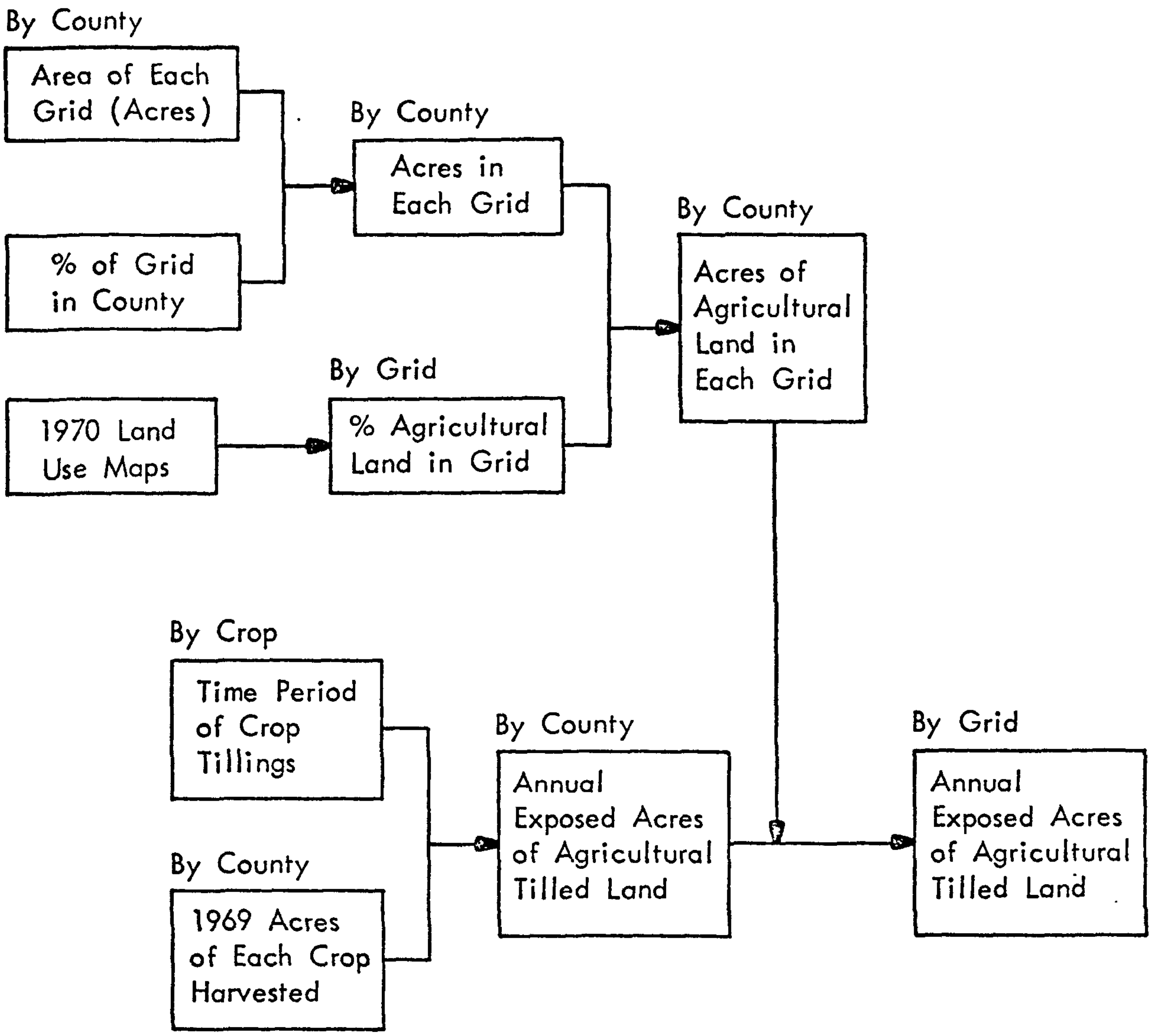

Figure 8. Procedure for determination of acreage of exposed agricultural land

Table 4. SEASONAL EXPOSED ACREAGE BY COUNTY

State	County[a/]	Average acres exposed				
		Winter	Spring	Summer	Fall	Average
Illinois	Bond	58,292	77,427	18,474	42,190	49,096
	Clinton	86,609	97,376	27,109	67,420	69,628
	Madison	104,702	138,675	37,021	79,008	89,851
	Monroe	53,762	60,500	25,744	49,070	47,269
	Randolph	65,426	78,736	27,379	54,667	56,552
	St. Clair	97,786	131,115	39,798	77,749	86,612
	Washington	86,719	119,832	38,340	69,983	78,718
Missouri	Franklin	26,462	19,943	15,061	27,822	22,322
	Jefferson	6,166	5,626	5,154	7,216	6,040
	St. Charles	51,505	56,288	22,584	45,657	44,008
	St. Louis	13,384	15,168	9,269	14,402	13,055

a/ St. Louis City not included; harvested cropland (acres) = 0.

TEMPORAL APPORTIONING FACTORS

Temporal apportioning factors for wind erosion are shown in Figure 9. Seasonal apportioning factors were scaled to the product of (a) seasonal values of exposed acreage by state and (b) the seasonal climatic factor[18] for the St. Louis AQCR. Hourly factors were proportioned to the probabilities that the wind speed will exceed 12 mph, the threshold value for the onset of wind erosion.

TEMPORAL APPORTIONING FACTORS

Source Type: Wind Erosion from Tilled Land

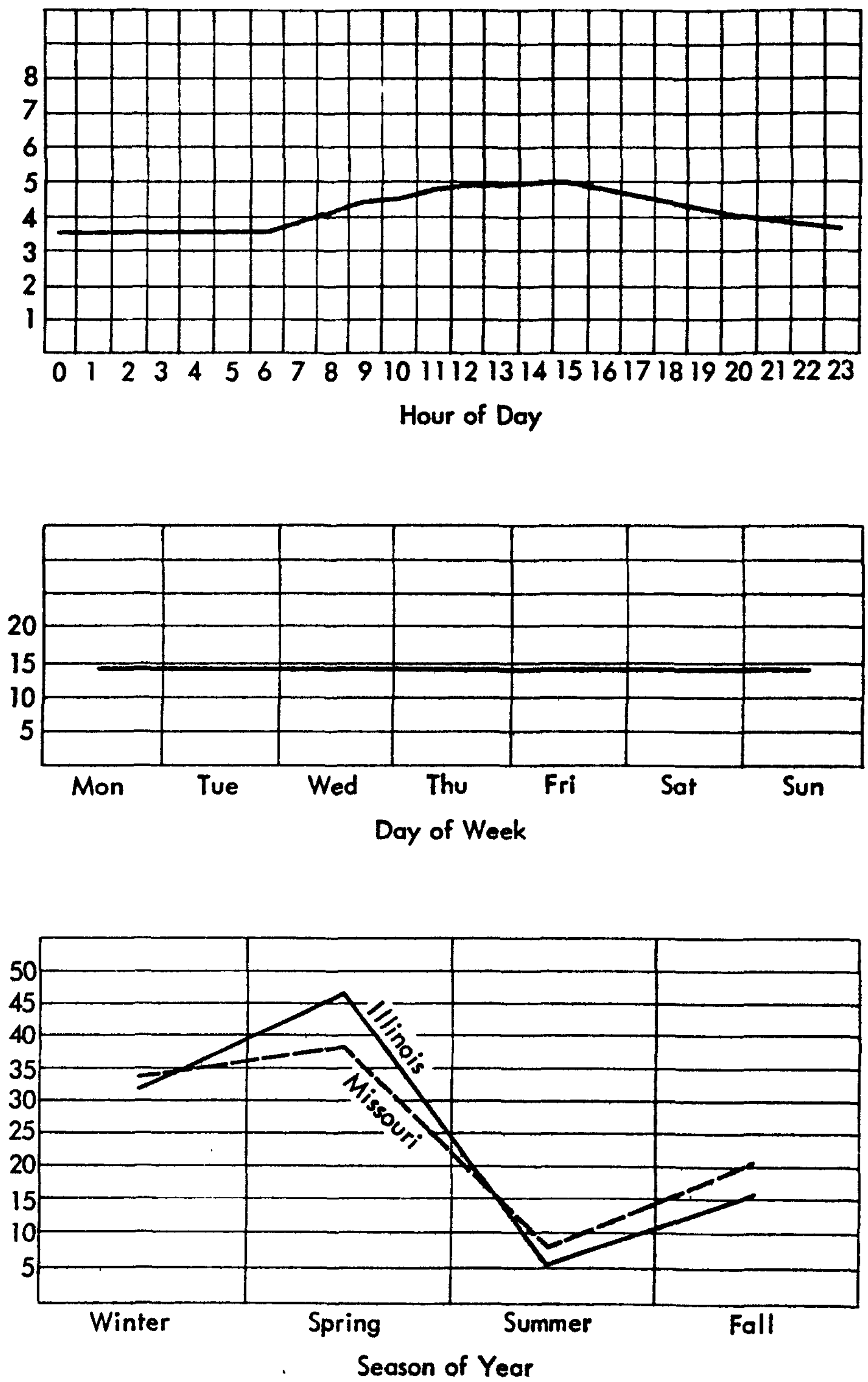

Figure 9. Percentage of total daily, weekly, and annual wind erosion from agricultural tilled land

CONSTRUCTION

GRID SOURCE EXTENT

Fugitive dust emissions from construction activities are directly related to the land area being worked, over a specific time period. Figure 10 presents the methodology used to determine annual acres of construction within each grid area. Construction activity considered in this study was confined to the Source Industrial Classification (SIC) Major Group 15 (Building Construction--General Contractors and Operative Builders) and Group 16 (Construction Other than Building Construction--General Contractors).

Detailed 1974 data for major building construction sites in the Missouri counties except Franklin were obtained from the East-West Gateway Coordinating Council.[19] These data included: county, location, census tract, description of activity, project name, size in acres (or square feet), and stage of development. All sites were located by grid and construction acreage was totaled by county. It was evident that the building construction centered around St. Louis County.

A detailed listing of road construction projects in the St. Louis area was also obtained from the East-West Gateway Coordinating Council.[20] For the Missouri counties except Franklin, road construction projects differentiated by type and mileage were assigned to the proper grid areas. Estimates of contruction acreage per mile of road construction, for each type of project, were used to convert mileage to acreage within each grid. Road construction acreage totals for St. Charles and St. Louis Counties, which amounted to less than 10% of building construction acreage, were disregarded.

