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VEHICLE BEHAVIOR IN AND AROUND COMPLEX SOURCES AND RELATED COMPLEX SOURCE CHARACTERISTICS VOLUME VI - MAJOR HIGHWAYS

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

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by

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SECTION I

CONCLUSIONS

1. Since highways are distinctly different from other complex sources, it has been necessary to develop a methodology for highways which is different from the general methodology developed in the first report on shopping centers. This methodology relates the parameters descriptive of highway traffic to highway parameters. These relationships are subsequently to be used by the sponsor to develop guidance for relating the highway's characteristics to air quality.

2. The methodology has been successfully applied to highways with quantitative results presented in this task report.

3. It is now appropriate to proceed to the next and last type of complex source (recreational areas), and apply the general methodology appropriately.

SECTION II
RECOMMENDATIONS

It is recommended that, as planned, the project officer employ this methodology to develop guidance for relating the traffic characteristics of highways to typical and peak air pollution concentrations.

SECTION III

INTRODUCTION

INTRODUCTION

OBJECTIVE AND SCOPE

The ability to estimate traffic characteristics for proposed developments and the resulting effects on air quality is an important prerequisite for promulgating State Implementation Plans which adequately address themselves to the maintenance of NAAQS. Prior to estimating the impact of a development (complex source) on air quality, it is necessary that traffic characteristics associated with the source be identified and related to parameters of the development which can be readily identified by the developer a priori. The purpose of this study is to identify traffic characteristics associated with specified varieties of complex sources and to relate these characteristics to readily identifiable parameters of the complexes. The end product of this task will then be used to develop an Air Pollution Technical Document which will provide guidance to enable control agencies to relate readily identifiable characteristics of complex sources to air quality.

The work is being performed in seven sub-tasks. Each sub-task is devoted to examining vehicle behavior and its relationship to readily obtainable parameters associated with a different variety of complex source. The seven categories of complex sources are:

1. Shopping centers (Report EF-263)
2. Sports complexes (stadiums) (Report EF-265)
3. Amusement parks (Report EF-268)
4. Major highways (Report EF-267 - the present report)
5. Recreational areas (e.g., State and National Parks)
6. Parking lots (e.g., Municipal) (Report EF-266)
7. Airports (Report EF-264)

This, the sixth task report, describes a special methodology developed for highways (different from that for the other six complex sources), and the analysis and results of its application.

APPROACH

Due to internal constraints, the sponsor has been forced to impose a tight schedule on this project, permitting only two to three weeks for the analysis and reporting of each sub-task. Accordingly, the employment of readily available traffic design information for each type of complex has been suggested as the general approach.

The approach was designed to permit the development of answers to the following questions posed by the sponsor, where the questions were felt relevant, using available traffic design and behavior data, and available data on parameters of the complex:

1. How much area is allotted to or occupied by a single motor vehicle?

2. How much or what percentage of the land occupied by the complex source (and the source's parking facilities) can potentially be occupied by vehicles? What is the usual percentage?

3. What portion of the vehicles within the complex are likely to be running at any given time during a 1-hour period? During an 8-hour period? We are interested in both peak and typical circumstance here.

4. What is the typical and worst case (slowest) vehicle speed over 1-hour and 8-hour periods?

5. How are moving and parked vehicles distributed within the complex property?

6. What are the design parameters for each type of complex which are likely to be known by the prospective developer beforehand?

7. Which ones of the design parameters in number 6 can be most successfully related to traffic and emissions generated by the complex? What is the best estimate for relationships between readily obtainable parameters and emissions?

8. What are the relationships of parking "lot" design to parking densities and vehicle circulation? What represents a typical design and/or a design which has highest parking densities, lowest vehicle speeds, longest vehicle operating times?

9. What meteorological conditions (i.e., atmospheric dilutive capacity) are likely to occur during periods of peak use? What use level is likely to occur during periods of worst meteorology (i.e., atmospheric dilutive capacity)

The technical approach developed and implemented in this report centers about the highway traffic parameters of volume and speed (or, equivalently, traffic density and speed, since density is derivable from speed and volume). It is these parameters which permit estimation of automobile emissions from highways and therefore allow a determination of the future highway's impact on NAAQS.

The effort was planned to focus on major highways; further discussions with the government project officer indicated that it would be best to concentrate on arterial roads or greater. As will be seen, it was subsequently determined that a quantitative treatment could be developed, within the time available, for highways with full control of access; the treatment is also considered applicable, with proper exercise of judgment, to some cases of partial control of access. The cases treated are those of "uninterrupted (or continuous) flow", where speed-volume-density relationships have been reasonably well quantified. Interrupted flow, whose most common example is the city street with signalized intersections, is considered difficult to describe in terms of speed-flow relationships, even by specialists in the field,[2] and is not treated here.

For the case of non-congested flow, traffic volume* (vehicles per hour) is determined by the demands (vehicles per hour) at the various entrances to and exits from the highway. Average highway speed is found to vary in an inverse fashion with the ratio of volume of traffic to capacity. Capacity is defined to be the maximum volume to be accommodated by the highway under ideal circumstances and is determined primarily by highway design characteristics. Hence both volume and speed are highly dependent on highway design characteristics. The interrelationships of volume, speed and density which have been measured on many occasions, and have undergone significant analytical interpretation,[2] form the basis for our methodology for highways.

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* While the terms volume and flow are used to denote different parameters in traffic and highway engineering (volume being used to represent periods of an hour or more, and flow periods of less than an hour), we have found it convenient to use them interchangeable in this study.

An additional point which renders this study different from those for the other six complex sources: each of the others required examination of the emission characteristics of automobiles only to the extent necessary to insure that the traffic behavior methodology could be used by the sponsor in conjunction with such emission data. It has been necessary, in this study of highways, to go more deeply into automotive emission data because of the different nature of this problem (especially the variety of speeds encountered).

The sponsor has expressed interest in information on the expected frequency of occurrence of new highways of various sizes; in our contacts with staff of the Federal Highway Administration[1] we have been told that their data are presently being processed to develop this type of information; the sponsor may contact them in the near future to obtain it.

As a final note, this study must be recognized as a condensed analysis of a massive amount of information in a field significant in its own right - that of traffic and highway engineering. As a result, shortcuts have been taken to focus on only those facets of the problem considered most important, and the elements considered most relevant to the problem at hand; there is thus the likelihood that points considered significant in traffic and highway engineering problems per se may have been minimized as a result. The analysis should be read with this point in mind.

SECTION IV

HIGHWAY CHARACTERISTICS AND PARAMETERS

The principal item which characterizes a highway is its spatial design. A map showing the proposed layout of the highway will show such features as right-of-way, lateral clearance, number of lanes, lane widths, highway curvature, location of traffic blockages such as signals or toll booths, and manner of access. Typical values for some of these parameters are shown in Table 1. Some of these variables characterize the level of service of the highway, which represents the capacity of the highway to tolerate specified traffic volumes at specified maximum safe operating speeds. Other such variables, such as the right-of-way, are not reflective of the level of service but are important in other ways in air quality impact analysis. Right-of-way defines the area surrounding the highway which is excluded from use except for the highway. Hence right-of-way can be used to determine where receptors might be stationed to measure pollutant concentrations, or simply distances at which air quality might be of concern.

Table 1. TYPICAL VALUES FOR SOME HIGHWAY DESIGN PARAMETERS

No. of lanes	2 to 8
Lane Width	9 to 12 feet
Lateral Clearance	0 to six feet
Right-of-Way	50 to 400 feet
Speed Limit	40 to 80 MPH

The spatial distribution of the highway in conjunction with land use maps and trip generation studies should be used to determine anticipated demands on the highway at particular segments, depending on the amount of residential, commercial and industrial development present or anticipated.

The effect of two of these parameters - lane width and lateral clearance - is seen in Tables 2 and 3 in terms of reduced highway capacity.

Table 2. EFFECT OF LANE WIDTH ON CAPACITY FOR UNINTERRUPTED FLOW CONDITIONS[2]

Lane Width (Ft)	Capacity (% of 12-ft Lane Cap.)	
	2-Lane Highways	Multilane Highways
12	100	100
11	88	97
10	81	91
9	76	81

Table 3. EFFECTIVE ROADWAY WIDTH DUE TO RESTRICTED LATERAL CLEARANCES UNDER UNINTERRUPTED FLOW CONDITIONS[2]

Clearance From Pavement Edge to Obstruction, Both Sides (Ft)	Effective Width of Two 12-ft Lanes (Ft)	Capacity of Two 12-ft Lanes (% of Ideal)
6	24	100
4	22	92
2	20	83
0	17	72

Highways are also characterized by curvature - both horizontal and vertical - and by grade, in addition to other alignment parameters. However the net significance of such parameters, at least from our standpoint, is to determine the design speed of the highway. Table 4 illustrates how design speeds relate to alignment parameters.

Table 4. ALIGNMENT STANDARDS IN RELATION TO DESIGN SPEED[2]

Design Speed, in MPH	Minimum Radius of Horizontal Curves in Feet	Maximum % of Grade	Min. Forward Sight Distance, in Feet	Min Length of Vertical Curve for Each 1% Change of Grade, in Feet
20	100	12	150	10
30	250	10	200	20
40	450	8	275	35
50	750	7	350	70
60	1100	5	475	150
70	1600	4	600	200

The design parameters of a highway are useful in our analysis only to the extent that they determine the capacity and design speed of the highway. Hence if either of these measures is available directly from the highway engineer, then it can be used directly. Generally design speed will be available, since it will normally be the same as the highway's speed limit. Section VII, Results, gives the procedure for determining highway capacity from design characteristics.

SECTION V

TRAFFIC PARAMETERS

Traffic flowing through a non-congested highway segment can be characterized sufficiently for our purposes by its volume and average speed. Volume is the number of vehicles passing over a given road segment during a given time, normally 1-hour or more. A complete set of definitions is given in Section IX. Table 5 gives some typical traffic volumes for urban freeways.

SPEED

Average speed is the arithmetic mean of speeds of vehicles passing over a segment of highway during a given time-frame. If vehicle emissions were independent of speed - that is, could be expressed as a constant number of grams of emission per mile per vehicle, we would not be concerned with vehicle speed.

The dependence of vehicle emissions on speed is seen in Figures 1, 2, and 3. Note that for each pollutant there are four lines: one corresponds to the familiar average trip speed and one to steady state speed. The other two reflect data from reference 7 on emissions during periods of acceleration and deceleration of speed in 15 mph increments (0-15, 15-30, 30-45, 45-60, 60-45, 45-30, 30-15, and 15-0). The points are plotted at the average speed of each increment. Average trip speed is defined as the total distance covered from start (i.e., starting of engine) to stop (i.e., turning off of engine) divided by the time required to make this trip. Typically average trip speed reflects periods of idling, such as encountered at signalized intersections. Steady state speed is the speed of a vehicle during periods of approximately constant

Table 5. VARIATIONS IN TRAFFIC FLOW OF URBAN FREEWAYS[8]

Location of Count Station	No. of Lanes	Route Number	Direc. of Travel	AADT[a]	Peak Day	Volume in Selected Highest Hours As a Percentage of Annual Average 24-Hour Volume (AADT)							
						Max.	10th	20th	30th	40th	50th	100th	200th
New England													
Maine													
0.7 mi W of US 1A, Bangor	4	I-395	EB			19.6	13.3	12.9	12.1	11.7	11.4	-	-
			WB			21.4	11.5	10.1	9.8	9.6	9.5	-	-
			Both	7,120	10,534								
1.7 mi from Augusta	4	I-95	NB			32.4	22.5	20.8	18.9	17.3	16.5	-	-
			SB			32.1	23.2	20.5	19.2	17.7	17.3	-	-
			Both	2,167	6,013[c]								
Massachusetts													
2.3 mi W of Mattapoisett	4	US 6	Both	15,988	25,509[c]	16.8	11.4	11.0	10.9	10.7	10.6	10.2	9.7
New Hampshire													
0.5 mi from Concord	4	I-93	Both	11,804	20,737	20.4	15.9	15.3	14.8	14.3	13.9	-	-
0.6 mi from Concord	4	I-93	Both	11,554	21,167[c]	21.4	16.6	15.6	14.9	14.5	14.1	12.5	-
0.5 mi S. Jct. US 3	4	I-93	Both	4,035	15,925[c]	24.7	20.2	19.1	18.2	17.4	16.5	14.2	-
2.0 mi from Manchester	4	I-193	Both	6,352	9,622	15.3	14.3	13.7	13.4	13.1	12.8	12.1	11.2
Rhode Island													
Pawtucket River Bridge	6	I-95	EB			11.2	8.8	-	-	-	-	-	-
			WB			11.1	10.3	9.8	8.6	8.2	-	-	-
			Both	19,216	24,293	10.1	9.7	9.2	8.7	8.3	8.2	-	-
Middle Atlantic													
New York													
Long Island Expwy. at 82nd Street	6	I-495	EB			9.4	8.4	8.2	8.1	8.0	7.9	7.6	7.1
			WB			9.4	8.8	8.6	8.3	8.2	8.1	7.6	7.1
			Both	127,910	157,940								
15 mi from N.Y. City, Nassau Co.	6	NYS 495	Both	119,300[b]	-	8.4	8.3	8.3	8.3	8.2	8.2	8.1	7.9
Cross Island Pkwy. at 114th Ave., New York City	6		NB			11.9	10.6	10.3	10.1	10.0	10.0	9.6	8.8
			SB			14.4	13.4	12.8	12.6	12.1	11.8	10.8	9.9
			Both	66,610	92,000[c]								
New England Thrwy., N.Y. City	6		NB			12.4	10.7	10.0	9.6	9.5	9.3	9.0	8.4
			SB			12.6	11.4	10.9	10.8	10.6	10.5	10.0	9.2
			Both	47,420	65,970[c]								

a. Average Annual Daily Total for calendar year 1962 except where noted otherwise.

b. For calendar year 1961.

c. Peak day occurred on a Saturday or Sunday.

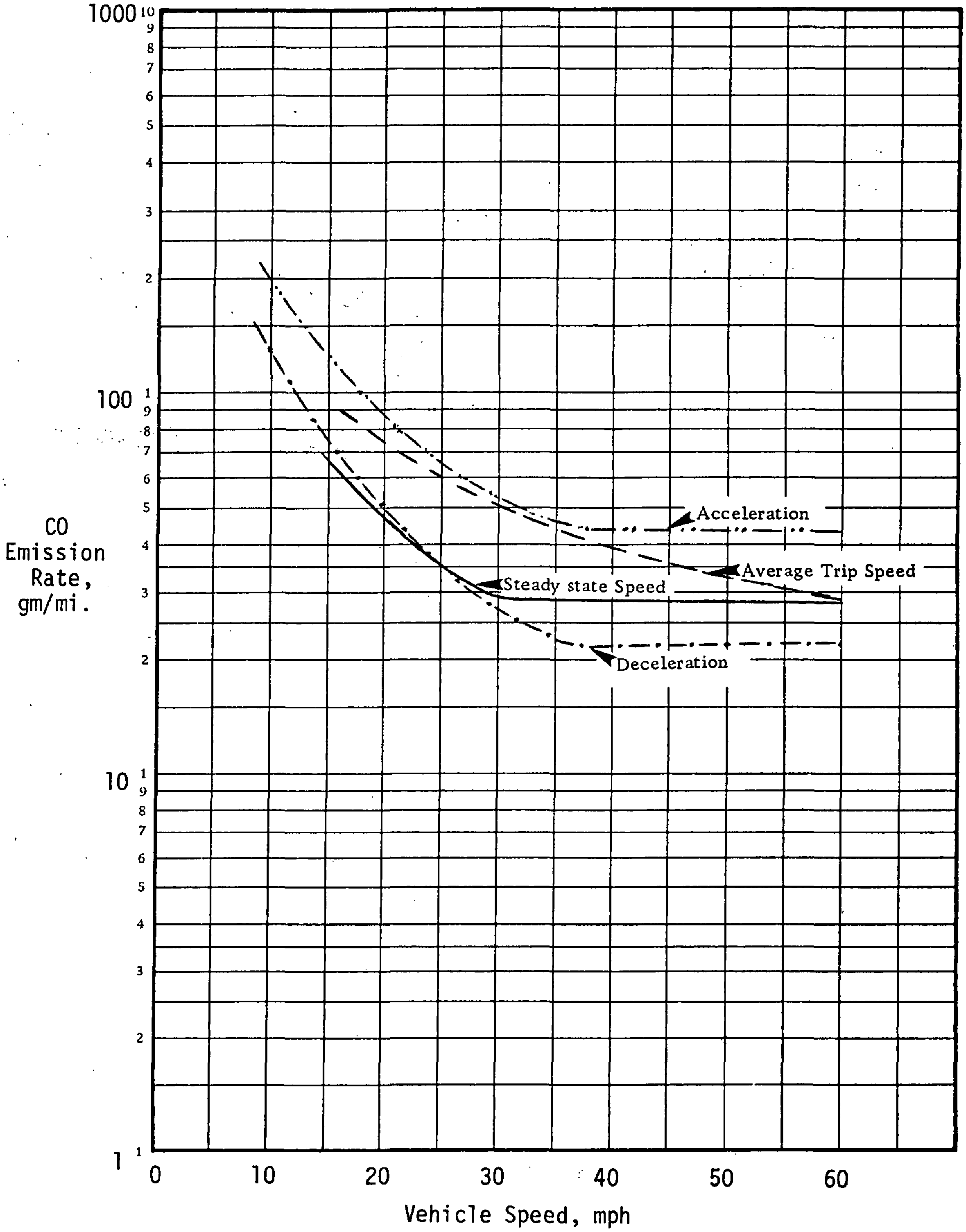


Figure 1. Various representations of CO emission rates as functions of vehicle speed.

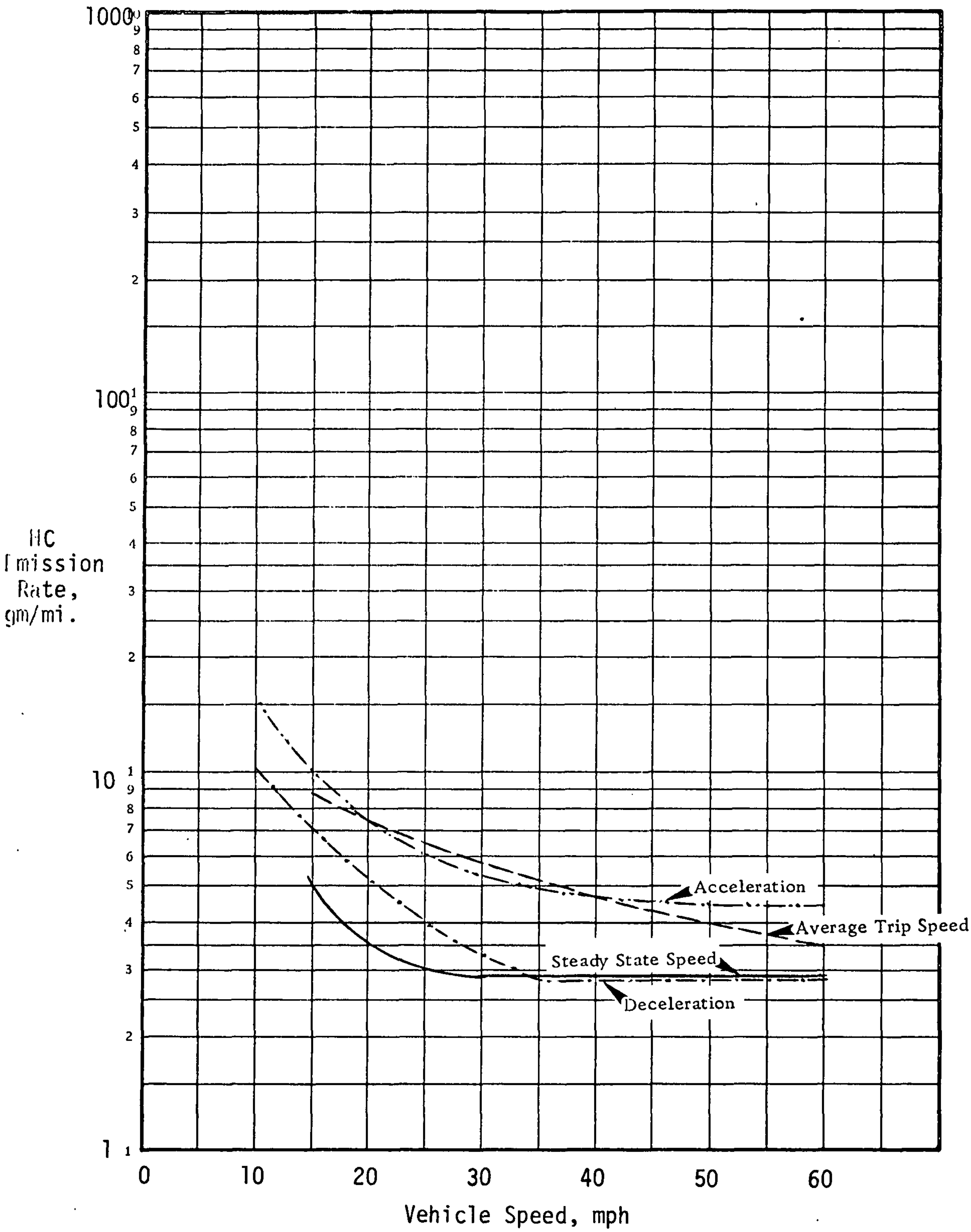


Figure 2. Various representations of HC emission rates as functions of vehicle speed.

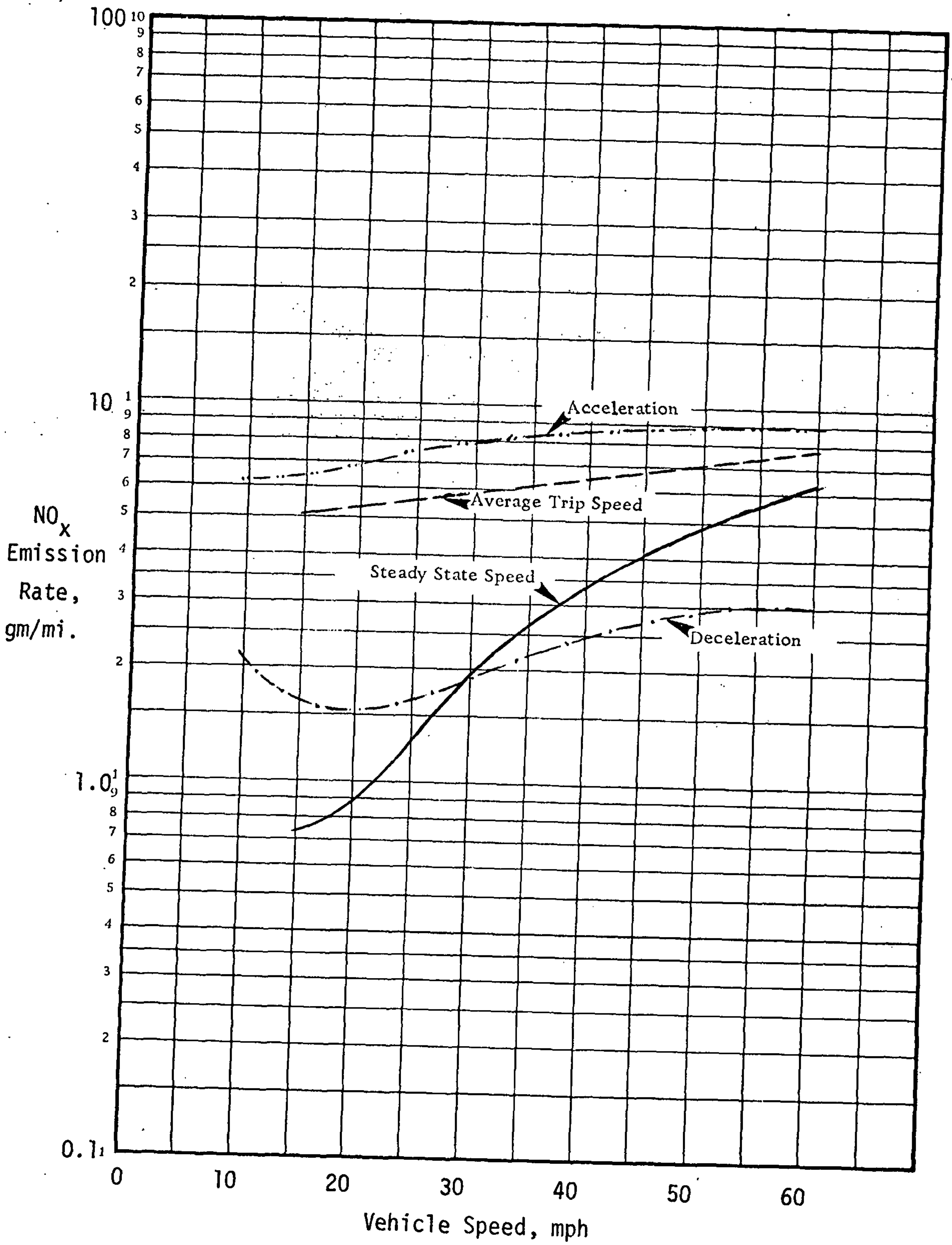


Figure 3. Various representations of NO_x emission rates as functions of vehicle speed.

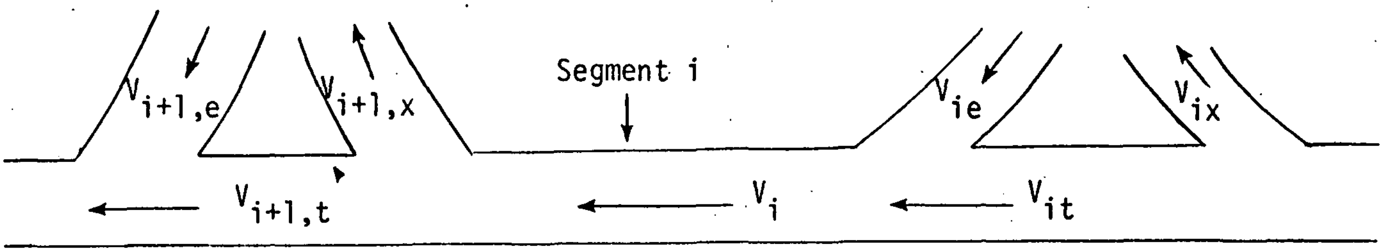
speed. While average trip speed is more appropriate for in-town driving conditions, it is apparent that steady-state speeds are more applicable to limited access highways, where the design features demand that vehicles enter and exit at high rates of speed, and only stop due to congestion or emergency situations. The average trip speed curves are included for comparison purposes.