Table 5 gives construction acreage by county. Construction acreage totals for Jefferson, St. Charles and St. Louis counties are slightly larger than the estimates reported earlier by MRI,[6] which were based on state construction receipts,[21] and county construction employment;[22] this is apparently due to increased area development. However, the St. Louis City construction acreage was smaller than the previously reported

CONSTRUCTION

GRID SOURCE EXTENT

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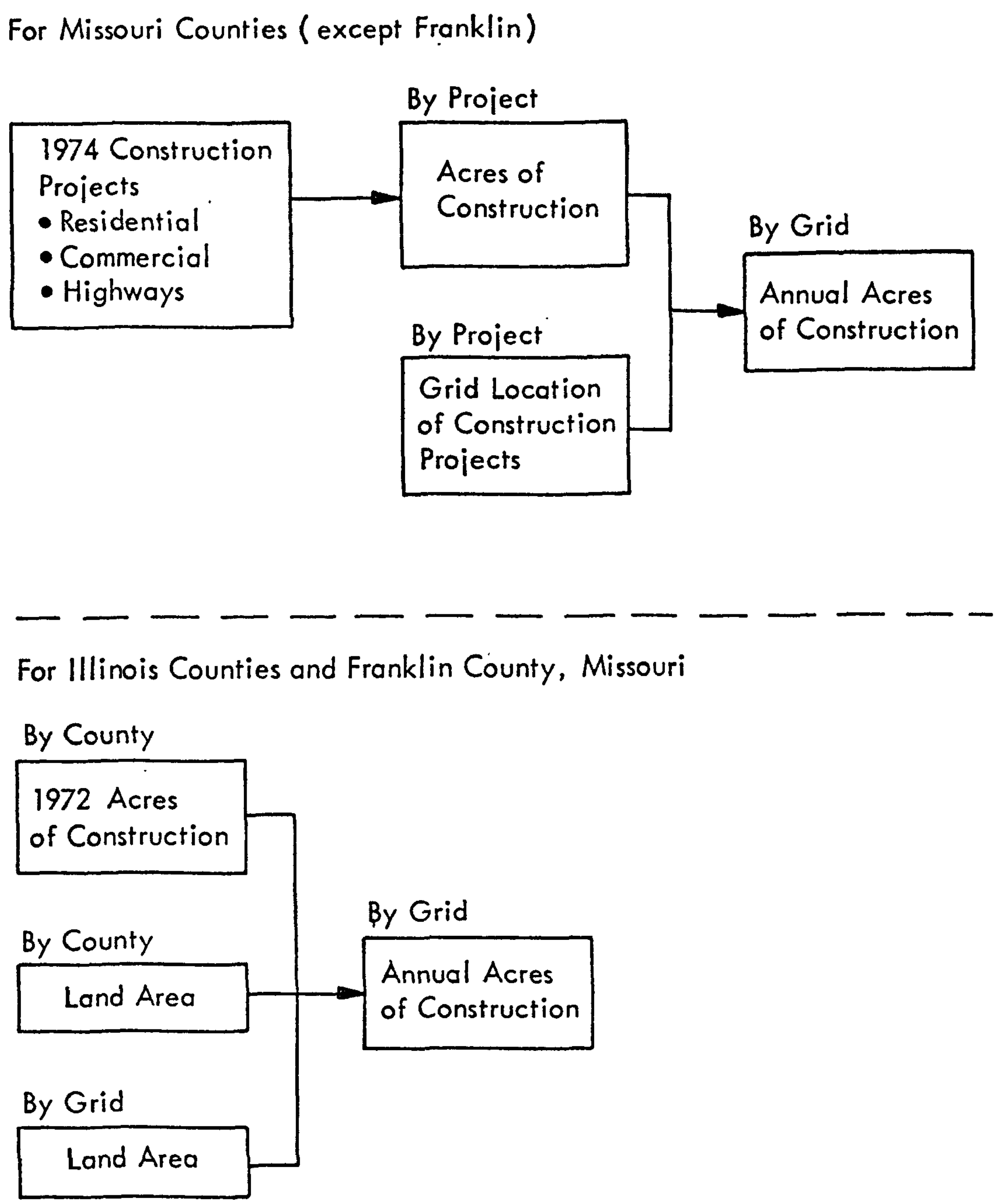

Figure 10. Procedure for determination of annual acres of construction

Table 5. CONSTRUCTION ACREAGE BY COUNTY

State	County	Construction acreage		
		Building	Road	Total
Illinois	Bond			143
	Clinton			254
	Madison			1,640
	Monroe			151
	Randolph			333
	St. Clair			1,760
	Washington			87
Missouri	Franklin			435
	Jefferson	989	204	1,193
	St. Charles	1,088	a/	1,088
	St. Louis City	234	62	296
	St. Louis	4,999	a/	4,999

a/ Road construction acres less than 10% of total.

value, which was based on the assumption that construction employees residing in the city worked only within the city.

For the remaining counties, i.e., Franklin County in Missouri and all of the Illinois counties, MRI estimates of total construction acreage[6/] (buildings plus roads) were apportioned to grids within a county on the basis of grid area.

EMISSION FACTOR

County-wide emission factors for dust emissions from construction activities were determined by multiplying a previously determined emission rate factor (1 ton/acre/month)[1/] by an average duration of construction within the county, weighted by the relative proportion of acreage differentiated by project type and the average duration for each project type. MRI estimates of the average duration of construction[6/] are:

6 months for residential buildings,

11 months for nonresidential buildings, and

18 months for nonbuilding construction.

The emission factor for construction can thus be written as follows:

$$EF_c = D \text{ tons/acre}$$

where D = weighted average duration of construction within a given county.

The value of D for St. Louis City and the Missouri counties of Jefferson, St. Charles, and St. Louis was determined to be 9.1 months, and the value for the remaining counties was estimated to be equal to 12 months.[6/]

TEMPORAL APPORTIONING FACTORS

Temporal apportioning factors for determining construction emissions by hour of the day, day of the week, and season of the year were derived from analysis of the work cycle of construction activity (see Figure 11). Construction activity reaches its peak level during June and July and is lowest during December through February. Weekday activity is relatively uniform with some reduction on weekends. The hourly factor distribution has mid-morning and mid-afternoon peaks.

TEMPORAL APPORTIONING FACTORS

Source Type: Construction

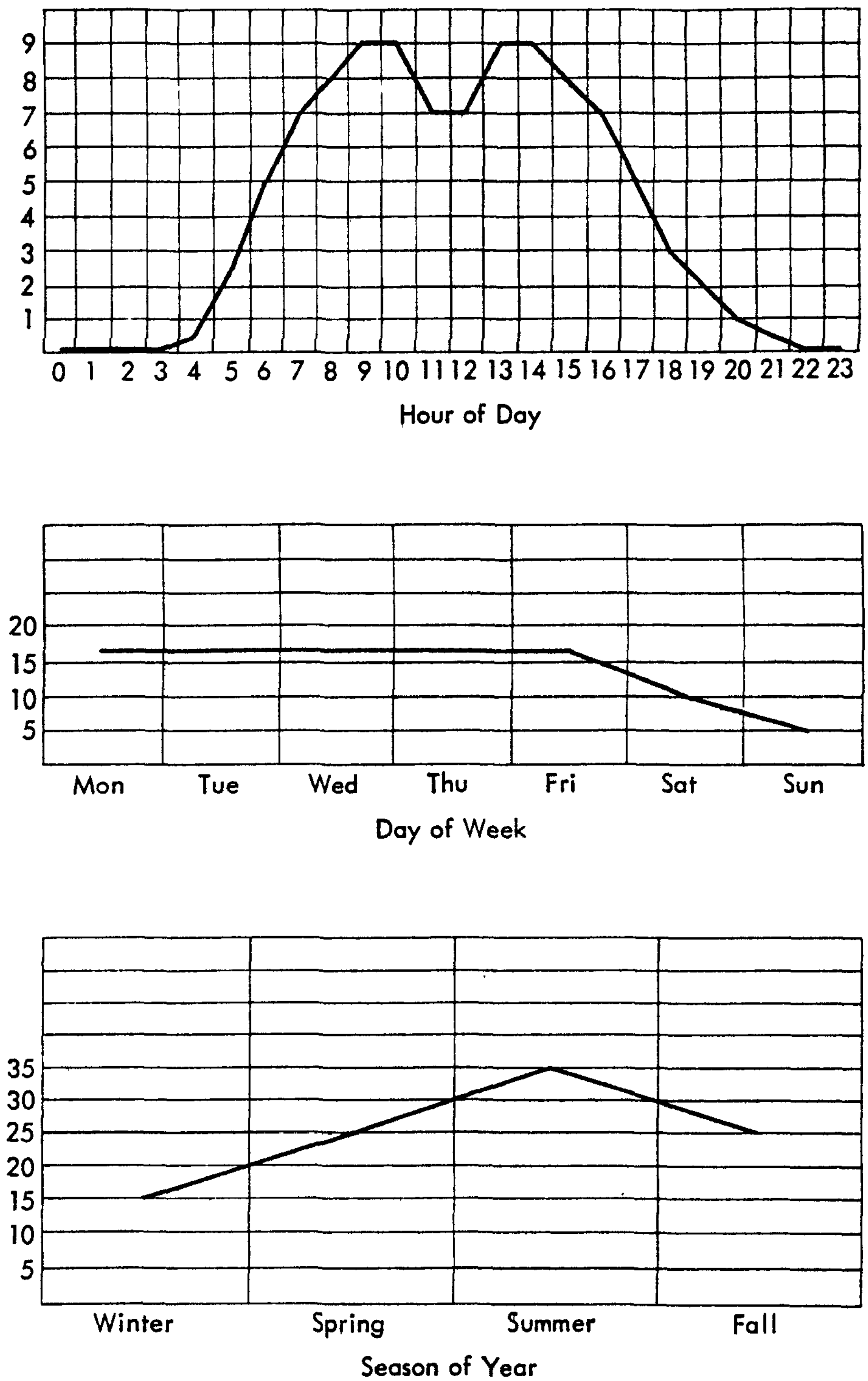

Figure 11. Percentage of total daily, weekly, and annual construction activity

AGGREGATE STORAGE

GRID SOURCE EXTENT

The amount of fugitive dust emissions from aggregate storage piles is proportional to the quantity of aggregate stored,[17] i.e., the tonnage put through the storage cycle. Figure 12 illustrates the methodology for determining the quantity of aggregate stored annually within each grid.

The following Source Classification Codes of the National Emissions Data System (NEDS) were identified as industrial producers and users of mineral aggregate:

SCC ID			
I	II	III	IV
3	05	All	All

A NEDS point source listing (August 25, 1975)[23] for the above codes was obtained for the St. Louis AQCR.

Aggregate storage data from the NEDS listing were analyzed and the grid numbers for aggregate user and producer industries were determined from the respective UTM coordinates. Only industries with open aggregate storage were considered in this study. Producers are stone quarries and sand/gravel processors, and users are cement manufacturing (wet and dry), and concrete batching. Asphalt batching plants in the St. Louis area normally store aggregate in enclosed areas.

The methodology employed to determine the amount of aggregate material stored on-site by a producer or user industry and the average period of storage is presented below.

Stone quarries - The amount of aggregate material stored annually is specified in the NEDS output. An estimated 3-month storage period is assumed from previous experience with the stone quarry industry.