It is also apparent that normally speed will be approximately constant between interchanges, since the cross-sectional design of a highway is generally constant between interchanges. However, it is to be expected that speed will vary from one segment between interchanges to another, since cross-sectional design and speed limits vary in this fashion. Therefore, it is necessary to evaluate speeds for each segment between interchanges where highway design is known to change.

When capacity is exceeded, and traffic begins to slow down as density and congestion increase, it is probable that there will be significant amounts of acceleration and deceleration about the nominal speed for the case in point. Since Figures 1-3 show significant differences of these curves from the steady-state ones (especially in the case of acceleration), it is suggested that, where the traffic density represents a demand which significantly exceeds capacity, the mean of the two curves (acceleration and deceleration) may be used to more properly reflect the emission vs. speed relationship.

TRAFFIC DEMAND

If a highway's design is adequate to meet traffic demands, then the volume of traffic on a given highway segment is determined by these demands. Consider the diagram below, which shows the relationship between traffic demands and actual traffic volume for one direction of a limited access highway.



V_{ie} and V_{it} represent the demands placed on the segment i, with $V_i = V_{ie}+V_{it}$ representing the actual volume of traffic which the segment experiences. The traffic demand on the next segment (i+1) down stream is $V_{i+1} = V_{i+1,e}+V_{i+1,t}$ where $V_{i+1,t} = V_i-V_{i+1,x}$. Hence a knowledge of traffic demands at the various entrances to and exits from a highway is necessary to determine expected traffic volumes.

Traffic demands are subject to two basically different types of time variations, one being periodic, the other non-periodic. Principal periodic variations include diurnal, weekly and seasonal variations. Non-periodic variations include normal growth patterns, generated traffic, and development traffic, in addition to the implementation of public transit programs.

Periodic Variations in Traffic Demand

Typical diurnal variations are shown in Figure 4 for highways in urban and rural environments. Both curves show an expected increase in traffic volume during the daylight hours, while urban traffic shows morning and evening peaks corresponding to commuting traffic. Since these peaks are related to the work cycle, it is to be expected that diurnal variations during the weekend are substantially different. The contrast is shown in Figure 5 which gives diurnal variation for weekdays on one curve and for Sunday on the other. Note that the morning peak for weekdays is entirely absent for Sundays, and the evening peak is shifted to later hours for Sundays, probably reflecting returning weekend traffic. Day of week variations are also significant and vary substantially for urban and rural traffic, as can be seen in Figure 6. While there is likely to be consistency in these variations from one urban region to another, rural variations are probably less constant. It is apparent from these figures that the worst traffic volumes will exist on Friday evenings, a time when return-from-work and weekend traffic overlap.

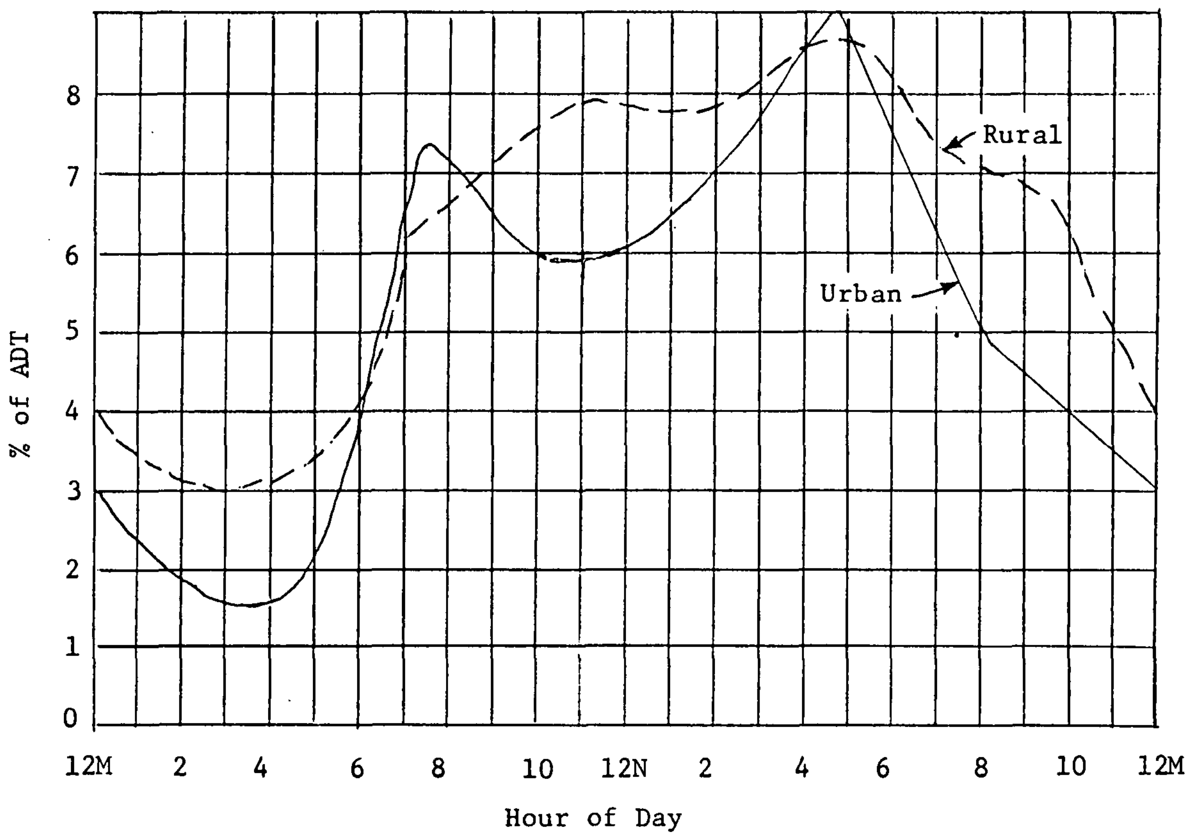


Figure 4. TYPICAL CALIFORNIA MOTOR VEHICLE TRAVEL DISTRIBUTION BY ANNUAL AVERAGE HOUR OF THE DAY[2]

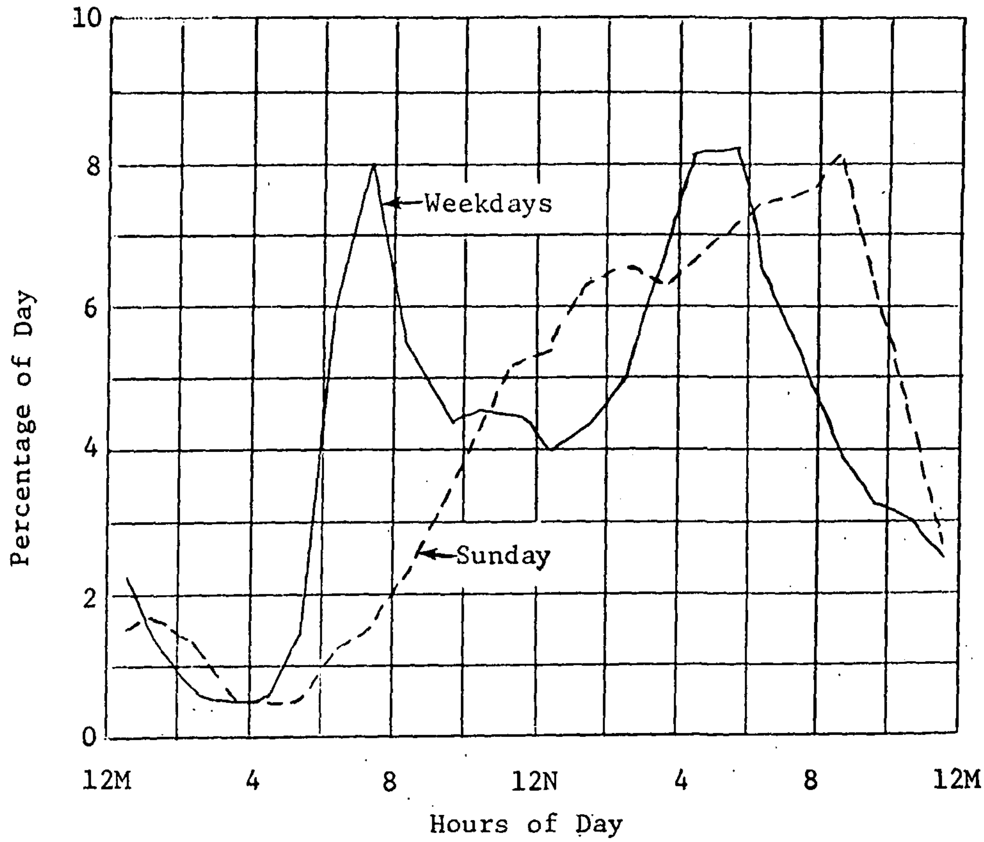


Figure 5. WEEKDAY VS SUNDAY TRAFFIC[2]

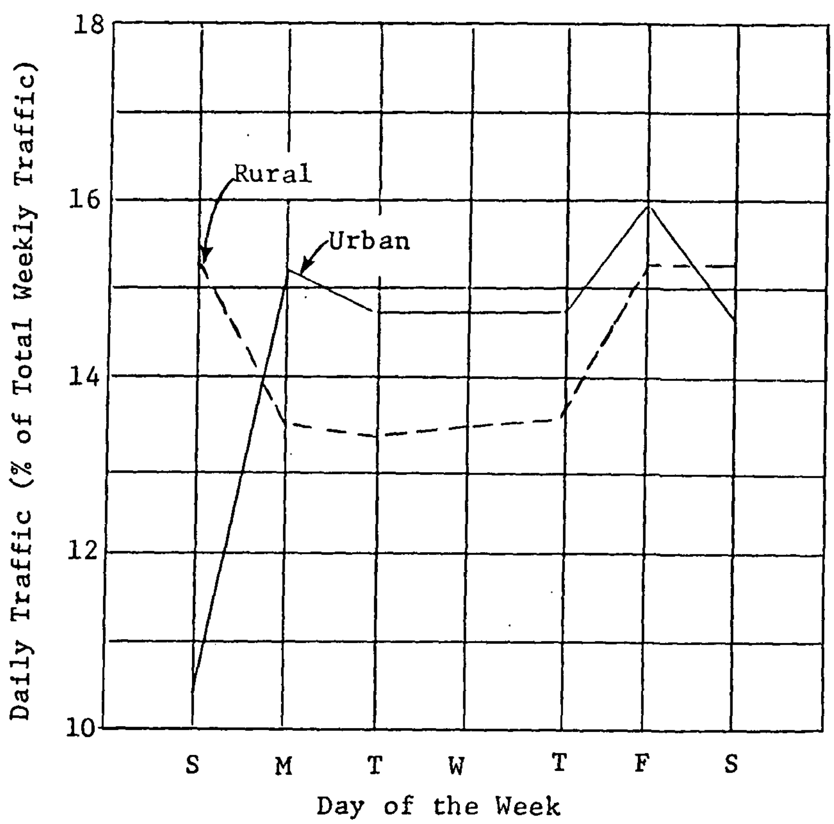


Figure 6. DAILY CHANGES IN TRAFFIC[2]

Seasonal variations are shown in Figure 7, for rural and urban Washington state and for Tucson. Of particular interest here is the dramatic difference in these seasonal variations. While both rural and urban Washington state reach peaks during the summer months, Tucson experiences a low in traffic volume during these months. These differences are due largely to climatological differences between Washington and Tucson. Due to the widely varying climatological conditions from one part of the country to another, it is apparent that these variations in traffic demand for a particular area must be based on volume data for the region in which that area is located.

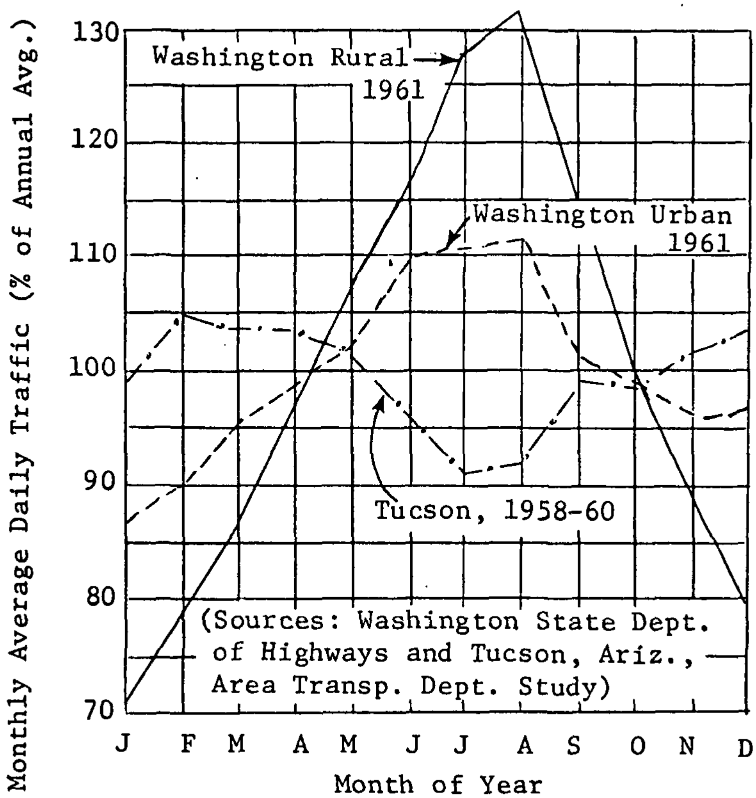


Figure 7. EXAMPLES OF MONTHLY TRAFFIC VOLUME VARIATIONS[2]

Typically traffic demands are considered in terms of average annual daily traffic and peak hour traffic. Table 5 gives some observed values for these two volume measures for several highways. Normally traffic design is based on the thirtieth highest hourly traffic volume anticipated.[2] Figure 8 shows the relationship between peak hour traffic and AADT.

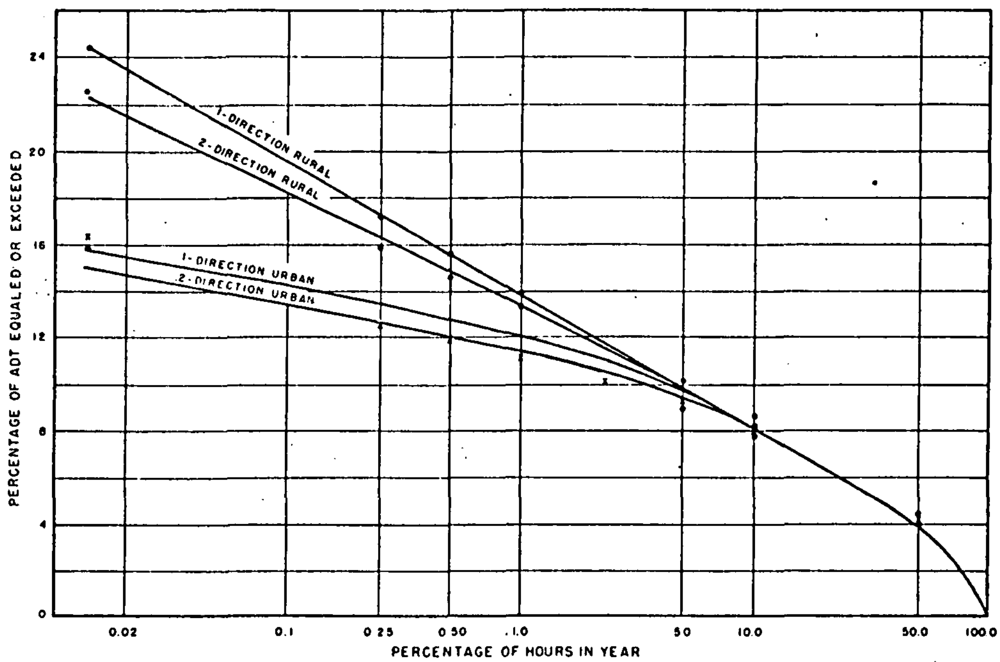


Figure 8. PERCENTAGE OF ADT RECORDED DURING ALL HOURS OF THE YEAR ON 113 SELECTED URBAN AND RURAL ROADS, 1959-1960.[1]

This figure shows that, for one direction of travel, the highest peak hour for urban highways is approximately 13% of the AADT. From the discussion of the periodic variation in demand, it is seen that this peak demand will usually occur during the late afternoon hours of a Friday, the time of year depending on climate. Warmer climates will tend to have a winter peak, cooler climates a summer peak, corresponding to increased recreational traffic during these times.

Non-Periodic Variations in Traffic Demand

Traffic growth factors are discussed in some detail in reference 3. This publication outlines the three types of traffic growth which have been mentioned above. Normal traffic growth is that growth which is due to the general increase in the number and use of motor vehicles. Such traffic growth is clearly indicated by Figure 9, which shows the number of vehicle miles traveled from 1920 to the early 1960's, with expected growth trends indicated beyond. It is a relatively straightforward matter to apply this normal growth factor to existing traffic demands to arrive at an expected traffic demand in ten years subsequent to completion of a highway facility. This normal growth can be calculated based on 4.6% increase in travel miles per year.[2]

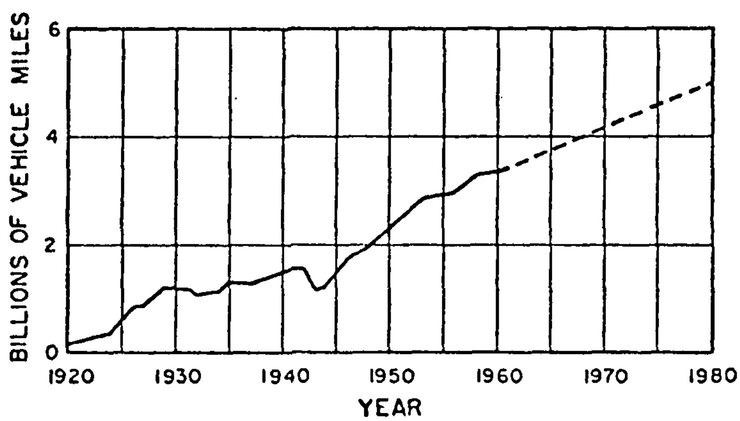


Figure 9. TOTAL MOTOR VEHICLE TRAVEL AND FORECAST FOR SELECTED STATES[3]

Generated and development traffic will be less easily evaluated, since these traffic demands depend principally on the region through which the highway passes. Generated traffic is defined as "motor vehicle trips (other than public transit) which normally would not have been made if the new facility had not been provided."[3] An example of a generated trip is one which was previously made to a different destination, but for which the change is attributable to the attractiveness of the improved highway.

Increases due to generated traffic demand are usually experienced within a year or two after the opening of a new highway facility, since general public awareness of improved access due to the new facility is achieved during that time. Increases due to generated traffic are widely varying and will have to be based on judgment. For rural highways, generated traffic is likely to run greater than 5% (of existing traffic volume), but less than 25%.[3]

Development traffic is defined as that traffic "due to improvement on adjacent land over and above the development which would have taken place had not the new or improved highway been constructed."[3] This increase in traffic is likely to continue for years subsequent to completion of a new highway. The magnitude of increase due to development traffic is dependent largely on the availability of land for development adjacent to the new highway. Highways constructed through a highly developed area will experience little growth in volume due to development traffic, although they may experience the shorter term generated growth, as described above. Highways which are constructed through a completely restricted region, such as a federal reserve, or park, should experience no development growth. On the other hand, land is typically available for development along a new highway, and the amount of this land which is readily accessible and its zoning, along with other factors which make development attractive, may be studied to estimate the number and types of developments which would be expected. From this information the number of trips expected to be generated may be evaluated for each interchange. In terms of our previous notation, V_{ie} and V_{ix}, the demand volumes at a particular interchange i may be predicted, or at least the proportions of these demands which are due to development.

Future plans for public transit programs (other than those which already exist) must be taken into account in the evaluation of traffic parameters of proposed highways. Vehicle demand (V_{ix} and V_{ie}) is reduced by effective public transit programs.

Thus, the importance of trip generation analyses, both for present and future expected demands, cannot be overemphasized.

Percentage Use by Trucks

Since trucks are considerably less maneuverable than passenger cars, a significant percentage of trucks on a highway will adversely effect capacity. For example, studies have shown that, even in level terrain, 20% usage level by trucks will reduce highway capacity by 17%; in mountainous terrain, the reduction is 58%.[2] Therefore the evaluation of highway capacity (as specified in Results) has taken into account percentage use by trucks.

SECTION VI

ANALYSIS

There are two analytic approaches to consideration of the impact of new or improved highways which must be considered. The first of these is the meso- or macro- approach.* This approach assumes that the air quality impact of highways can be measured by the number of vehicle miles traveled during a given time period, and the average speed of vehicles traveling during the time period. The impact of a new highway in a region will be measured by the number of additional vehicle miles, and the effect that the new facility has on average speed.

The second and intuitively simpler approach is the micro approach. This approach considers the highway as a line source of emissions (or a series of line sources), the intensity of which fluctuates with time and location. A diffusion model is used to predict pollutant intensities due to the highway, and these intensities are compared to background concentrations, which may also be based on model predictions or on direct measurements. The micro approach has the advantage that local variations in pollutant concentrations can be ascertained and the effect of weather conditions can more accurately be taken into account.

Fortunately the same parameters which enter into the macro analysis can be readily applied to the micro analysis. While the key variables in macro analysis are vehicle miles traveled and average speed, the key variables in micro analysis are vehicle density and average speed. Let us consider a typical highway segment of length d with a traffic volume

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* DOT customarily uses the term "meso" and EPA "macro" for this concept.

of V vehicles per hour traveling at a speed of s mph. The vehicle miles traveled during a time period T (1 or 8 hours) is

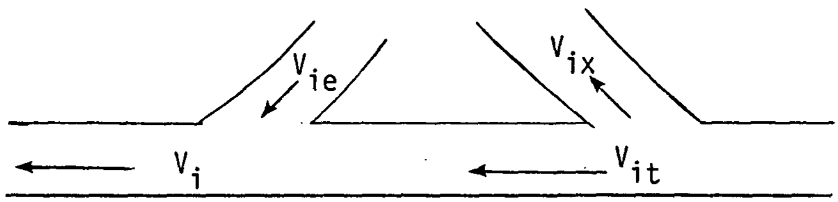
$$VMT = T \times V \times d.$$

On the other hand, vehicle density is simply

$$D = \frac{V}{s}.$$

For a given segment of highway the analysis variables for macro analysis are readily transformed to those of micro analysis.

Let us consider a segment of highway in one direction with n exchanges, one of which is shown below.



At this interchange denoted by i, the exit volume is denoted by V_{ix}, the entering volume by V_{ie}, and the through volume by V_{it}. V_{ie} and V_{ix} are demands on the highway (as discussed in the previous section) which must be known either in terms of a ratio $[V_{ix}/(V_{ix}+V_{it})]$ or absolute numbers. V_i is the sum of previous interchange differences $(V_{ie}-V_{ix})$ and the initial volume V_o (that is, the entering volume demand at the upstream end of the segment being considered). That is,

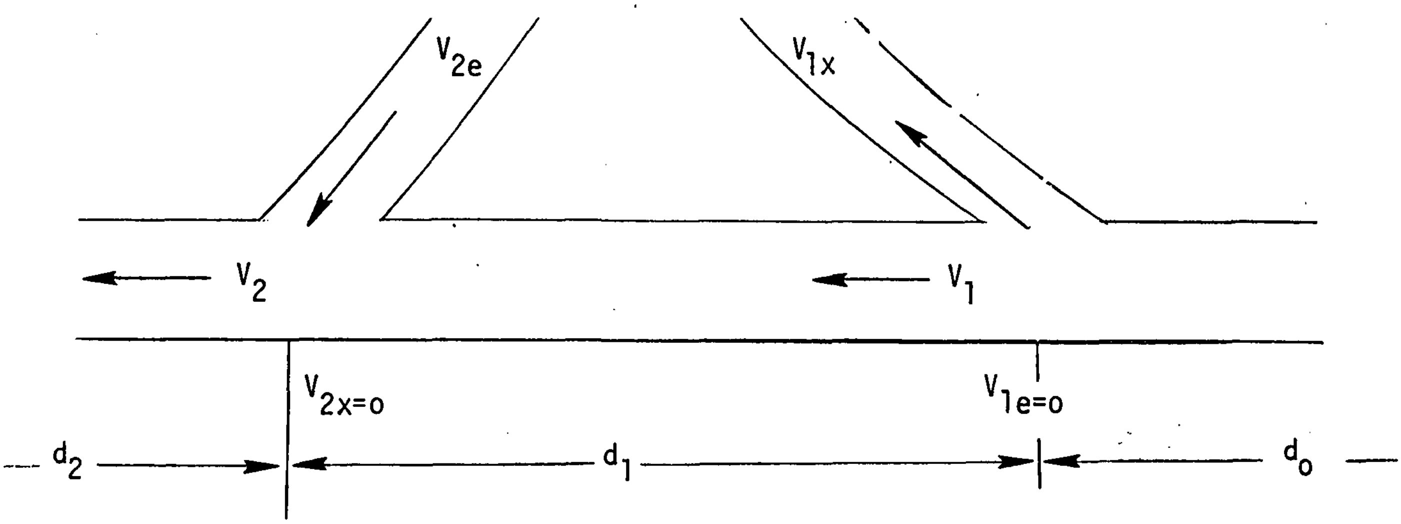
$$V_i = V_o + \sum_{J=1}^{i} (V_{je}-V_{jx}).$$

If we denote the distance in miles between interchange i and i+1 as d_i, the total vehicle miles travelled along the highway being considered is

$$VMT = \sum_{i=o}^{n} d_i x V_i$$

where d_o is the distance from the upstream end of the segment to the first interchange, and d_n is the distance from the last or nth interchange to the downstream end of the segment.