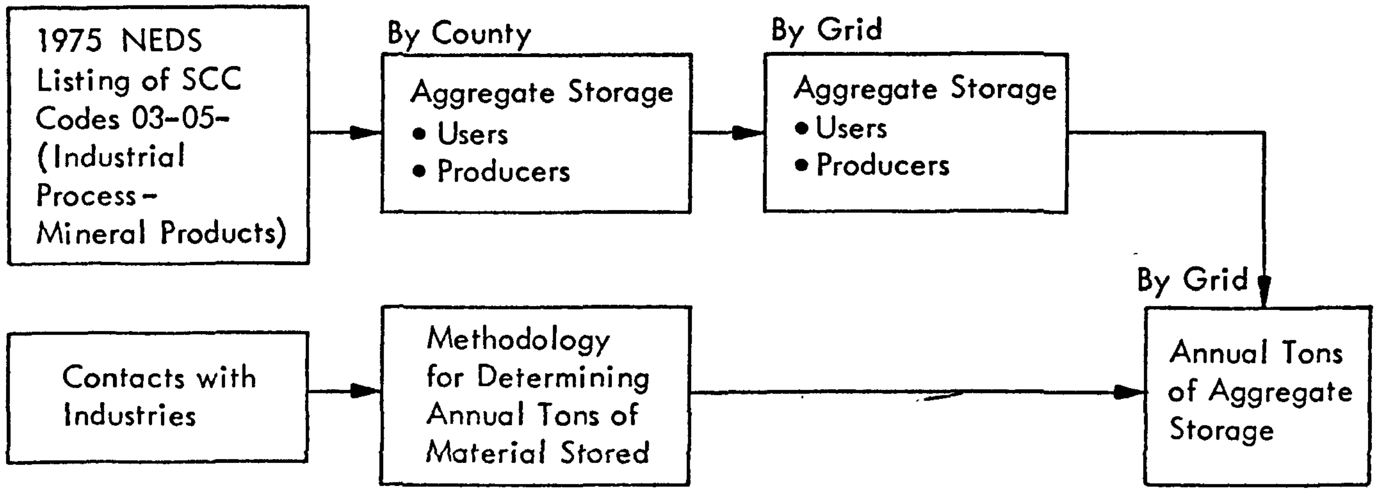

Figure 12. Procedure for determination of annual tons of aggregate storage

Sand and gravel - The amount of aggregate material stored in an annual period is taken to be 50% of the tonnage processed. An estimated 3-month inventory period is assumed from previous experience with the sand and gravel industry.

Cement manufacturing - The following equation for calculating the amount of aggregate stored by this user industry was determined from telephone contacts with area plants and a literature survey:

$$\underset{\text{(tons)}}{\text{Aggregate stored}} = \underset{\text{(tons)}}{\text{Cement produced}} \times 1.2 \, \frac{\text{tons aggregate}}{\text{tons cement}}$$

The NEDS output designates tons of cement produced from wet and dry process facilities. On the average, aggregate material used in cement manufacturing is stored for 1 week.

Concrete batching - Cubic yards of concrete produced by each batching plant is specified in the NEDS listing. Based on contacts with this user industry, the following conversion factors were obtained: (a) 1 cu yd of concrete is equivalent to 2 tons, and (b) approximately 75% of each ton of concrete produced is comprised of aggregate material taken from open storage. The average aggregate storage period for this user industry is 1 week.

Table 6 summarizes by county the quantity of aggregate stored annually for each of the above user and producer industries.

EMISSION FACTOR

The emission factor for dust emissions from aggregate placed in open storage for a period of 3 months is:

$$EF_s = 0.33 \text{ lb/ton placed in storage}$$

which includes emission contributions from wind erosion (33%), movement of traffic among the storage piles (40%), and loading and unloading operations (27%).[1/] The corresponding emission factor for a 1-week storage cycle is 0.22 lb/ton placed in storage.

TEMPORAL APPORTIONING FACTORS

Temporal apportioning factors (see Figure 13) were determined separately for the emission contributions from storage pile activity and from wind erosion. The factors for storage pile activity were derived on the basis of the information from industrial personnel and NEDS data.

Table 6. ANNUAL ACRES OF AGGREGATE STORED BY COUNTY

State	County	Aggregate storage (tons/year) Sand/ gravel	Stone quarry	Cement manufacturing	Concrete batching	Total
Illinois	Bond	0	0	0	0	0
	Clinton	0	20,000	0	11,300	31,300
	Madison	0	74,000	0	0	74,000
	Monroe	0	46,800	0	0	46,800
	Randolph	0	275,000	0	0	275,000
	St. Clair	0	1,900,000	0	0	1,900,000
	Washington	0	100,000	0	0	100,000
Missouri	Franklin	0	0	0	37,950	37,950
	Jefferson	12,950	8,000	1,232,700	54,000	1,307,650
	St. Charles	0	220,000	0	125,550	345,550
	St. Louis City	0	0	0	0	0
	St. Louis	189,500	64,000	1,709,600	0	1,163,100

TEMPORAL APPORTIONING FACTORS

Source Type: Aggregate Storage

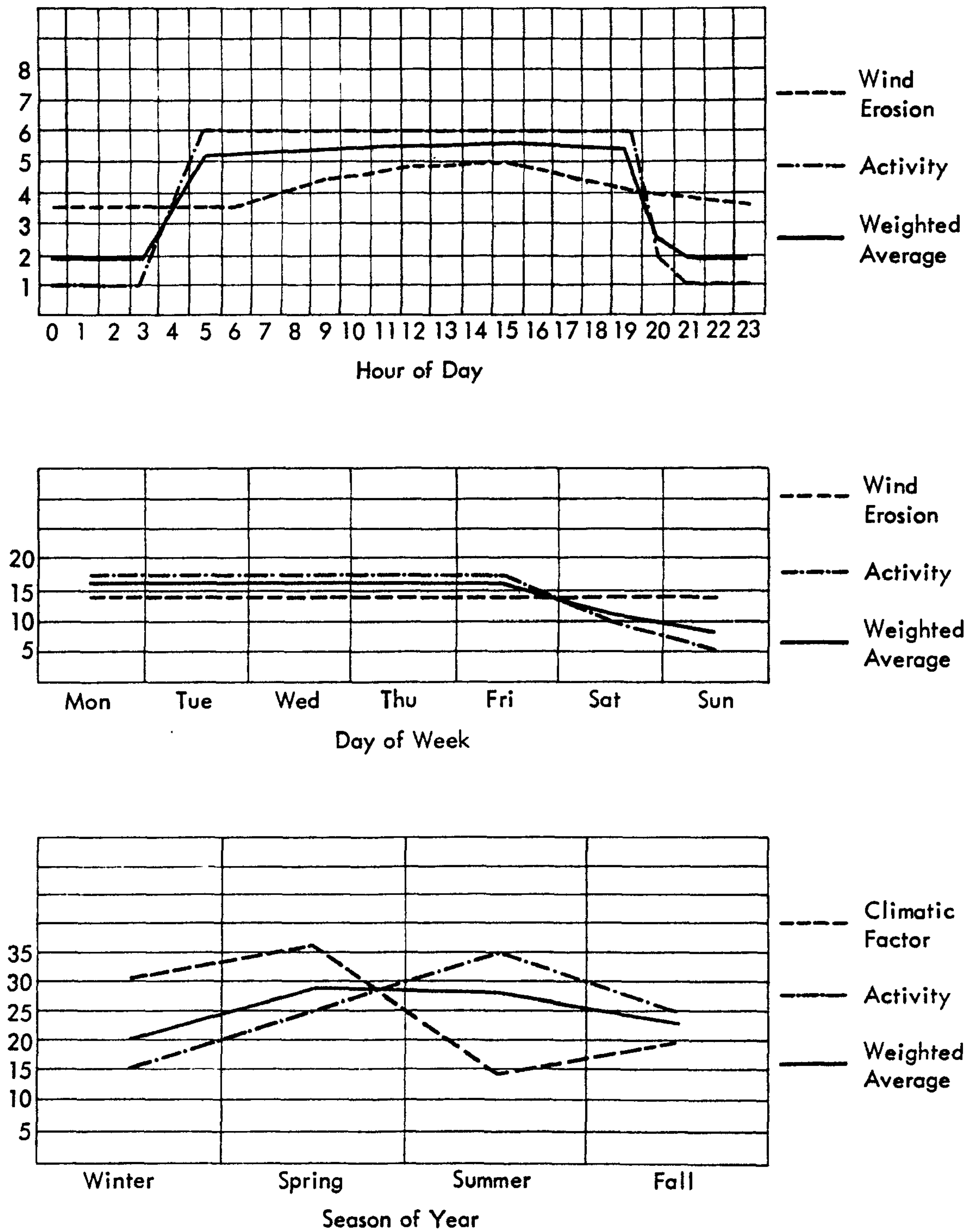

Figure 13. Percentage of total daily, weekly, and annual aggregate storage operations

For aggregate producers (stone quarries and sand/gravel processors), approximately 75% of the industry operates year-round and the remaining 25% operate 9 months during the year. Production rates are at peak level during June and July, and are lowest during December through February. For most of the year, the operating schedule is 6 days/week and 15 hr/day.

For aggregate users (cement manufacturing and concrete batching), approximately 60% of the industry in the St. Louis AQCR operate year-round, and the remaining 40% operate 9 to 10 months during the year. Production rates change seasonally with demand for concrete for local construction projects. The operating schedule is normally 6 days/week and 16 hr/day. Spring and summer are peak seasons, and activities decline during the winter months (December through February).

Seasonal and hourly apportioning factors for wind erosion from stockpiles were based on observed variations in governing climatic conditions. Seasonal factors were scaled to values of the climatic factor for wind erosion,[18/] and hourly factors were proportioned to the probability that the wind speed will exceed 12 mph, the threshold value for the onset of wind erosion.

UNPAVED AIRSTRIPS

GRID SOURCE EXTENT

The landing/takeoff (LTO) cycle is the designated measure of source extent for fugitive emissions from unpaved airstrips. Figure 14 illustrates the procedure used to determine LTO cycles on unpaved airstrips by grid.

Airport data were extracted from an "Airport Services"[24/] computer tape obtained by MRI from the Federal Aviation Administration (FAA) under EPA Contract No. 68-02-1437. Data on this tape include the following information for each airport: site number, city, state, airport name, county code, latitude, longitude, airport type, number of total based aircraft, number of multi-engine based aircraft, runway pavement type, runway length, population served, ownership type, and usage type. A computer program was written to list all Missouri and Illinois airports and to output required data onto standard computer cards.

Nine airports within the St. Louis AQCR were designated as Pavement Type 5 (dirt or gravel runways). However, seven of these airports did not have any based aircraft and the remaining two were helicopter bases.

Airstrips with Pavement Type 4 (turf runways) numbered 43, of which, 25 turf airstrips (excluding heliports) listed based aircraft. Grid numbers for each of these 25 airstrips (see Table 7) were determined from latitude and longitude indicated on the FAA tape.

Regional FAA officials estimated the number of operations per based aircraft at small airport facilities to be in the range of 400 to 800 operations per year with a typical value being 500, i.e., 250 LTO cycles per year.[6/] The total number of LTO cycles on unpaved airstrips in each grid was calculated by multiplying 250 LTO cycles per year times the total number of aircraft based at unpaved airstrips within each grid.

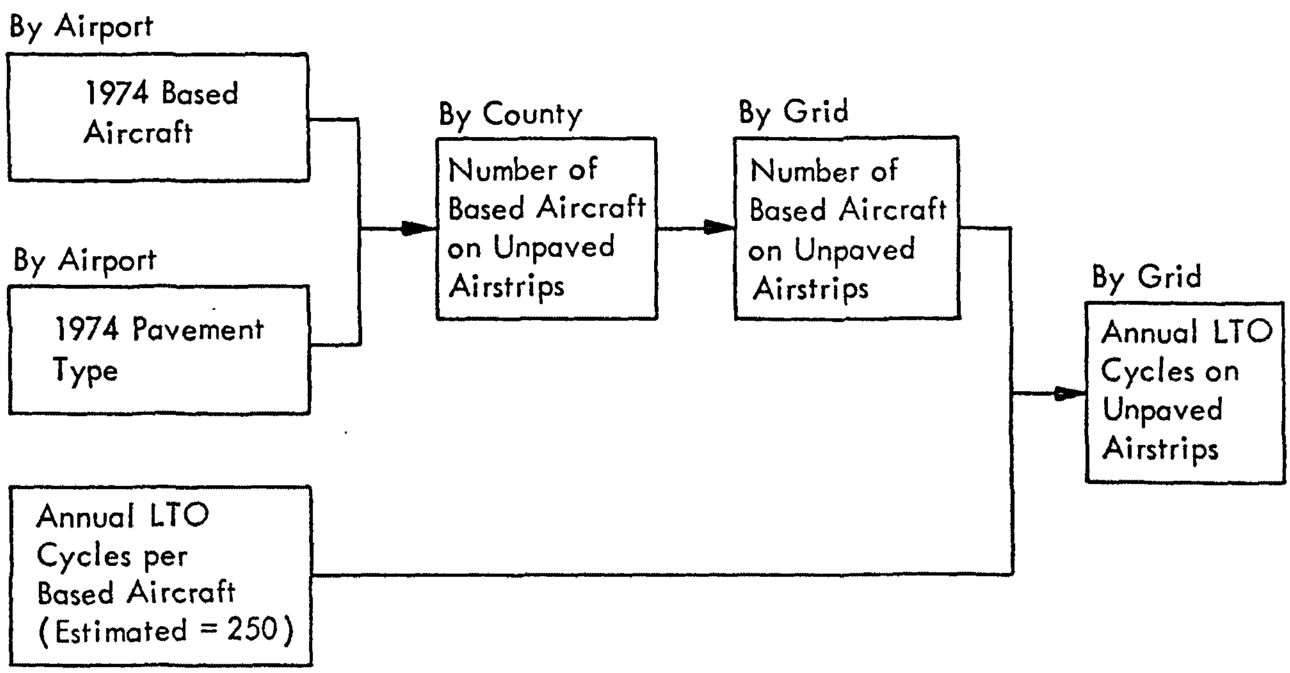

Figure 14. Procedure for determination of annual LTO cycles on unpaved airstrips

Table 7. DATA ON UNPAVED (TURF) AIRSTRIPS BY COUNTY

State	County	No. of turf airstrips with based aircraft	Grid location	LTO cycles/ year
Illinois	Bond	2	1,764	500
	Clinton	3	1,739, 1,761, 1,784	2,500
	Madison	3	1,595, 1,641, 1,710	5,250
	Monroe	4	951, 990, 1,057, 2,273	12,000
	Randolph	3	1,579, 1,582, 1,633	750
	St. Clair	7	1,456, 1,484, 1,586, 1,617 (2), 1,639, 2,341	8,750
	Washington	1	1,842	250
Missouri	Franklin	0	-	0
	Jefferson	1	185	3,000
	St. Charles	1	166	1,250
	St. Louis	0	-	0
	St. Louis City	0	-	0

EMISSION FACTOR

The emission factor for unpaved airstrips, in units of pounds of dust per landing/takeoff cycle, was derived by analogy to the equation for unpaved roads,[6] doubled to include propeller-generated wind erosion. The expression for dirt airstrips is given by:

$$EF_a = 2\left[0.49\ s_a \left(\frac{S_a}{30}\right) \left(\frac{d}{365}\right)\ (1)\right]$$

where s_a is the silt content (percent) of dirt airstrips (equivalent to the agricultural soil silt content), S_a is the average aircraft ground speed (mph), d is the number of dry days per year, and (1) mile is the approximate length of runway used for an LTO cycle[6] including taxiing. Regional FAA officials[6] estimated S_a to be 40 mph; and, on the average, there are 250 dry days per year in the St. Louis area.[5]

During the months of July through October, turf airstrips will approximate dirt airstrips due to dry weather conditions and higher volume of traffic. It was estimated that the emission factor for turf airstrips should be one-half the factor for dirt airstrips to account for the effect of grass cover in reducing wind erosion. The emission factor for turf airstrips ranged from 4.5 to 31 lb/LTO cycle for agricultural silt contents ranging from 10 to 70%.

TEMPORAL APPORTIONING FACTORS

Temporal apportioning factors were derived from the following information (see Figure 15):

1. Air traffic, i.e., landings and takeoffs, occurs primarily between the hours of dawn to dusk.

2. Approximately 50% of the air traffic occurs on weekends and holidays.

3. Approximately 70% of the air traffic occurs between the months of April through October.

TEMPORAL APPORTIONING FACTORS

Source Type: Unpaved Airstrips

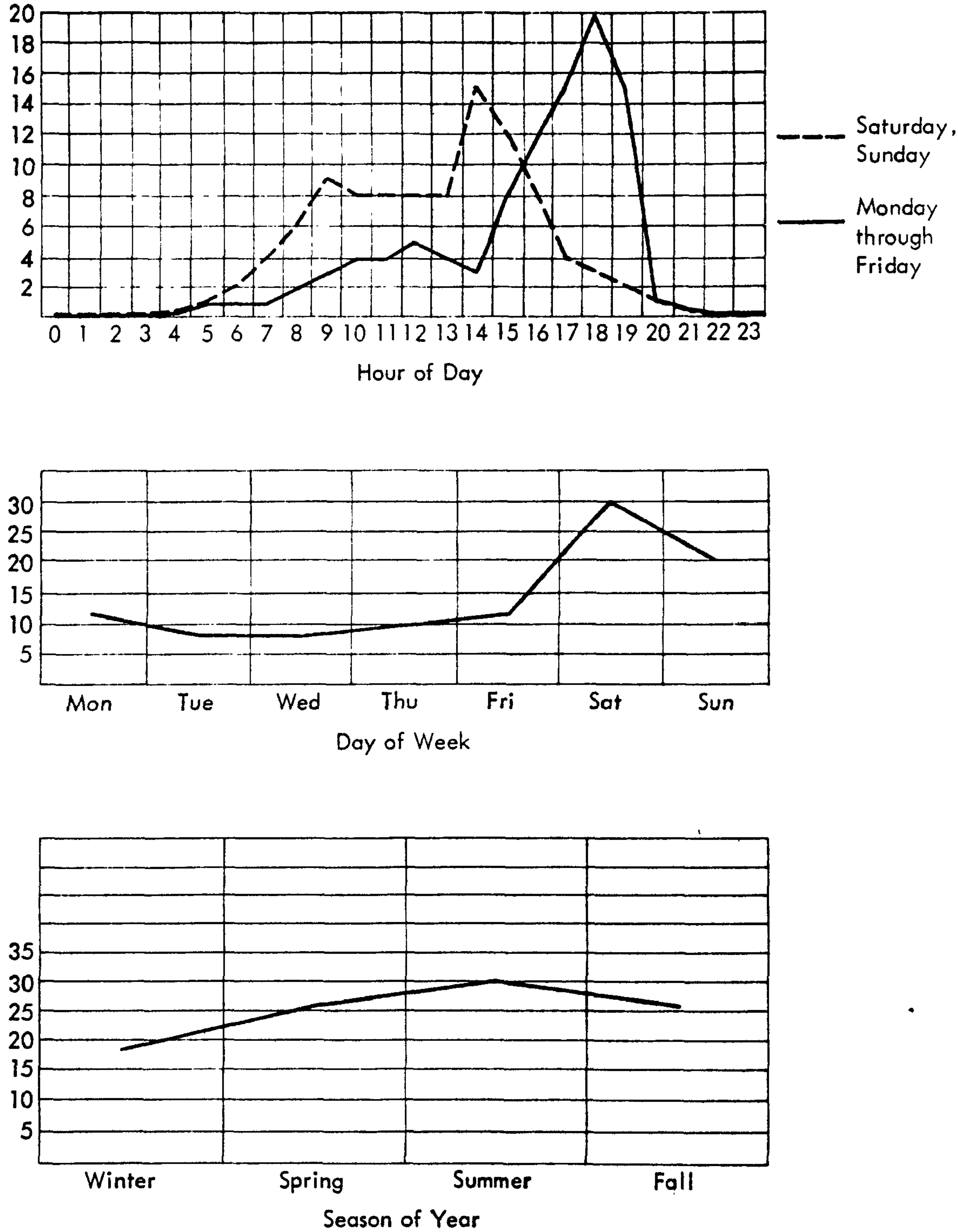

Figure 15. Percentage of total daily, weekly, and annual LTO cycles

DATA TABULATIONS AND CALCULATED RESULTS

Tables 8 and 9 illustrate example data tabulations prepared for this project. Table 8 gives data on (a) annual extent of fugitive dust sources and (b) agricultural soil silt content, for the first 35 grids in the RAPS study region. Table 9 presents the hourly adjustment factors for a Sunday in the winter season. A complete set of example calculations is detailed in Appendix A.

The preceding data were used as input for two computer programs:

1. Program 1, which calculates the annual emissions of fugitive dust for each source category, by grid, and

2. Program 2, which calculates hourly emissions of fugitive dust within a specified grid, for any hour of the year, through multiplication of the annual emissions total by the particular hourly adjustment factor.

Simplified logic diagrams of these programs are presented in Figures 16 and 17. Both programs were written in Fortran IV to provide compatibility with most computer systems. Example output for the annual emissions computer program is illustrated in Figure 18.