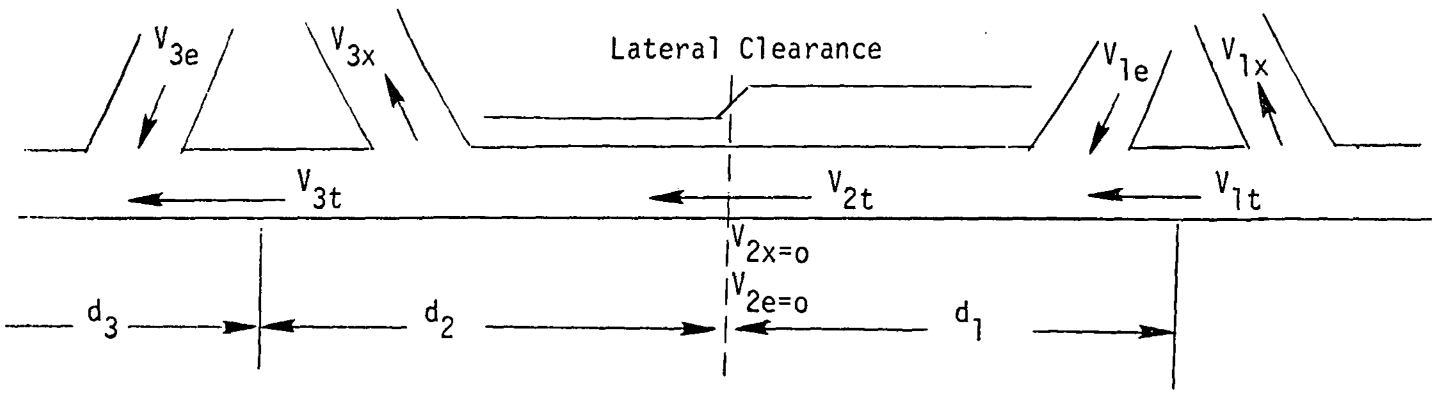
The above notation can be adapted to the situation where an interchange is "one-sided"; that is, an exit or entrance exists, but not both. For these the appropriate V_{ix} or V_{ie} may simply be set equal to zero. This approach could also be used for the situation where the distance between an exit and an entrance is extraordinarily great, as



This situation has been represented by treating the interchange as two separate interchanges labeled 1 and 2 and by setting V_{1e} and V_{2x} both equal to zero.

As indicated previously speed has been shown to be a critical variable in the evaluation of impact of highways on air quality. For carbon monoxide and hydrocarbons the rate of emission in grams per mile decreases as the steady-state speed of the vehicle increases, to about 30 mph, and is relatively unchanging with further increases. For NO_x, emissions increase with increasing speed above 15 mph.

Occasionally situations arise where the speed is not constant between interchanges. As an example, the cross-sectional design of the highway might change, as in the case of changing lateral clearance sometimes necessitated in urban areas. As another example a change in the terrain might alter the vertical and horizontal alinement of the highway, hence altering the operating speed. These situations may be treated consistently with the notation above by defining the segment between interchanges into subsegments, each having relatively constant speed. Consider the following example:



A stretch of highway which would normally be treated as one segment has been divided into two, to reflect differing operating speeds caused by a change in lateral clearance. The point at which the speed changes is defined here as a "pseudo" interchange, with both V_{2x} and V_{2e} set to zero. Such a refined segment breakdown will not be necessary unless the speed difference is significant.

For the macro approach, it is possible to take into account speed variations by summarizing results in the following fashion: X VMT at 40 mph, Y at 45 mph, etc. It may be more convenient to use the concept of a speed correction factor, as suggested in reference 3. However, the speed correction factor used there is for average trip speed, while we wish to use a correction factor based on steady state speeds (see Figures 1 to 3). If, say, 30 mph is selected as the standard speed, the speed correction factor for NO_x at 60 mph is approximately 3.5. If a given segment of highway has a volume of 2,000 vehicles per hour and is 10 miles in length, then it experiences 20,000 VMT during that hour. However, if the steady-state speed during that hour is 60 mph, then its equivalent vehicle miles traveled (EVMT) will be 3.5 x 20,000, or 70,000 EVMT. The advantage of this approach in macro analysis is that the EVMT for all segments of a highway being considered can be summed, even though operating speed may vary from segment to segment. Hence EVMT may be stated as follows:

$$EVMT = \sum_{i=o}^{n} c(s_i) \times d_i \times V_i$$

Where $c(s_i)$ is the correction factor corresponding to speed s_i in segment i for a particular pollutant. Conveniently, the CO and HC factors are 1.0 above 30 mph.

Studies have shown very typical patterns in the relationship between speed and volume, which can perhaps be most clearly understood in terms of traffic density. As traffic density increases flow increases in a linear fashion until density becomes such as to cause a reduction in speed. This phenomenon can be observed in Figure 10. Curves for highways in Detroit and Los Angeles show that speed is not affected for low volumes. As density increases volume continues to increase, despite a lowering of average speed, up to a point of critical density, beyond which flow and speed both decrease, while density continues to increase. This relationship is illustrated by Figure 11. It is at this point of critical density that volume is maximized--that is, the highway's capacity is reached. Traffic flow beyond critical densities is widely varying, ranging from near capacity down to zero.

From the above it is apparent that capacity is a key variable in analyzing the flow along the highway. Traffic flow demands which are well below capacity will not cause a forced flow (or stop-and-go) situation, although speed may be diminished for higher flows. The highway's capacity may be derived according to well defined guidelines established in the Highway Capacity Manual,[2] utilizing the design characteristics of the highway. Such design characteristics include number and width of lanes, lateral clearance, and other variables outlined in the previous section. These guidelines for establishing highway capacity are outlined in the Results section.

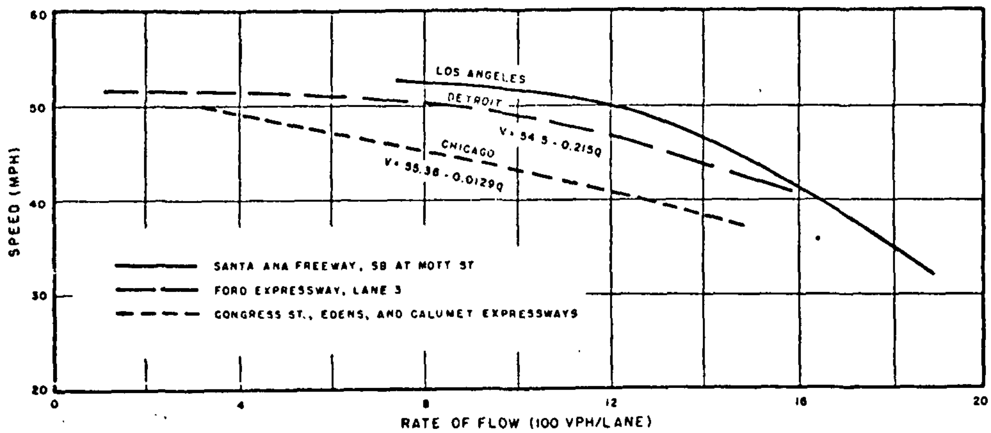


Figure 10. SPEED-FLOW RELATIONSHIPS FOR THREE DIFFERENT HIGHWAYS[9,10,11]

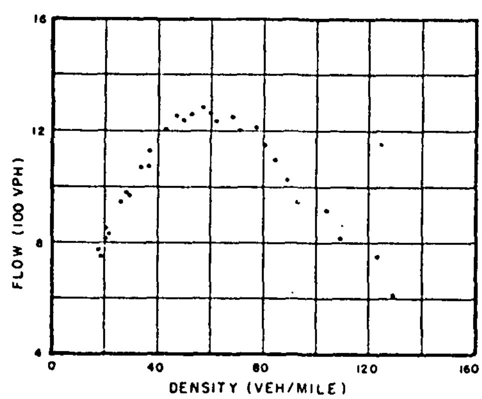


Figure 11. EXAMPLE OF FLOW-DENSITY RELATIONSHIP IN LIMITED-ACCESS TRAFFIC FLOW (HOLLAND TUNNEL, NEW YORK)[12]

If the capacity corresponding to a segment i is determined to be C_i, then the volume to capacity ratio is V_i/C_i. If this ratio is less than 1, and the critical density has not been reached (the solid lines in Figure 12), then Figure 12 illustrates how the operating speed S_i corresponds to a particular design speed for segment i.

As the critical density is reached and exceeded, the volume begins to decrease and the speed continues to decrease; this phenomenon is represented in approximate form by the dashed curve in Figure 12.

These curves are of course interpretable, and useful, in a variety of ways, and represent the distillate of a vast amount of information from a number of sources, adapted from the Highway Capacity Manual.[2] Another interpretation is found by examining the range of speeds which may be associated with a given volume of traffic, where the higher speeds represent conditions of low density, free flow; intermediate speeds represent light to moderate restrictions, and the lower speeds (still at the same volume) represent increasingly higher densities and severe restrictions, ranging finally to stoppages of traffic for long periods of time, and maximum densities. These conditions, called levels of service, are designated conditions A through F, as described in the Appendix. It is of use to note that one study (reference 6) has addressed the question of traffic density under stopped conditions on freeways by means of still photography, with a result indicating a "jam," or stopped density (the maximum expected) of the order of 200 vehicles per mile. While this is useful in micro-analyses of extreme cases of congestion, it is not intended to imply that such conditions are important in impact analyses; rather, this figure (approximately 200 vehicles per mile) may be useful in examining maximum possible emission rates, by combining it with the "at idle" emission rates from reference 7 as follows: CO, 16.19 gm/min.; HC, 1.34 gm/min.; and NO_x, 0.11 gm/min. These data, incidentally, fit precisely with the steady-state emissions of Figures 1, 2, and 3, when the latter are converted to grams per minute at various speeds, and extrapolated to zero speed.

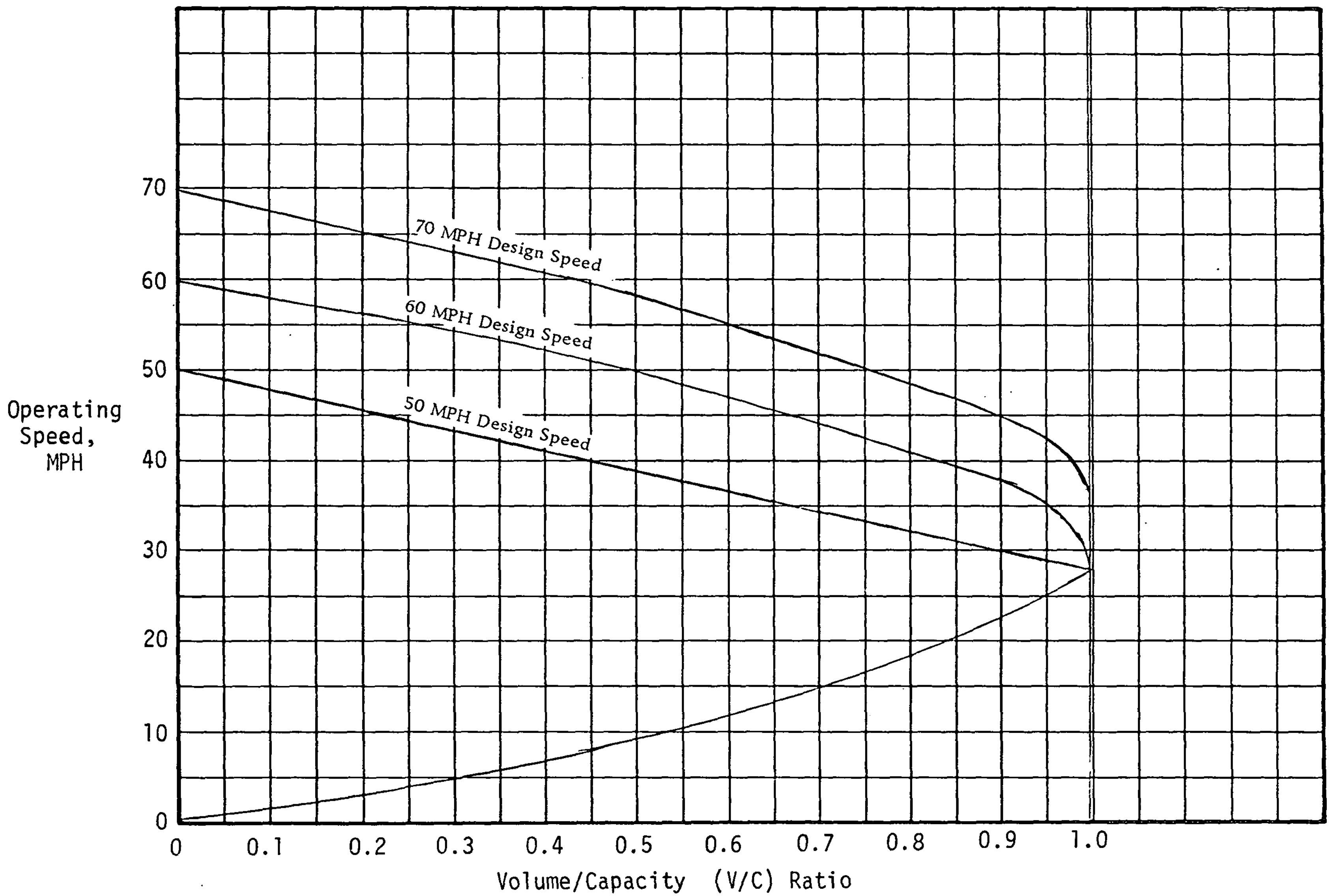


Figure 12. RELATIONSHIPS AMONG V/C RATIO AND OPERATING SPEED, IN ONE DIRECTION OF TRAVEL, ON FREEWAYS AND EXPRESSWAYS, UNDER UNINTERRUPTED FLOW CONDITIONS (Adopted from Reference 2)

Public Transit Systems

Figure 13 shows the anticipated impact of a transit system on miles traveled for a new highway. This impact is measured by Δ VMT, the reduction in vehicle miles traveled due to the transit system. The magnitude of the reduction will obviously depend on a number of factors, such as the effectiveness of the transit system and the amount of traffic on the highway which is due to intra-region travel (particularly commuter and shopper traffic). Obviously if most of the traffic on the highway is due to through traffic, then the existence of an urban mass transit system which uses the highway will have little effect on total VMT.