Table 8. EXAMPLE CODED SOURCE EXTENT AND CORRECTION FACTOR DATA

Grid No.	Coordinates (UTM Zone 15) E	Coordinates (UTM Zone 15) N	Size (km)	Source extent: Unpaved roads (10^2 veh. mi.) Gravel	Unpaved roads Dirt	Land tilling (acres)	Wind erosion (acres)	Construction (10^{-1} acres)	Aggregate storage (tons)	Dirt airstrips (LTO cycles)	Correction factor: Silt content (%)
1	640	4,235	10	8,827	0	11,103	944	147	0	0	40
2	640	4,245	10	10,690	0	11,102	945	153	0	0	40
3	640	4,265	10	8,260	0	11,102	945	156	0	0	59
4	640	4,280	5	1,296	0	2,774	236	23	0	0	59
5	645	4,230	5	907	242	2,776	236	46	0	0	40
6	645	4,255	5	1,490	0	2,776	236	46	0	0	40
7	645	4,260	5	2,203	0	2,776	236	46	0	0	40
8	645	4,275	5	1,101	0	2,776	236	46	0	0	59
9	645	4,280	5	2,389	0	2,774	236	34	43,050	0	59
10	650	4,230	5	583	0	2,776	236	46	0	0	40
11	650	4,235	10	10,496	0	11,105	944	184	0	0	40
12	650	4,245	10	7,710	0	11,105	944	184	0	0	40
13	650	4,255	10	8,876	0	11,105	944	184	0	0	40
14	650	4,265	10	6,673	0	11,448	944	178	0	0	59
15	650	4,275	5	405	0	2,774	236	32	0	0	59
16	655	4,230	5	713	0	2,776	236	46	0	0	40
19	660	4,235	10	7,580	0	11,105	944	184	0	0	40
20	660	4,245	10	5,377	0	11,105	944	184	0	0	40
21	660	4,255	10	7,256	0	11,105	944	184	0	0	40
22	660	4,265	10	5,759	101	11,102	945	156	0	0	59
25	665	4,230	5	1,684	0	2,776	236	46	0	0	30
26	670	4,230	5	1,500	0	2,776	236	46	0	0	40
27	670	4,235	10	6,738	0	11,105	944	184	0	0	40
28	670	4,245	5	1,555	0	2,776	236	46	0	0	40
29	670	4,250	5	1,745	0	2,776	236	46	0	0	40
32	670	4,260	5	130	0	2,776	236	46	0	0	40
33	670	4,265	3	0	0	999	85	17	0	0	67
34	670	4,268	1	0	0	110	9	2	0	0	67
35	670	4,269	1	0	0	110	9	2	0	0	50
37	671	4,268	1	0	0	110	9	2	0	0	50
38	671	4,269	1	0	0	110	9	2	0	0	50
39	672	4,268	1	0	0	110	9	2	0	0	50
40	672	4,269	1	0	0	110	9	2	0	0	50
43	673	4,265	1	0	0	110	9	2	0	0	67
44	673	4,266	1	0	0	110	9	2	0	0	67

Table 9. HOURLY ADJUSTMENT EXAMPLE CODED FACTORS

		Hourly adjustment factors (10^{-6})								
	Time of	Unpaved	Land tilling		Wind erosion			Aggregate	Unpaved
Number	day	roads	Illinois	Missouri	Illinois	Missouri	Construction	storage	airstrips
01	01	283	3	1	1,667	1,713	8	311	36
02	02	252	3	1	1,667	1,713	8	311	36
03	03	189	3	1	1,667	1,713	8	311	36
04	04	63	3	1	1,620	1,665	8	311	36
05	05	63	3	1	1,667	1,713	38	311	72
06	06	377	78	39	1,667	1,713	188	851	360
07	07	1,227	130	65	1,667	1,713	375	851	720
08	08	2,139	156	78	1,805	1,855	525	867	1,440
09	09	1,667	182	91	1,944	1,998	600	884	2,160
10	10	1,919	182	91	2,083	2,141	675	900	3,240
11	11	1,919	208	104	2,129	2,188	675	900	2,880
12	12	1,887	208	104	2,222	2,283	525	916	2,880
13	13	1,699	182	91	2,268	2,331	525	916	2,880
14	14	1,887	182	91	2,268	2,331	675	916	2,880
15	15	2,328	208	104	2,315	2,378	675	933	5,400
16	16	2,265	182	91	2,315	2,378	600	933	4,320
17	17	2,517	182	91	2,222	2,283	525	916	2,880
18	18	2,863	156	78	2,083	2,141	375	900	1,440
19	19	1,919	130	65	1,991	2,046	225	884	1,080
20	20	1,510	104	52	1,944	1,998	150	884	720
21	21	1,070	78	39	1,805	1,855	75	425	360
22	22	692	26	13	1,805	1,855	30	311	72
23	23	440	10	5	1,759	1,808	8	311	36
24	24	283	3	1	1,713	1,760	8	311	36

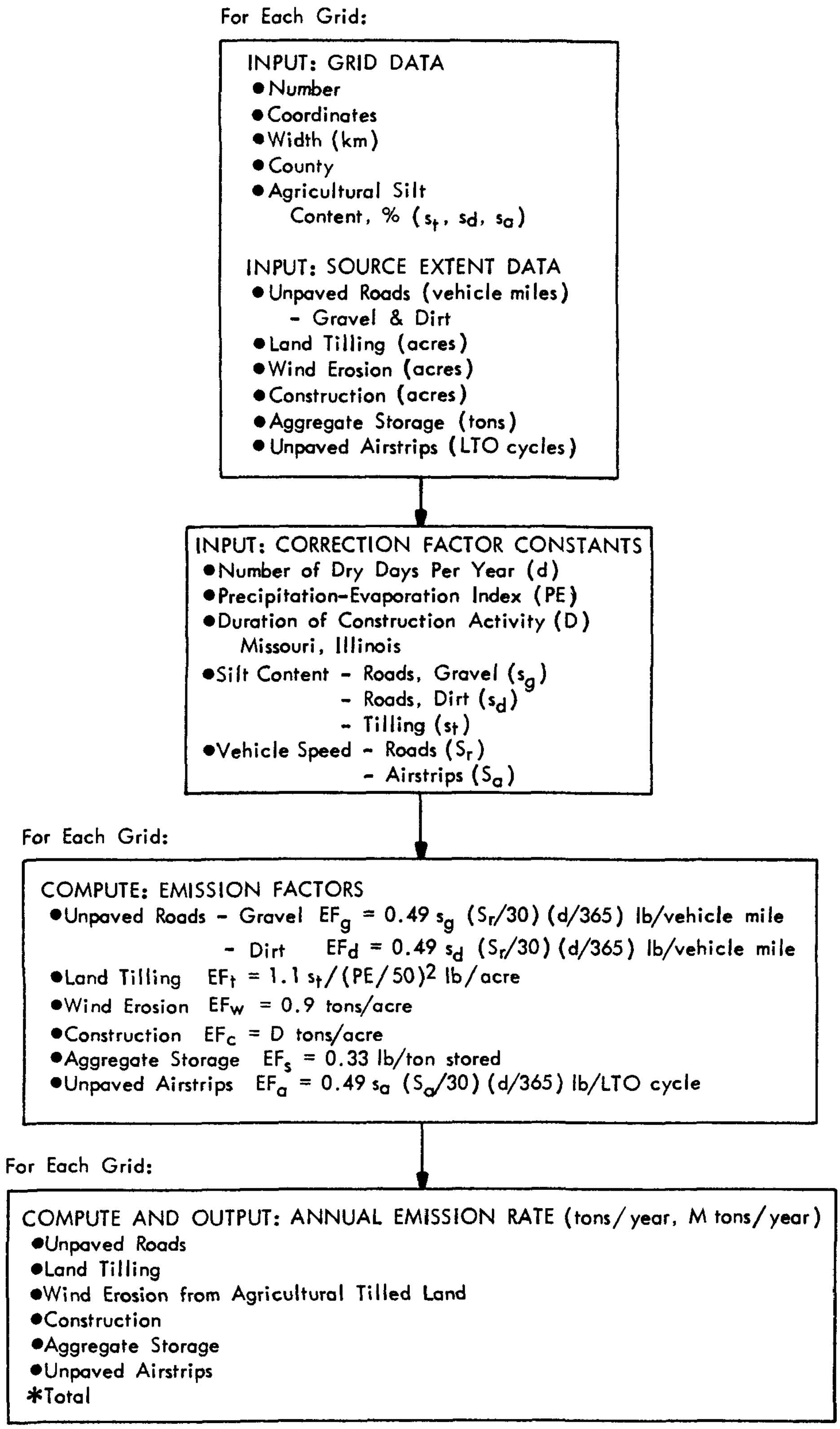

Figure 16. Simplified flow diagram of calculation procedure for annual emissions by grid

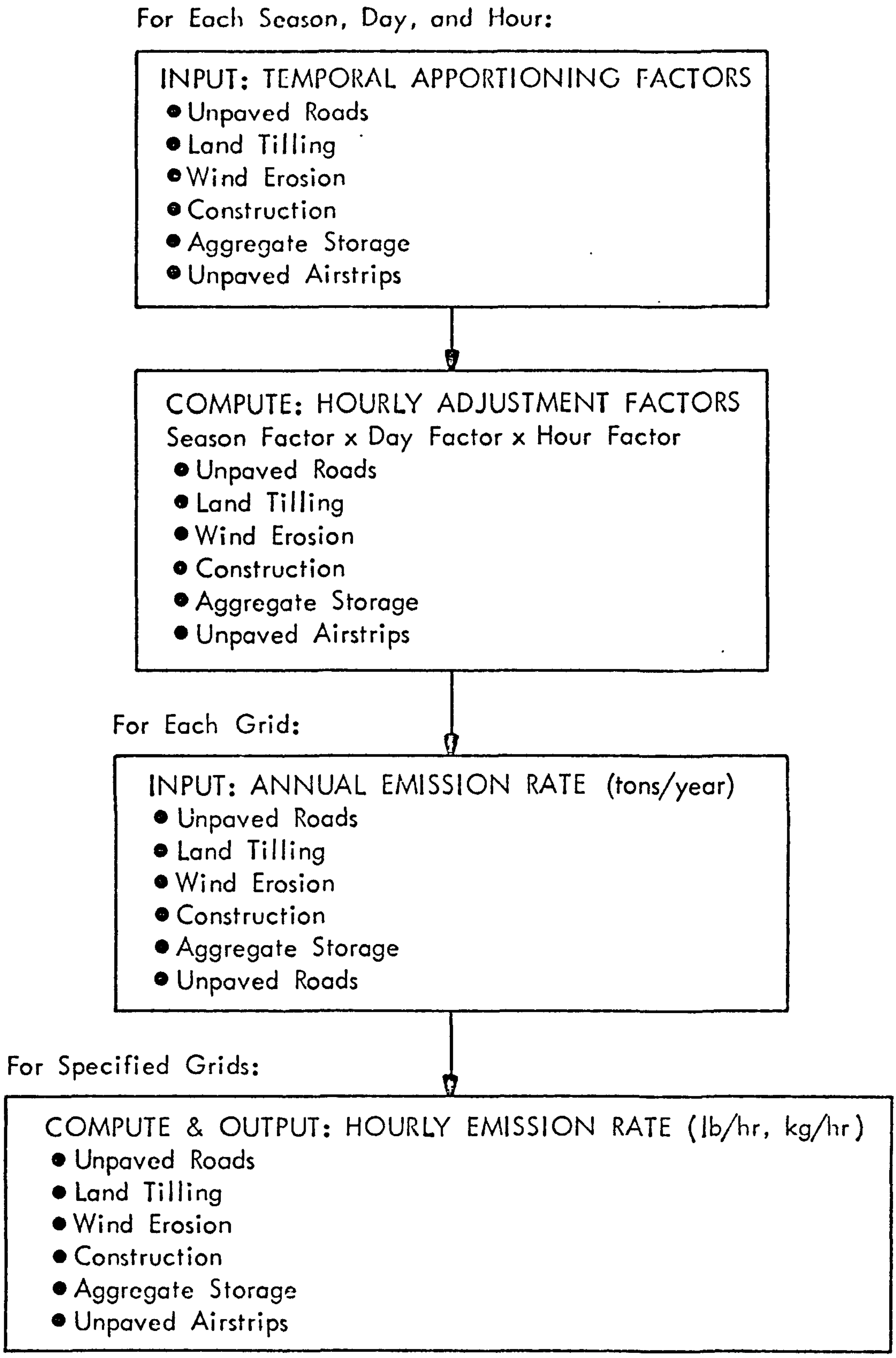

Figure 17. Simplified flow diagram of calculation procedure for hourly emissions by grid

CALCULATED ANNUAL EMISSION RATES BY GRID

GRID	COORDINATE GRID E	N	S[a]	C[b]	UNPV. ROADS	AG. TILLING	WIND EROSION	CONSTRUCTION	AG. STORAGE	UNP.AIRSTRIP	**TOTAL**
					EMISSION RATE (TONS/YR)						
1	640	4235	10	8	2369.99	70.61	849.6	176.4	0.000	0.000	3467
2	640	4245	10	8	2870.19	70.61	850.5	183.6	0.000	0.000	3975
3	640	4265	10	8	2217.75	104.15	850.5	187.2	0.000	0.000	3360
4	640	4280	5	8	347.97	26.04	212.4	27.6	0.000	0.000	614
5	645	4230	5	8	405.96	17.65	212.4	55.2	0.000	0.000	691
6	645	4255	5	8	400.05	17.65	212.4	55.2	0.000	0.000	685
7	645	4260	5	8	591.49	17.65	212.4	55.2	0.000	0.000	877
8	645	4275	5	8	295.61	26.04	212.4	55.2	0.000	0.000	589
9	645	4280	5	8	641.43	26.04	212.4	40.8	7.103	0.000	928
10	650	4230	5	8	156.53	17.65	212.4	55.2	0.000	0.000	442
11	650	4235	10	8	2818.10	70.62	849.6	220.8	0.000	0.000	3959
12	650	4245	10	8	2070.08	70.62	849.6	220.8	0.000	0.000	3211
13	650	4255	10	8	2383.15	70.62	849.6	220.8	0.000	0.000	3524
14	650	4265	10	8	1791.65	104.15	849.6	213.6	0.000	0.000	2959
15	650	4275	5	8	108.74	26.04	212.4	38.4	0.000	0.000	386
16	655	4230	5	8	191.44	17.65	212.4	55.2	0.000	0.000	477
19	660	4235	10	8	2035.18	70.62	849.6	220.8	0.000	0.000	3176
20	660	4245	10	8	1443.69	70.62	849.6	220.8	0.000	0.000	2585
21	660	4255	10	8	1948.19	70.62	849.6	220.8	0.000	0.000	3089
22	660	4265	10	8	1646.25	104.15	850.5	187.2	0.000	0.000	2788
25	665	4230	5	8	452.14	13.24	212.4	55.2	0.000	0.000	733
26	670	4230	5	8	402.74	17.65	212.4	55.2	0.000	0.000	688
27	670	4235	10	8	1809.11	70.62	849.6	220.8	0.000	0.000	2950
28	670	4245	5	8	417.51	17.65	212.4	55.2	0.000	0.000	703
29	670	4250	5	8	468.52	17.65	212.4	55.2	0.000	0.000	754
32	670	4260	5	8	34.90	29.57	212.4	55.2	0.000	0.000	332
33	670	4265	3	8	0.00	10.64	76.5	20.4	0.000	0.000	108
34	670	4268	1	8	0.00	.87	8.1	2.4	0.000	0.000	11
35	670	4269	1	8	0.00	.87	8.1	2.4	0.000	0.000	11
37	671	4268	1	8	0.00	.87	8.1	2.4	0.000	0.000	11
38	671	4269	1	8	0.00	.87	8.1	2.4	0.000	0.000	11
39	672	4268	1	8	0.00	.87	8.1	2.4	0.000	0.000	11
40	672	4269	1	8	0.00	.87	8.1	2.4	0.000	0.000	11
43	673	4265	1	8	0.00	1.17	8.1	2.4	0.000	0.000	12
44	673	4266	1	8	0.00	1.17	8.1	2.4	0.000	0.000	12
45	673	4267	1	8	0.00	1.17	8.1	2.4	0.000	0.000	12
46	673	4268	1	8	0.00	.87	8.1	2.4	0.000	0.000	11
47	673	4269	1	8	0.00	.87	8.1	2.4	0.000	0.000	11
48	674	4265	1	8	0.00	1.17	8.1	2.4	0.000	0.000	12
49	674	4266	1	8	0.00	1.17	8.1	2.4	0.000	0.000	12

a/ Grid size (width) in kilometers.
b/ County which represents major portion of grid.

Figure 18. Example computer output of annual emissions by grid

ANALYSIS OF RESULTS AND ESTIMATED ACCURACIES

Table 10 presents a county breakdown of annual fugitive dust emissions in the Metropolitan St. Louis AQCR. This data represents all grids which lie entirely or partially within a specific county. As indicated, unpaved roads and wind erosion from agricultural tilled land account for more than 80% of the total fugitive dust emissions for the St. Louis area.

The total quantity of particulate emissions smaller than 30 µm in diameter emitted by fugitive dust sources considered in this project is 1,145,000 tons/year. Assuming that 20% of the emissions (i.e., the portion smaller than 5 µm in size) will be transported to ambient air quality monitoring stations (see Appendix B), then 229,000 tons/year of fugitive dust will have an impact on regional air quality and must be taken into account in modeling the St. Louis AQCR. In comparison, total nonfugitive emissions for the St. Louis AQCR are 355,000 tons/year;[25] thus, fugitive emissions may be said to represent 39% of the total particulate pollutant problem.

Table 11 presents estimates for possible error in the calculated values corresponding to a 90% confidence level and were determined by a progressive analysis of errors associated with each calculation step. Composite ranges of error are presented for calculated source extent, corrected emission factors, and hourly adjustment factors.

Table 10. SUMMARY OF ANNUAL EMISSIONS BY COUNTY

State	County	Emission rate (tons/year)						
		Unpaved roads	Agricultural tilling	Wind erosion	Construction	Aggregate storage	Unpaved airstrips	Total
Illinois	Bond	46,594	5,612	44,186	1,716	0	7.8	98,115
	Clinton	56,874	7,804	62,665	3,048	5.2	39.1	130,435
	Madison	69,509	8,796	80,865	19,680	12.2	70.4	178,932
	Monroe	21,338	4,852	42,542	1,812	7.7	174.6	70,726
	Randolph	50,431	6,132	50,896	3,996	45.4	10.9	111,511
	St. Clair	62,286	9,509	77,950	21,120	313.5	133.0	171,311
	Washington	57,524	9,115	70,846	1,044	16.5	3.9	138,549
	Subtotal	364,556	51,820	429,950	52,416	400.5	439.7	899,582
Missouri	Franklin	44,721	3,750	20,089	5,220	6.3	0	73,788
	Jefferson	18,478	678	5,436	12,765	215.8	33.6	37,606
	St. Charles	19,818	2,478	39,607	9,901	57.0	9.8	71,870
	St. Louis City	0	0	0	3,256	0	0	3,256
	St. Louis	0	1,395	11,749	45,491	323.9	0	58,958
	Subtotal	83,017	8,303	76,881	76,633	603.0	43.4	245,478
	Total	447,573	60,123	506,831	129,049	1,003.5	483.1	1,145,058

Table 11. ESTIMATED ERRORS FOR TABULATED DATA

Source category	Estimated relative error		
	Source extent	Corrected emission factor	Hourly adjustment factor
Unpaved roads	± 5%	± 20%	± 15%
Agricultural tilling	± 15%	± 30%	± 20%
Wind erosion	± 30%	± 20%	± 15%
Construction	± 35%	± 30%	± 20%
Aggregate storage	± 25%	± 30%	± 20%
Unpaved airstrips	± 15%	± 25%	± 20%

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APPENDIX A

EXAMPLE CALCULATIONS
(RAPS GRID NO. 1)

GRID DATA

Number: 1
UTM Coordinates: E 640, N 4235
Size (length): 10 km
County: Franklin
State: Missouri

ANNUAL SOURCE EXTENT

Unpaved Roads: gravel = $8,827 \times 10^2$ vehicle miles
soil = 0 vehicle miles

Agricultural Tilling: 11,104 acres
Wind Erosion: 944 acres
Construction: 147×10^{-1} acres
Aggregate Storage: 0 tons
Unpaved Airstrips: 0 LTO cycles

CORRECTION FACTORS

Number of Dry Days Per Year (d): 250 days
Precipitation-Evaporation Index (PE): 93
Duration of Construction Activity (D): 12 months
Silt Content: Unpaved roads, gravel (s_r): 16%
Dirt (s_r): 40%
Agricultural tilling (s_t): 40%
Unpaved airstrips (s_a): 40%
Vehicle Speed: Unpaved roads (S_r): 30 mph
Unpaved airstrips (S_a): 40 mph

ANNUAL EMISSION FACTORS

Unpaved Roads: $$EF_r = 0.49\ s_r \left(\frac{S_r}{30}\right)\left(\frac{d}{365}\right) \frac{\text{lb}}{\text{vehicle mile}}$$

Gravel: $$EF_r = 0.49\ (\text{lb})\left(\frac{30}{30}\right)\left(\frac{250}{365}\right) = 5.37\ \frac{\text{lb}}{\text{vehicle mile}}$$

Dirt: $$EF_r = (0.49)(40)\left(\frac{30}{30}\right)\left(\frac{250}{365}\right) = 13.4\ \frac{\text{lb}}{\text{vehicle mile}}$$

Land Tilling: $$EF_t = \frac{1.1\ (s_t)}{(PE/50)^2}\ \frac{\text{lb}}{\text{acre}}$$

$$EF_t = \frac{1.1\ (40)}{(93/50)^2} = 12.72\ \frac{\text{lb}}{\text{acre}}$$

Wind Erosion: $EF_w = 0.9$ tons/acre

Construction: $EF_c = D \frac{tons}{acre}$

$$EF_c = 12 \text{ months} \times \frac{1 \text{ ton/acre}}{\text{month}} = 12 \text{ ton/acre}$$

Aggregate Storage: $EF_s = 0.33 \frac{lb}{\text{ton stored}}$

Unpaved Airstrips: $EF_a = 0.49\ (s_a) \left(\frac{S_a}{30}\right)\left(\frac{d}{365}\right) \frac{lb}{\text{LTO cycle}}$

$$EF_a = 0.49\ (40) \left(\frac{40}{30}\right)\left(\frac{250}{365}\right) = 17.9 \frac{lb}{\text{LTO cycle}}$$

ANNUAL EMISSIONS

Annual Emissions (tons) = Annual Source Extent x Annual Emission Factor

Unpaved Roads: gravel $= \frac{(8,827 \times 10^2 \text{ veh. mile})(5.37 \text{ lb/veh. mile})}{2,000 \text{ lb/ton}}$

$= 2,370$ tons

dirt = 0 tons

Land Tilling: $\frac{(11,104 \text{ acres})(12.72 \text{ lb/acre})}{2,000 \text{ lb/ton}} = 70.6$ tons

Wind Erosion: (944 acres)(0.9 tons/acre) = 850 tons

Construction: $(147 \times 10^{-1}$ acres)(12 tons/acre) = 176.4 tons

Aggregate Storage: (0 tons)(0.33 lb/ton)(1 ton/2,000 lb) = 0 tons

Unpaved Airstrips: (0 LTO cycles)(17.9 lb/LTO cycles)(1 ton/2,000 lb) = 0 tons

TEMPORAL APPORTIONING FACTORS

Temporal Apportioning Factor = (Seasonal Factor)(Day of the Week Factor)(Hour of the Day Factor)