Frequently mass transit systems will utilize one lane of a multilane artery, thereby reducing significantly the capacity of the highway to carry other traffic. If the mass transit system is not successful in attracting users, this reduction in highway capacity will result in congestion and potential air quality impact.

This special situation may be treated by considering the lane restricted to mass transit and the remainder of the highway separately. The schedule and routes of the mass transit system may be utilized to calculate VMT and speed for macro analysis, and maximum density and associated speed for micro analysis. The expected usage of the remainder of the highway must be calculated in the normal fashion, with capacity based only on lanes available, and input traffic demands reflecting decreases due to the mass transit system. The resulting EVMT for macro analysis can be obtained by adding the values for the mass transit and usual traffic. Micro analysis would utilize one line to represent pollutant source intensity due to mass transit, a second to represent the line source intensity due to the remainder of the traffic (or the two intensities could be added to be represented by one line). Emission factors for the mass transit system will reflect the usage of heavy-duty vehicles. The factor used will depend on the type of pollutant, the year and age of the vehicle, and weather it is diesel or gasoline fueled. The appropriate tables are contained in reference 3.

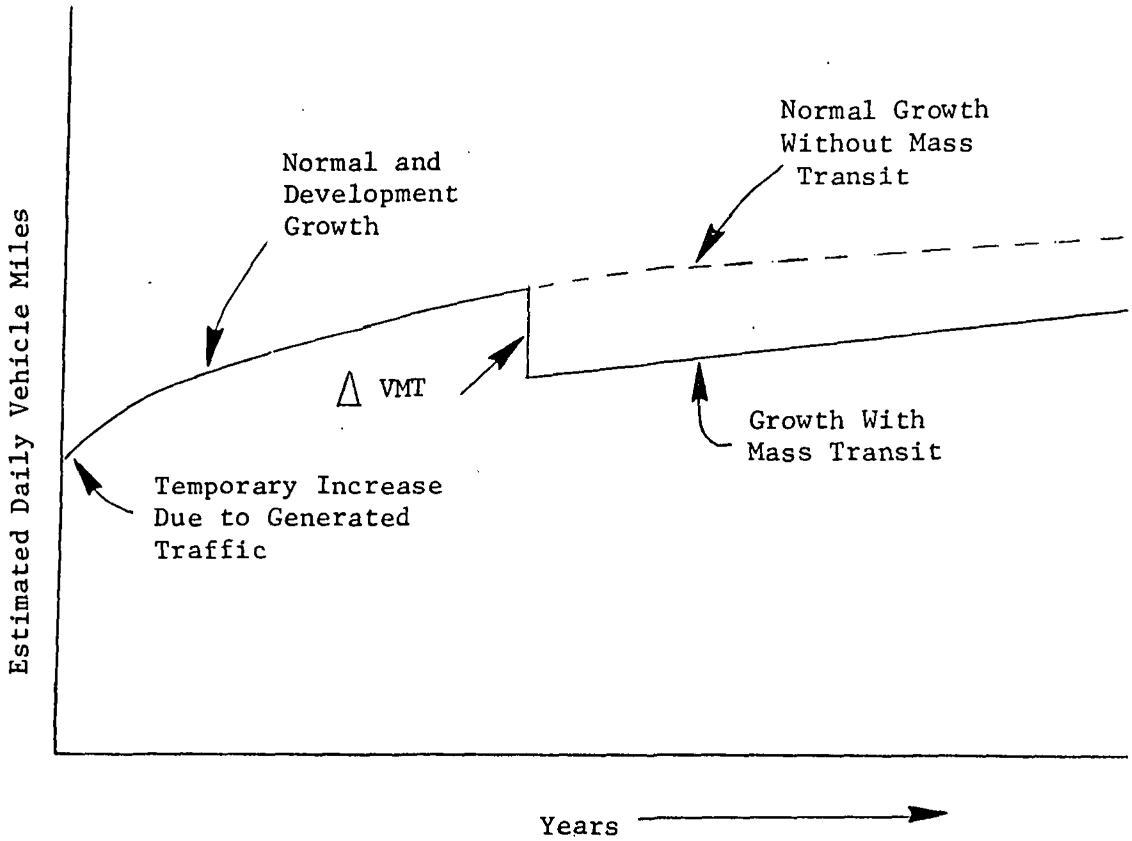


Figure 13. EXPECTED GROWTH ON NEW FACILITY SHOWING IMPACT OF MASS TRANSIT PROGRAM

SECTION VII

RESULTS

THE METHODOLOGY

As indicated earlier, we wish to obtain as end product of this study procedures to evaluate the impact of new or improved highway facilities from both macro-analytic and micro-analytic approaches. To reiterate, macro-analysis utilizes proportionate modelling to determine the impact of new facilities on the overall air quality of a designated area, while the micro approach utilizes diffusion modelling to predict pollutant concentrations and their detailed spacial distribution.

MACRO-ANALYSIS

The objective of macro-analysis is to determine the increase in total equivalent vehicles miles travelled for a designated area. Since the net result of the analytic approach outlined here is the number of EVMT due to the new highway, the base EVMT (and any resulting reduced EVMT in the road network excluding the highway) must be available from other studies. Obviously the impact of the new highway (in terms of percentage increase in EVMT) is highly dependent on how the designated area is defined. If we consider the width of the designated area to be the dimension perpendicular to the direction of the highway, then the greater the width, the smaller will be the measured impact of the new highway. However, this report does not attempt to address the difficult question of how to define a designated area, except to suggest that such a definition should closely align with meaningful urbanization or geographic boundaries.

The first step in impact analysis is to obtain a map (or maps) showing the spatial design of the highway, through the designated area. Other input should include cross-sectional design specifications, anticipated traffic demands, and land use maps. The steps to be carried out for macro-analysis should proceed as follows:

1. Consider each direction of travel separately. Divide the highway into segments having uniform levels of service, as described in the Analysis Section. Within each of these segments, operating speed and capacity should be uniform, and there should be no inflow or outflow of traffic within the segment (that is, exits and/or entrances should define endpoints of segments). If special bus lanes exist, consider these separately from the remainder of highway.

2. Based on highway design specifications and percentage use by trucks, evaluate the capacity of each segment. The capacity for segment i may be evaluated by use of the formula

$$C_i = 2{,}000\ N\ W\ T$$

Where C_i = Capacity in vehicles per hour,
N = Number of lanes,
W = Adjustment for lane width and lateral clearance taken from Table 6,
T = Truck factor from Table 7 and includes adjustment for grade.

Note that more refined tables for evaluating T are available (in reference 2) which take into account steepness and length of grade.

3. Evaluate the demand on each segment i according to the discussion of Section IV; that is,

$$V_i = V_{i-1} + (V_{ie} - V_{ix}), \quad i = 1 \text{ to } n.$$

Note that the initial V_o is known, which, along with the V_{ie} and V_{ix} defines each subsequent V_i.

Table 6. COMBINED EFFECT OF LANE WIDTH AND RESTRICTED LATERAL CLEARANCE ON CAPACITY AND SERVICE VOLUMES OF DIVIDED FREEWAYS AND EXPRESSWAYS WITH UNINTERRUPTED FLOW[2]

DISTANCE FROM TRAFFIC LANE EDGE TO OBSTRUCTION (FT)	ADJUSTMENT FACTOR,ª W, FOR LANE WIDTH AND LATERAL CLEARANCE							
	OBSTRUCTION ON ONE SIDE OF ONE-DIRECTION ROADWAY				OBSTRUCTIONS ON BOTH SIDES OF ONE-DIRECTION ROADWAY			
	12-FT LANES	11-FT LANES	10-FT LANES	9-FT LANES	12-FT LANES	11-FT LANES	10-FT LANES	9-FT LANES
(a) 4-Lane Divided Freeway, One Direction of Travel								
6	1.00	0.97	0.91	0.81	1.00	0.97	0.91	0.81
4	0.99	0.96	0.90	0.80	0.98	0.95	0.89	0.79
2	0.97	0.94	0.88	0.79	0.94	0.91	0.86	0.76
0	0.90	0.87	0.82	0.73	0.81	0.79	0.74	0.66
(b) 6- and 8-Lane Divided Freeway, One Direction of Travel								
6	1.00	0.96	0.89	0.78	1.00	0.96	0.89	0.78
4	0.99	0.95	0.88	0.77	0.98	0.94	0.87	0.77
2	0.97	0.93	0.87	0.76	0.96	0.92	0.85	0.75
0	0.94	0.91	0.85	0.74	0.91	0.87	0.81	0.70

ª Same adjustments for capacity and all levels of service.

Table 7. AVERAGE GENERALIZED ADJUSTMENT FACTORS FOR TRUCKS ON FREEWAYS AND EXPRESSWAYS, OVER EXTENDED SECTION LENGTHS[2]

PERCENTAGE OF TRUCKS, P_T	FACTOR, T, FOR ALL LEVELS OF SERVICE		
	LEVEL TERRAIN	ROLLING TERRAIN	MOUNTAINOUS TERRAIN
1	0.99	0.97	0.93
2	0.98	0.94	0.88
3	0.97	0.92	0.83
4	0.96	0.89	0.78
5	0.95	0.87	0.74
6	0.94	0.85	0.70
7	0.93	0.83	0.67
8	0.93	0.81	0.64
9	0.92	0.79	0.61
10	0.91	0.77	0.59
12	0.89	0.74	0.54
14	0.88	0.70	0.51
16	0.86	0.68	0.47
18	0.85	0.65	0.44
20	0.83	0.63	0.42

4. From the design speed (typically 70 mph for Interstate highways) and the volume demand to capacity ratio (V_i/C_i) evaluate the operating speed S_i for each segment i from Figure 12.

5. From the equation below (developed in the Analysis Section), evaluate the Equivalent Vehicle Miles Traveled.

$$EVMT = \sum_{i=o}^{n} c(S_i) \times d_i \times V_i$$

Where $c(S_i)$ is the speed correction factor, d_i is the length in miles of segment i, and V_i is the demand on segment i in vehicles per hour.

6. If some of the segments defined in (1) above correspond to lane-restricted public transit, then the EVMT corresponding to these segments should be evaluated and added to the value derived above. Obtain the schedule and routes of transit system. From the schedule evaluate the number of trips during a given time frame (1 or 8 hours) and the expected operating speed. Then use the following equation to evaluate EVMT due to transit trips for a highway.

$$EVMT = \sum_{i=o}^{n} N_i \times d_i \times c\,(S_i)$$

where

N_i = Number of transit trips over segment i during time period,
d_i = Length in miles of segment i,
$c(S_i)$ = Speed correction factor for heavy duty vehicles (assume equal to 1 until data becomes available).

The demands for use of non-transit lanes in Step 3 above should be adjusted for the impact of the urban transit system, if this has not been done already. This can be done by evaluating the expected number of passengers to be carried by the transit system. It is also necessary to know the percentage of these which would normally be riding in a private automobile and the average number of passengers per automobile. The reduced demand is given by:

$$D = \frac{P \times N}{A \times T}$$

where

- D = The reduced demand in vehicles per hour,
- P = The percentage of passengers who would normally ride in a private auto,
- N = The number of passengers to be carried by the transit system during time period T,
- A = The average number of passengers per auto,
- T = The time period being considered (1 or 8 hours).

MICRO-ANALYSIS

Micro-analysis centers about diffusion modeling of a highway as a line emission source or a series of line emission sources. The objective of this methodology is to provide a means of obtaining the line source intensity, which is normally expressed in units of grams of pollutant per unit distance per unit time. While the geometry of the line source is determined by highway design, the actual source intensity varies with location and time. Since traffic density is reasonably constant within segments, it is reasonable to limit our consideration of location to differentiation between segments.

For a given segment, volume demand and operating speed are obtained as outlined in Macro-Analysis. Density can be derived by the following equation:

$$D_i = \frac{V_i}{S_i}$$

where

- D_i = Density in vehicles per mile,
- V_i = Volume demand in vehicles per hour,
- S_i = Speed in miles per hour.

The line source intensity is the product of emission rate per vehicle and density. Thus:

$$I_i = e_i \; c(S_i) \frac{V_i}{S_i}$$

where

I_i = Line source intensity in gms per hour per mile,
e_i = Pollutant rate of emission in gms per hour for one vehicle,
$c(S_i)$ = Speed correction factor,
and V_i and S_i are as defined above.