Example: (Winter Factor)(Sunday Factor)(Hour 0 Factor)

Unpaved Roads: $(0.214)(0.147)(0.009) = 283 \times 10^{-6}$

Agricultural Tilling: 1×10^{-6}

Wind Erosion: $1,713 \times 10^{-6}$

Construction: 8×10^{-6}

Aggregate Storage: 311×10^{-6}

Unpaved Airstrips: 36×10^{-6}

HOURLY EMISSIONS

Hourly Emissions (tons) = Annual Emissions (tons) x Temporal Apportioning Factor

Example: Winter, Sunday, Hour 0, Grid 1

Unpaved Roads: $(2{,}370 \text{ tons})(283 \times 10^{-6}) = 0.671$ tons

Agricultural Tilling: $(70.6 \text{ tons})(1 \times 10^{-6}) = 70.6 \times 10^{-6}$ tons

Wind Erosion: $(850 \text{ tons})(1{,}713 \times 10^{-6}) = 1.46$ tons

Construction: $(176.4 \text{ tons})(8 \times 10^{-6}) = 1.41 \times 10^{-3}$ tons

Aggregate Storage: $(0 \text{ tons})(311 \times 10^{-6}) = 0$ tons

Unpaved Airstrips: $(0 \text{ tons})(36 \times 10^{-6}) = 0$ tons

METRIC UNITS CONVERSION

Annual Emissions (Mtons) = Annual Emissions (tons) x 0.907185 (Mtons/ton)

Hourly Emissions (Mtons) = Hourly Emissions (tons) x 0.907185 (Mtons/ton)

APPENDIX B

FACTORS AFFECTING ATMOSPHERIC TRANSPORT OF FUGITIVE DUST

This appendix presents an assessment of factors which determine the drift distances of fugitive dust particles in the atmosphere. Drift distance is defined as the horizontal displacement from the point of particulate injection to the point of particulate removal by ground-level deposition.

Factors to be considered in this assessment may be grouped into two categories:

1. Meteorological factors - properties of the atmosphere which affect contaminant advection and turbulent diffusion over surfaces of varying roughness scales.

2. Source factors - height of injection and particulate properties which affect gravitational settling and vertical mixing.

This assessment does not treat atmospheric washout of particulate matter.

METEOROLOGICAL FACTORS

Fugitive dust particles are typically injected into the lower portion of the "surface layer" region of the atmosphere which extends from ground level to a height of about 100 m. In this region the profile of the wind and its turbulence characteristics are strongly dependent on surface roughness properties.

For neutral atmospheric stability, the vertical profile of mean wind speed, $u(z)$, in the surface layer is described by a logarithmic relationship:

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_o}\right) \tag{1}$$

where u_* = friction velocity

k = von Karman's constant (0.4 for clear fluids)

z_o = surface roughness height

Neutral stability occurs with wind speed exceeding 12 mph or with overcast conditions regardless of wind speed.

The friction velocity, u_* , is related to the rate of momentum exchange at the surface:

$$u_* = (\tau_o / \rho_a)^{1/2} \quad (2)$$

where τ_o = surface shear stress

ρ_a = density of air

Within the surface layer, the vertical flux of momentum (and hence u_*) is known to be roughly constant and the eddy diffusivity is given by

$$\epsilon\ (z) = k u_*\ z \quad (3)$$

Aerodynamic roughness height, z_o , is related to the size, shape and spatial density of the roughness elements. Based on similarity concepts Lettau[1/] has derived the following expression for evenly spaced elements:

$$z_o = \frac{H\,a}{2A} \quad (4)$$

where H = effective height of roughness elements

a = silhouette area normal to the wind

A = total ground area per element

1/2 = average drag coefficient.

Figure B-1 gives roughness heights for various natural and man-made roughness features.

SOURCE FACTORS

The primary source factors which affect the drift distance of a fugitive dust particle are injection height, h , and particle settling velocity, V_s , which may be approximated by the Stoke's relationship:

$$V_s = 0.00301\ \rho_p\ D^2 \quad (5)$$

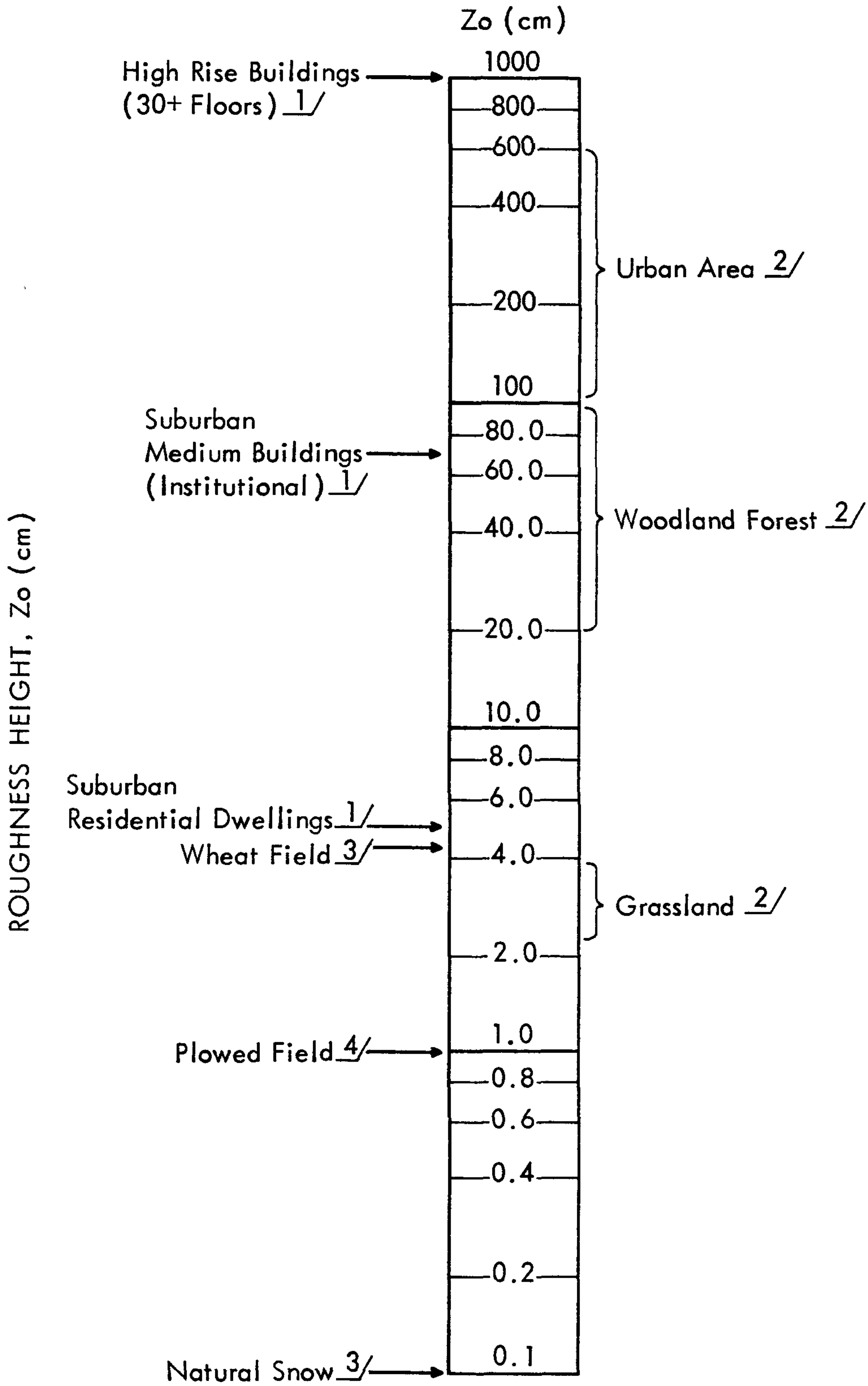

Figure B-1. Roughness heights for various surfaces where V_s = terminal settling velocity (cm/sec)

ρ_p = density of particle (g/cm^3)

D = particle diameter (μm)

Fugitive dust particles typically have a mineral composition with a density of about 2.5 g/cm^3.

CALCULATION OF DRIFT DISTANCE

In the past, most analyses of the atmospheric disperison of particles with appreciable settling tendencies have focused on the distribution of settling rate, $S(x)$, expressed as:

$$S(x) = V_s \; C_o(x) \tag{6}$$

where C_o = the ground-level concentration of particulate with settling velocity V_s

x = downwind distance from the source

Accordingly, an Eulerian approach to the problem has been taken.

However, analysis of particle drift with no net effect of atmospheric turbulence, is most conveniently treated by a Lagrangian approach. This is illustrated in the following section.

Case 1: Monodisperse particles, single injection height, negligible turbulence effect.

Consider the case of a steady stream of monodisperse particles released from a continuous crosswind line source at height h . It is assumed that each particle during its lifetime in the atmosphere is subjected to a balanced set of vertical turbulent velocity fluctuations with the result that the particle does not deviate appreciably from the trajectory it would have in the absence of turbulence.

The vertical position, z_p , of the particle as a function of time is given by

$$z_p(t) = h - V_s t \tag{7}$$

Substitution of Eq. (7) into Eq. (1) gives the following expression for the horizontal speed of the particle:

$$u_p = \frac{u_*}{k} \ln\left(\frac{h-V_s t}{z_o}\right) \tag{8}$$

The particle drift distance, x_p , is given by:

$$x_p = \int_o^{\frac{h-z_o}{V_s}} u_p dt \tag{9a}$$

where the upper limit of integration is the lifetime of the particle in the atmosphere. Integration of Eq. (9a) yields

$$x_p = \frac{u_* h}{kV_s} \left[\ln\left(\frac{h}{z_o}\right) - 1\right] + \frac{u_* z_o}{kV_s} \tag{9b}$$

To determine the effect of injection height and roughness height on the drift distance of particles of given aerodynamic sizes, the wind speed at z = 100 m was fixed at 6.9 m/s (15.4 mph) and friction velocities were determined from Eq. (1). The results are shown in Table B-1 for injection heights of 1, 3 and 10 m and for roughness heights spanning the range given in Table B-1. Figure B-2 shows the variations of x_p for h = 3 m, measured above z_o .

As expected, for particles of a given size, drift distance increases with injection height and decreases with roughness height. The latter effect is a direct result of the decrease in wind velocity near the surface caused by obstacles to the flow.

Case 2: Monodisperse particles, single injection height, turbulent atmosphere.

The analysis presented under Case 1 assumed that all particles generated from a particular fugitive dust source were deposited at the same point downwind (x_p). Clearly, however, particles subjected to a preponderance of downward turbulent velocity fluctuations will settle from the atmosphere at distances less than x_p and particles propelled above the trajectory defined above may drift far beyond x_p . In other words, because of the random nature of turbulent velocities, x_p approximates the distance at which half of the particles have deposited on the surface.