In summary, the traffic parameters derived for macro-analysis can be directly translated for use in micro-analysis. Diffusion modeling can be used to reflect spatial distribution of pollutant concentrations and to reflect more sensitively the actual geometric design of the highway, surrounding terrain, and anticipated weather conditions.

METEOROLOGICAL ASPECTS

The meteorological characteristics which most importantly affect atmospheric dilutive capacity are mixing height, wind speed and atmospheric stability. A convenient summary of mixing height and wind speed characteristics which affect air pollution potential is given in the Office of Air Programs Publication No. AP-101 (Holzworth 1972). Atmospheric stability may be determined in terms of cloud cover, solar radiation and wind speed by a method proposed by Pasquill and shown in Table 8. For ground level sources, such as automobiles on highways, the ground level concentrations, both in the vicinity and downwind of the sources will be inversely proportional to wind speed and mixing height, and directly proportional to atmospheric stability (i.e., the more stable the atmosphere, the higher the concentration).

The seasons of peak use of highways have been cited as the winter months in the southern part of the country, and the summer months in the northern part. The peak 1-hour and 8-hour periods will occur during Friday afternoon

Table 8. KEY TO STABILITY CATEGORIES (after Turner 1970)

Surface Wind Speed (at 10 m), m sec^{-1}	Day			Night	
	Incoming Solar Radiation			Thinly Overcast or $\geq$ 4/8 Low Cloud	$\leq$ 3/8 Cloud
	Strong	Moderate	Slight		
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	C	D	D	D

The neutral class, D, should be assumed for overcast conditions during day or night.

NOTE: Class A is the most unstable, class F the most stable class. Night refers to the period from 1-hour before sunset to 1-hour after sunrise. Note that the neutral class, D, can be assumed for overcast conditions during day or night, regardless of wind speed.

"Strong" incoming solar radiation corresponds to a solar altitude greater than 60° with clear skies; "slight" insolation corresponds to a solar altitude from 15° to 35° with clear skies. Table 170, Solar Altitude and Azimuth, in the Smithsonian Meteorological Tables (List 1951) can be used in determining the solar altitude. Cloudiness will decrease incoming solar radiation and should be considered along with solar altitude in determining solar radiation. Incoming radiation that would be strong with clear skies can be expected to be reduced to moderate with broken (5/8 to 7/8 cloud cover) middle clouds and to slight with broken low clouds.

and evening, when home-bound commuter traffic combines with weekend departures. The single hour on any given weekend is generally during departure, say, 5 to 6p.m. The peak 8-hour period would encompass the total combined period and thus would run about, say, 2p.m. to 10p.m.

Mean afternoon wind speeds and mixing heights for the winter months are shown in Figures 14 and 15, and for the summer months in Figures 16 and 17, taken from Holzworth (1972). During the afternoon and into the early evening, atmospheric stability classes B, C and D may occur, with classes C and D being the most prevalent. As periods further into the evening are considered, class D becomes even more prevalent, with class E beginning to occur.

The period when meteorological conditions are least favorable for diluting pollutants is the period when highways are generally in periods of lesser use. This would be the period from very late evening until approximately sunrise. It is most often during this period that mixing heights are lowest, wind speeds are lightest, and atmospheric stability is greatest.

Special attention should be paid, depending on the location, to the possible coincident occurrence, say on the last business days before Thanksgiving and Christmas, of the normal homeward bound commuter load, together with shoppers and holiday bound travelers, as potentially creating the highest peak load encountered.

THE NINE QUESTIONS

While the specific information called for by the task work statement has been provided in the sections from Highway Characteristics and Parameters through Meteorological Aspects, the nine questions spelled out as part of the statement warrant specific response. This is given concisely here, with the question abbreviated.

1. Area allotted to or occupied by a single vehicle? Not relevant to highways, except in the "stopped" or "jam" condition (approximately 200 vehicles per mile).

2. Percentage of highway potentially occupied by vehicles? The usual percentage? Treated in related sense as vehicle density in Analysis and Results sections.