Table B-1. PARTICLE DRIFT DISTANCES CALCULATED FROM EQ. (9b)

Injection height,[a] h (m)	Roughness height, z_o (m)	Friction velocity, u* (cm/sec)	Drift distance, x_p, by particle size: 30 µm	20 µm	10 µm	5 µm	1 µm
1	0.01	30.0	40.6 m	91.2 m	366 m	1,460 m	36.6 km
	0.05	36.4	29.5	66.4	266	1,060	26.7
	0.10	40.0	24.2	54.4	218	871	21.8
	0.50	52.2	12.5	28.1	113	450	11.3
3	0.01	30.0	157.1 m	353 m	1,418 m	5.66 km	141.8 km
	0.05	36.4	128.2	288	1,157	4.62	115.7
	0.10	40.0	112.9	254	1,019	4.07	101.9
	0.50	52.2	73.5	165	663	2.65	66.3
	1.00	60.0	56.4	127	509	2.03	50.9
10	0.01	30.0	655 m	1,474 m	5.92 km	23.6 km	592 km
	0.05	36.4	582	1,309	5.25	21.0	525
	0.10	40.0	541	1,216	4.88	19.5	488
	0.50	52.2	423	952	3.82	15.3	382
	1.00	60.0	363	816	3.28	13.1	328

a/ Injection height measured above roughness height.

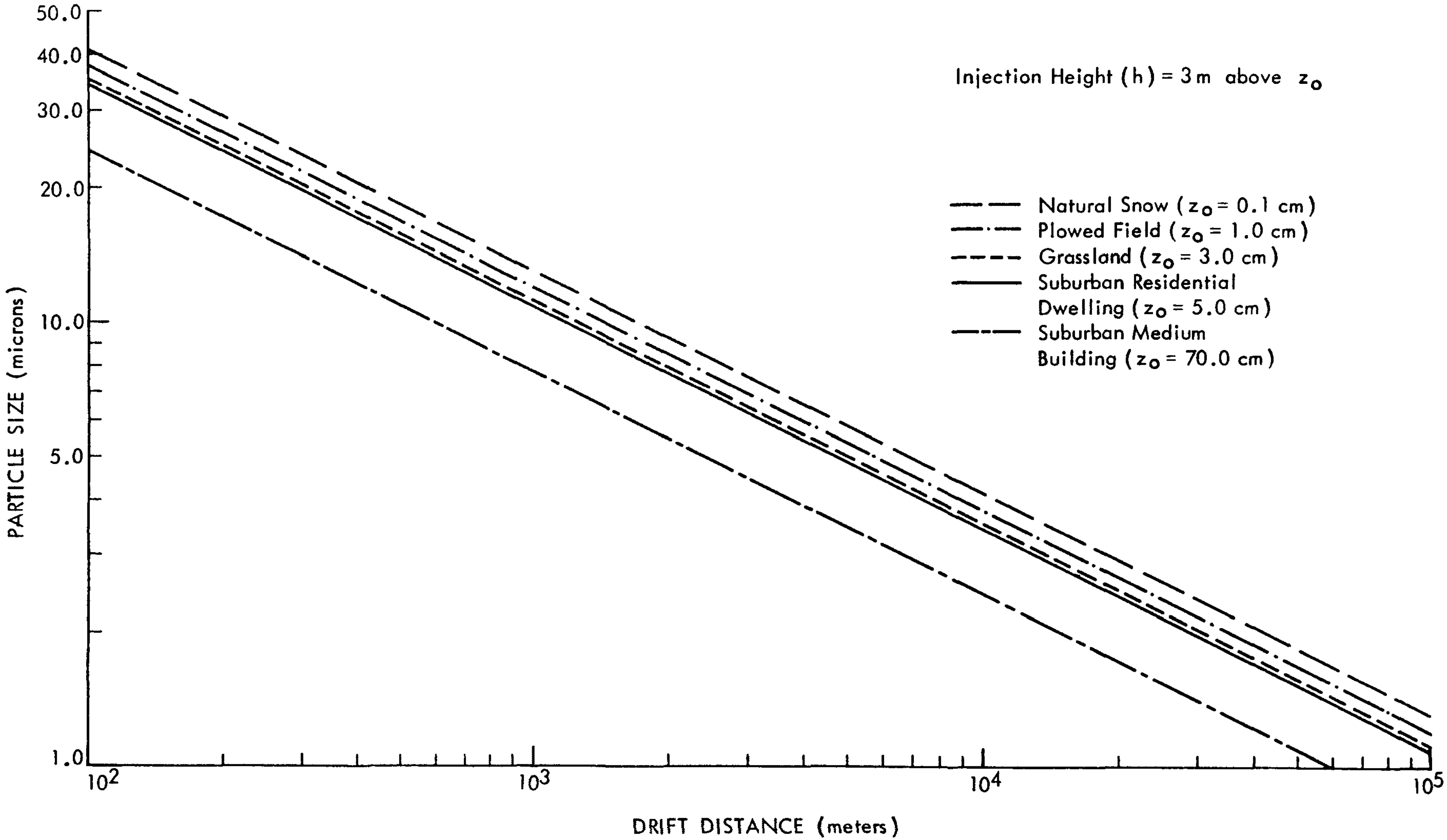

Figure B-2. Relationship between particle size and drift distance

The specific question addressed here has to do with the form of the settling rate distribution. Recalling Eq. (6), this problem reduces to finding the distribution of ground-level concentration by solving the appropriate transport equations and accompanying boundary conditions.

The phenomena of quasi-steady advection and turbulent diffusion from a continuous line source under the condition of uniform wind speed is described by the following equation:

$$U \frac{dC}{dx} = pU \frac{d}{dz}\left(z \frac{dC}{dz} \right) + V_s \frac{dC}{dz} \tag{10}$$

where C = particulate concentration

U = uniform speed of crosswind

p = turbulence parameter.

The uniform wind speed, U , is assumed to have the value given by the Case 1 velocity profile at z = h. The quantity pUz becomes the coefficient of eddy diffusivity.

Although Eq. (10) is not amenable to analytical solution for the case in point, it has been shown[5] that the distribution of ground-level concentration has the following form:

$$Co(x) = A \frac{e^{-h/px}}{x^{1+\alpha}} \tag{11}$$

where A = constant

$$\alpha = \frac{V_s}{pU}$$

The function given in Eq. (11), and hence the settling rate, reaches a maximum at:

$$x_{max} = \frac{h}{p\ (1+\alpha)} \tag{12}$$

and then decays to zero as $x \longrightarrow \infty$. Values for x_{max} are given in Table B-2 based on values of p determined by comparing the two forms of the eddy diffusivity, yielding

$$p = ku_*/U \quad . \tag{13}$$

Table B-2. DISTANCES TO POINT OF MAXIMUM SETTLING, x_{max} , CALCULATED FROM EQ. (12)

Injection height, h (m)	Roughness height, z_o (m)	Turbulence parameter, p	Friction u_* (cm/sec)	Values of α and x_{max} (m) by particle size: 30 µm α	30 µm x_{max}	20 µm α	20 µm x_{max}	10 µm α	10 µm x_{max}	5 µm α	5 µm x_{max}	1 µm α	1 µm x_{max}
1	0.01	0.0347	30.0	0.564	18.4	0.251	23.0	0.0625	27.1	0.0157	28.4	0.00062	28.8
	0.05	0.0534	36.4	0.465	12.8	0.207	15.5	0.0515	17.8	0.0129	18.5	0.00052	18.7
	0.10	0.0695	40.0	0.423	10.1	0.188	12.1	0.0469	13.7	0.0118	14.2	0.00047	14.4
	0.50	0.2308	52.2	0.324	3.27	0.144	3.79	0.0359	4.18	0.0090	4.29	0.00036	4.33
3	0.01	0.0281	30.0	0.564	68.3	0.251	85.3	0.0625	100.5	0.0157	105.1	0.00062	106.7
	0.05	0.0391	36.4	0.465	52.4	0.207	63.6	0.0515	73.0	0.0129	75.7	0.00052	76.7
	0.10	0.0470	40.0	0.423	44.9	0.188	53.7	0.0469	61.0	0.0118	63.1	0.00047	63.8
	0.50	0.0893	52.2	0.324	25.4	0.144	29.4	0.0359	32.4	0.0090	33.3	0.00036	33.6
	1.00	0.1456	60.0	0.282	16.1	0.125	18.3	0.0312	20.0	0.0078	20.4	0.00031	20.6
10	0.01	0.0232	30.0	0.564	276	0.251	345	0.0625	406	0.0157	424	0.00062	431
	0.05	0.0302	36.4	0.465	226	0.207	274	0.0515	315	0.0129	327	0.00052	331
	0.10	0.0347	40.0	0.423	203	0.188	243	0.0469	275	0.0118	285	0.00047	288
	0.50	0.0534	52.2	0.324	141	0.144	164	0.0359	181	0.0090	186	0.00036	187
	1.00	0.0695	60.0	0.282	112	0.125	128	0.0312	140	0.0078	143	0.00031	144

The constant A in Eq. (11) may be evaluated by equating the emission rate E to the integrated settling rate.

$$E = \int_0^\infty C_o V_s \, dx = A V_s \int_0^\infty \frac{e^{-h/px}}{x^{1+\alpha}} \, dx \tag{14}$$

With the transformation $y = b/x$ where $b = h/p$, the above equation becomes

$$E = \frac{AV_s}{b^\alpha} \int_0^\infty e^{-y} \, y^{(\alpha-1)} \, dy = \frac{AV_s \Gamma(\alpha)}{b^\alpha} \tag{15}$$

where $\Gamma(\alpha)$ is the gamma function.

Similarly it can be shown that the mass fraction K of particles remaining suspended beyond some distance x is given by:

$$K = \frac{\Gamma\left(\alpha, \frac{b}{x}\right)}{\Gamma(\alpha)} \tag{16}$$

where the incomplete gamma function $\Gamma(\alpha, b/x)$ is defined as

$$\Gamma\left(\alpha, \frac{b}{x}\right) = \int_0^{b/x} e^{-y} \, y^{\alpha-1} \, dy \tag{17}$$

The above analysis assumes that particles of all sizes are uniformly responsive to turbulent diffusion. More realistically, the time constant of particle response to vertical velocity fluctions increases with increasing aerodynamic particle size.

In studies of the vertical flux of particulates over an agricultural field undergoing wind erosion, Gillette et al.[6] have characterized this phenomena in terms of the ratio V_s/u_* . If settling velocity is small compared to the root mean square velocity fluctuation, i.e., $V_s/u_* < 0.1$, the particulate is dispersed as a gas. On the other hand for $V_s/u_* \sim 1$, settling effects begin to predominate. Clearly, in the latter case, the settling distribution is more strongly focused around the distance xp .

Case 3: Polydisperse particles, distributed injection height, turbulent atmosphere.

This case is treated by separately analyzing the dispersion of particles within narrow size ranges and injection height ranges and by superimposing the results. The analytical techniques to be used are those described above.

REFERENCES TO
APPENDIX B

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16. ABSTRACT

This report outlines the methodology that was used in developing an hourly fugitive dust emissions inventory for the Metropolitan St. Louis Air Quality Control Region as part of the Regional Air Pollution Study (RAPS). The inventory encompassed the following source categories: (a) unpaved roads, (b) agricultural land tilling, (c) wind erosion of agricultural land, (d) construction sites, (e) aggregate storage piles, and (f) unpaved airstrips.

Results presented in this report include temporal apportioning factors, county totals of annual source extent and annual emissions for each source category.

17. KEY WORDS AND DOCUMENT ANALYSIS

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