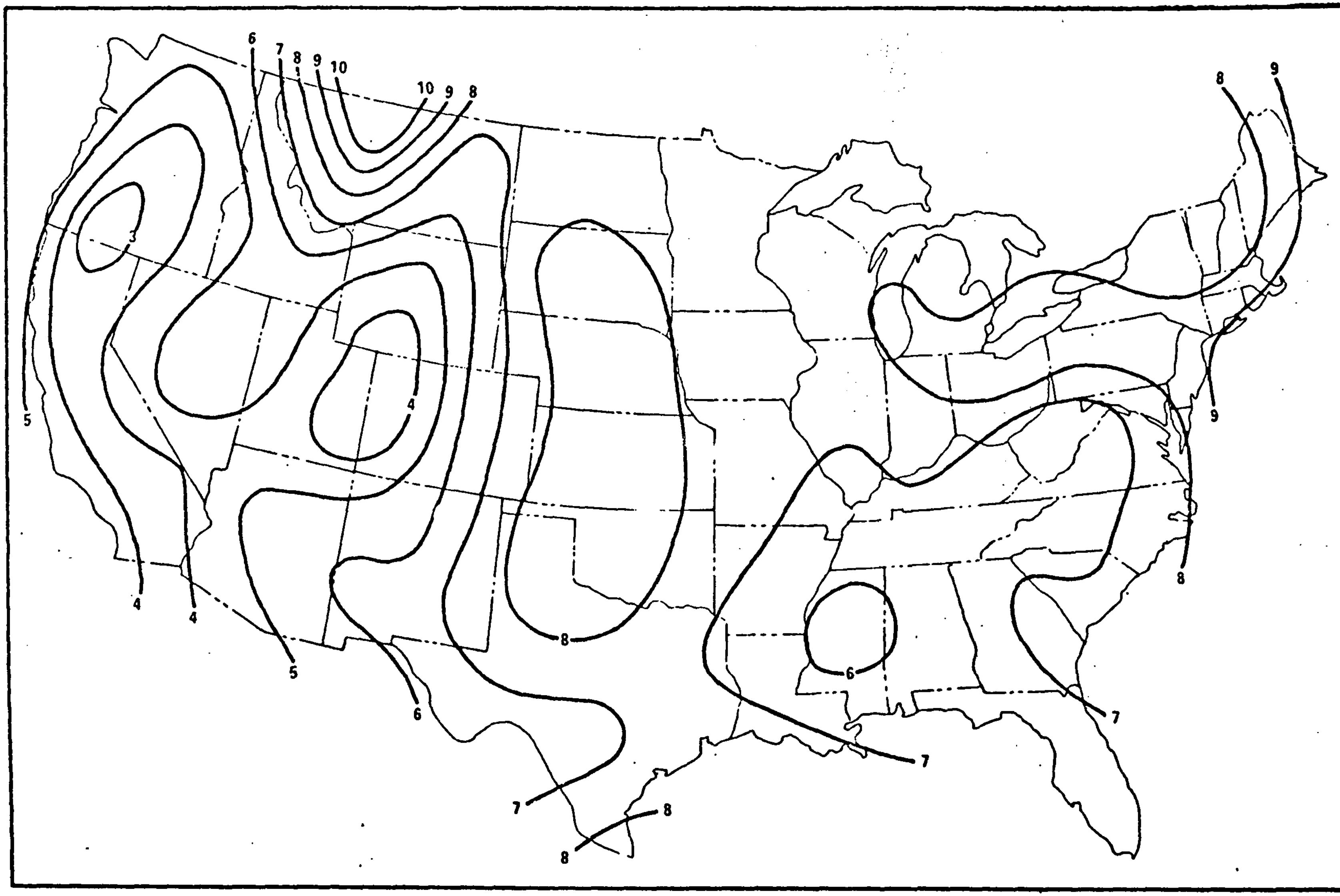


Figure 14. ISOPLETHS (m sec^{-1}) OF MEAN WINTER WIND SPEED AVERAGED THROUGH THE AFTERNOON MIXING LAYER

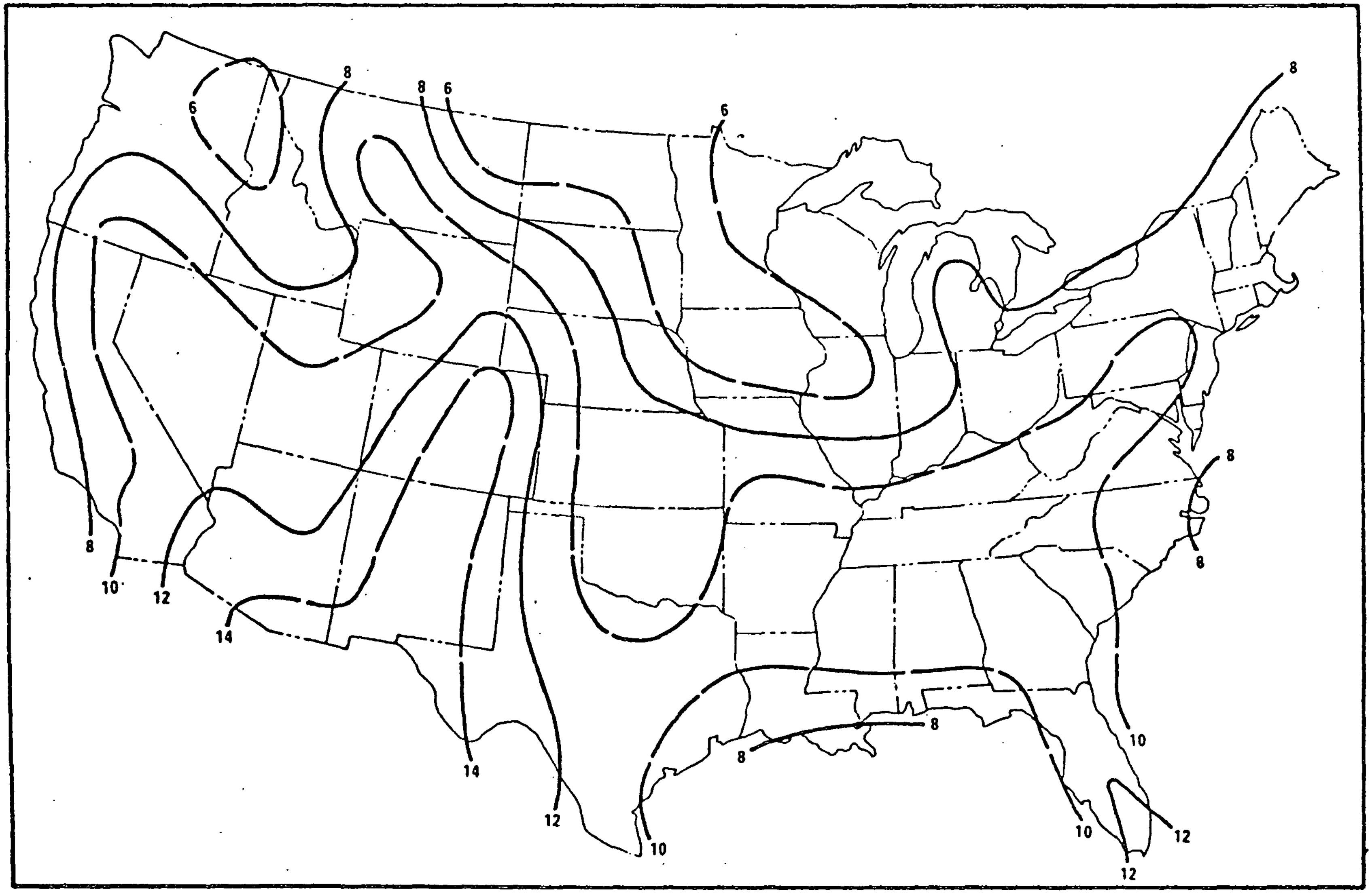


Figure 15. ISOPLETHS ($m \times 10^2$) OF MEAN WINTER AFTERNOON MIXING HEIGHTS

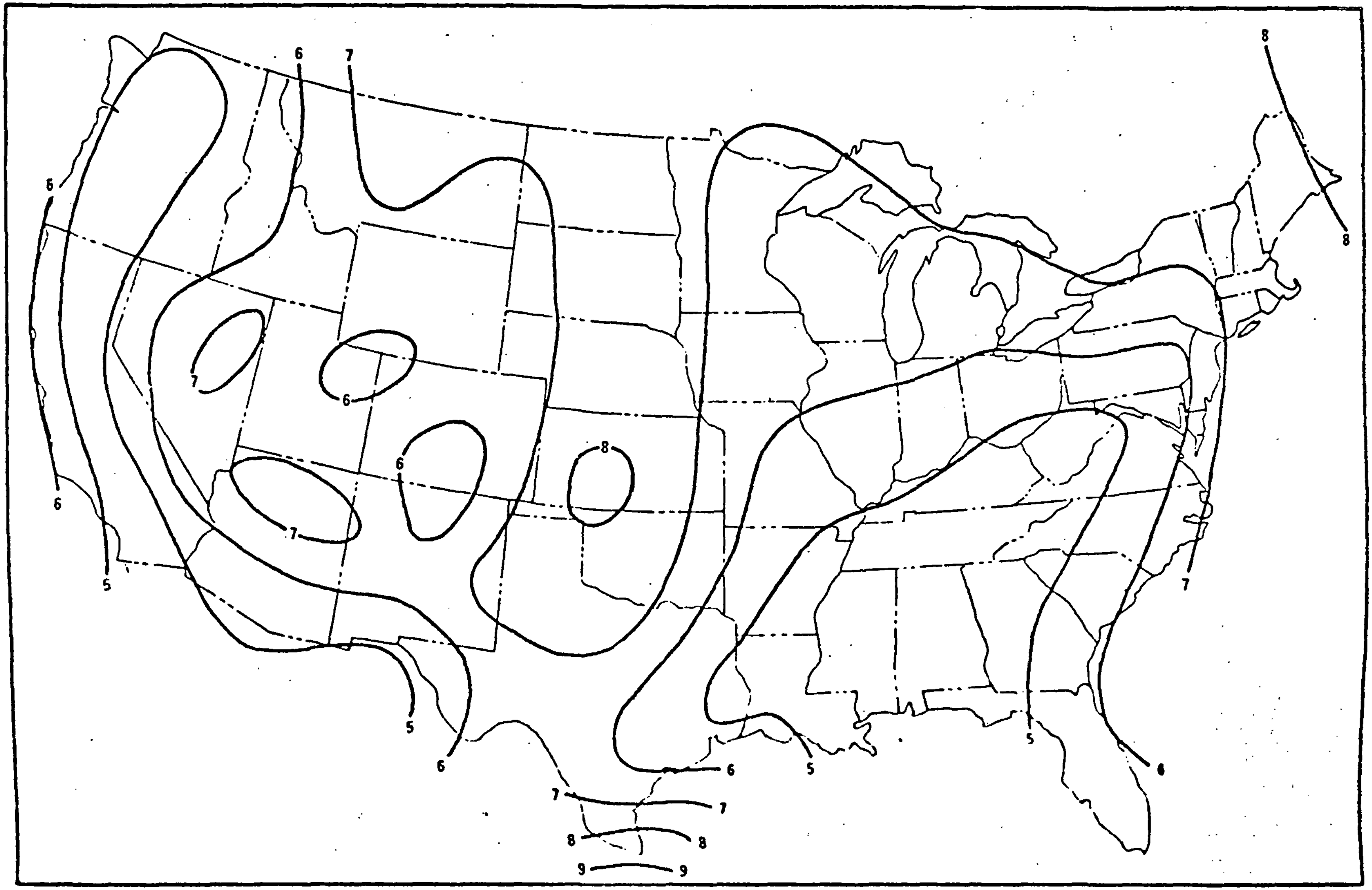


Figure 16. ISOPLETHS (m sec^{-1}) OF MEAN <u>SUMMER</u> WIND SPEED AVERAGED THROUGH <u>AFTERNOON</u> MIXING LAYER (Figure 5)

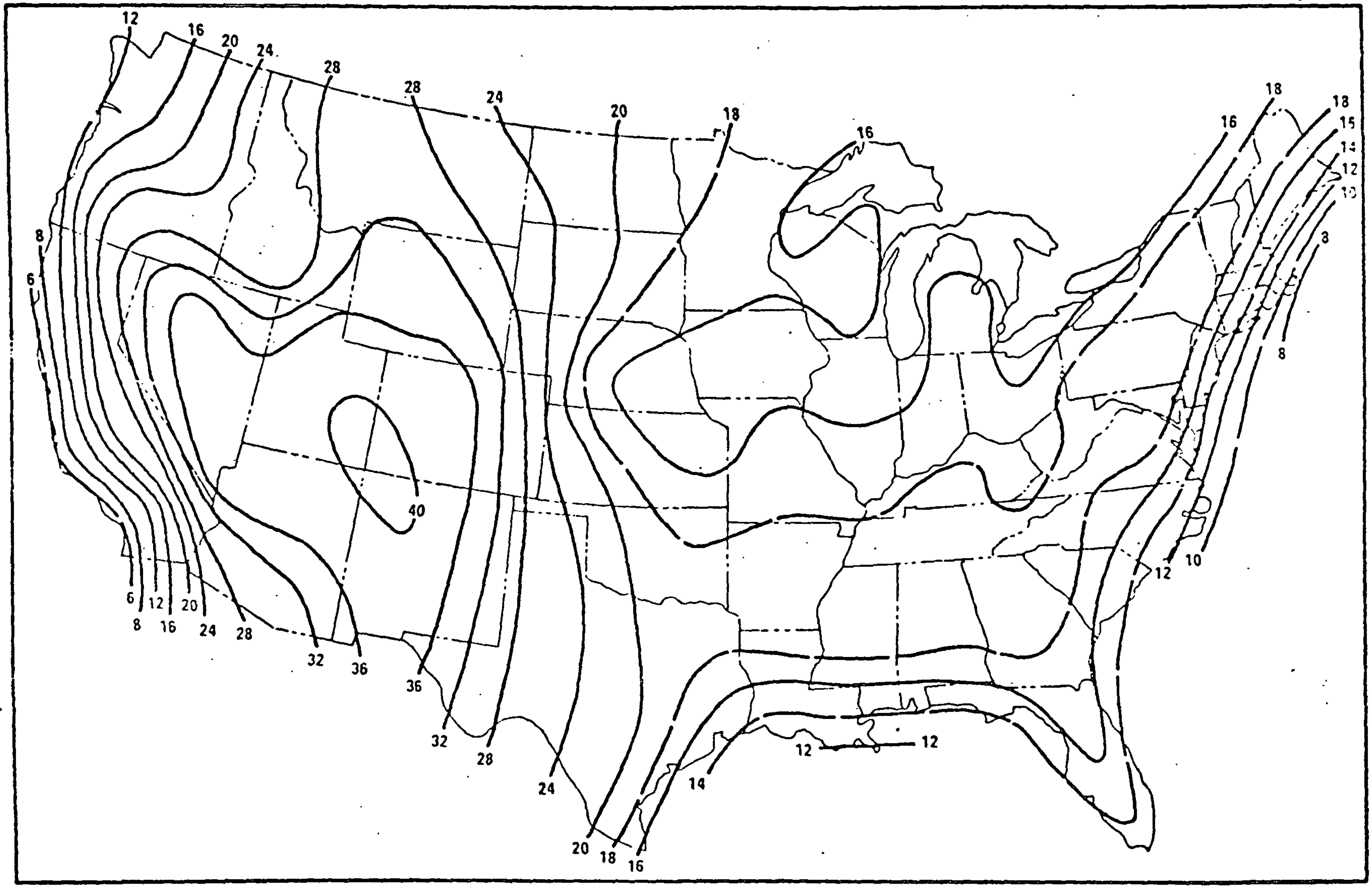


Figure 17. ISOPLETHS (mx10^2) OF MEAN SUMMER AFTERNOON MIXING HEIGHTS

3. Typical and peak values (absolute or fractional) of vehicles running for one- and eight-hour periods? These data are developed in Section V.

4. Typical and worst case (slowest) vehicle speeds? Treated in Sections VI and VII. Typical speeds correspond to normal flow. Worst speeds (idling) correspond to completely congested traffic flow.

5. Vehicle distribution within the complex? Ultimately defined by spatial design of highway. Vehicle density considered variable from segment to segment.

6. Design parameters of the complex likely to be known before hand? See section titled Highway Characteristics and Parameters.

7. Design parameters in question (6) which can be most successfully related to traffic, and hence emissions? See section titled Analysis.

8. Relationships of parking lot design to parking densities and vehicle circulation? What is typical design? Design with highest parking densities, lowest vehicle speeds, longest vehicle operating times? Not relevant to highways.

9. Meteorological conditions likely to occur during peak use? Use level during periods of worst meteorology? See section titled Meteorological Aspects.

Section VIII

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Section IX

SELECTED DEFINITIONS[2]

Functional Types

Arterial highways - A highway primarily for through traffic, usually on a continuous route.

Expressway - A divided arterial highway for through traffic with full or partial control of access and generally with grade separations at major intersections.

Freeway - An expressway with full control of access.

Major street or major highway - An arterial highway with intersections at grade and direct access to abutting property, and on which geometric design and traffic control measures are used to expedite the safe movement of through traffic.

Operations

Design speed - A speed selected for purposes of design and correlation of those features of a highway, such as curvature, superelevation, and sight distance, upon which the safe operation of vehicles is dependent.

Average highway speed - The weighted average of the design speeds within a highway section, when each subsection within the section is considered to have an individual design speed.

Operating speed - The highest overall speed at which a driver can travel on a given highway under favorable weather conditions and under prevailing traffic conditions without at any time exceeding the safe speed as determined by the design speed on a section-by-section basis.

Volume - The number of vehicles that pass over a given section of a lane or a roadway during a time period of one hour or more. Volume can be expressed in terms of daily traffic or annual traffic, as well as on an hourly basis.

Average annual daily traffic - The total yearly volume divided by the number of days in the year, commonly abbreviated as AADT.

Maximum annual hourly volume - The highest hourly volume that occurs on a given roadway in a designated year.

Tenth, twentieth, thirtieth, etc., highest annual hourly volume - The hourly volume on a given roadway that is exceeded by 9, 19, 29, etc., respectively, hourly volumes during a designated year.

Peak-Hour Traffic - The highest number of vehicles found to be passing over a section of a lane or a roadway during 60 consecutive minutes.

Rate of Flow - The hourly representation of the number of vehicles that pass over a given section of a lane or a roadway for some period less than one hour. It is obtained by expanding the number of vehicles to an hourly rate by multiplying the number of vehicles during a specified time period by the ratio of 60 min to the number of minutes during which the flow occurred. The term "rate of flow" will normally be prefixed by the time period for the measurement. For example, a 15-min count of N vehicles multiplied by 60/15 or 4 would produce a "15-min rate of flow of 4N vehicles per hour."

Interrupted Flow - A condition in which a vehicle traversing a section of a lane or a roadway is required to stop by a cause outside the traffic stream, such as signs or signals at an intersection or a junction. Stoppage of vehicles by causes internal to the traffic stream does not constitute interrupted flow.

Uninterrupted flow - A condition in which a vehicle traversing a section of a lane or a roadway is not required to stop by any cause external to the traffic stream although vehicles may be stopped by causes internal to the traffic stream.

Density - The number of vehicles occupying a unit length of the through traffic lanes of a roadway at any given instant. Usually expressed in vehicles per mile.

Average density - The average number of vehicles per unit length of roadway over a specified period of time.

Critical density - The density of traffic when the volume is at capacity on a given roadway. At a density either greater or less than the critical density, the volume of traffic will be decreased. Critical density occurs when all vehicles are moving at about the same speed.

Levels of Service - Traffic operational freedom on a highway of a particular type is considered equal to or greater than level of service A, B, C, or D, as the case may be, when specified values of the two separate conditions previously described are met. These conditions require that: (1) operating speeds or average overall speeds be equal to or greater than a standard value for the level considered, and (2) the ratio of the demand volume to the capacity of any subsection not exceed a standard value for that level. Level of service E describes conditions approaching and at capacity (that is, critical density). Level F describes conditions under high-density conditions when speeds are low and variable; it is not effectively described by combinations of speed and volume-to-capacity ratios, because these may vary widely.

Level of service A describes a condition of free flow, with low volumes and high speeds. Traffic density is low, with speeds controlled by driver desires, speed limits, and physical roadway conditions. There is little or no restriction in maneuverability due to the presence of other vehicles, and drivers can maintain their desired speeds with little or no delay.

Level of service B is in the zone of stable flow, with operating speeds beginning to be restricted somewhat by traffic conditions. Drivers still have reasonable freedom to select their speed and lane of operation. Reductions in speed are not unreasonable, with a low probability of traffic flow being restricted. The lower limit (lowest speed, highest volume) of this level of service has been associated with service volumes used in the design of rural highways.

Level of service C is still in the zone of stable flow, but speeds and maneuverability are more closely controlled by the higher volumes. Most of the drivers are restricted in their freedom to select their own speed, change lanes, or pass. A relatively satisfactory operating speed is still obtained, with service volumes perhaps suitable for urban design practice.

Level of service D approaches unstable flow, with tolerable operating speeds being maintained though considerably affected by changes in operating conditions. Fluctuations in volume and temporary restrictions to flow may cause substantial drops in operating speeds. Drivers have little freedom to maneuver, and comfort and convenience are low, but conditions can be tolerated for short periods of time.

Level of service E cannot be described by speed alone, but represents operations at even lower operating speeds than in level D, with volumes at or near the capacity of the highway. At capacity, speeds are typically, but not always, in the neighborhood of 30 mph. Flow is unstable, and there may be stoppages of momentary duration.

Level of service F describes forced flow operation at low speeds, where volumes are below capacity. These conditions usually result from queues of vehicles backing up from a restriction downstream. The section under study will be serving as a storage area during parts or all of the peak hour. Speeds are reduced substantially and stoppages may occur for short or long periods of time because of the downstream congestion. In the extreme, both speed and volume can drop to zero.

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A general methodology is presented for relating parameters of traffic behavior on major highways, including traffic volume and average speed, to more readily available characteristics of highways, including design speed and capacity. Such relationships are to be used to relate major highway characteristics to air quality.

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