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URBAN AIR SHED PHOTOCHEMICAL SIMULATION MODEL STUDY

VOLUME I - DEVELOPMENT AND EVALUATION

Appendix A - Contaminant Emissions Model and Inventory for Los Angeles

Office of Research and Development
U.S. Environmental Protection Agency
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VOLUME I -

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Appendix A -

Contaminant Emissions Model and Inventory for Los Angeles

by

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TABLE OF CONTENTS

TABLE OF CONTENTS (Contd.)

INTRODUCTION

During the last months of 1970, we prepared a pollutant emissions inventory for the Los Angeles Basin for use in the modeling of the transport, diffusion, and reaction of atmospheric contamination. Pollutant sources were grouped into five categories--automobiles (and other motor vehicles), aircraft, power plants, refineries and distributed fixed sources. Emissions rates for a 2 x 2 mile grid system covering the Basin were compiled for nitrogen oxides, carbon monoxide, and hydrocarbons. Temporal variations in emissions rates were also determined. The complete inventory is reported in "Contaminant Emissions in the Los Angeles Basin--Their Sources, Rates, and Distribution," by P.J.W. Roberts, P.M. Roth, and C.L. Nelson (1971).

Early in 1972, we had the opportunity to make a number of modifications and extensions for the emissions inventory. The changes which affected all segments of the original inventory, were motivated by a variety of factors, but most heavily by a desire to improve the accuracy or the resolution of the inventory, or to correct errors. It is the purpose of this report to document all modifications and extensions that were implemented. In general, this report is segmented similarly to its predecessor, the exceptions being that (1) changes applicable to all portions of the inventory are included in an introductory general section and (2) the one modification to the refinery inventory, as a matter of convenience, is included in the section dealing with distributed fixed sources. Finally, we wish to point out that only changes are reported here; we have not attempted to present a final version of the inventory, either in summary or in detail, in this document. One must read both this report and the original to construct the complete inventory.

I. GENERAL

In this brief section, we document two points of general applicability concerning the treatment of nitrogen oxide emissions.

First, in using this inventory in conjunction with an airshed model, it is necessary to specify the fraction of total NO_x emissions from each class of sources that is NO_2 . As the measurement of the individual oxides is rarely made, we can only estimate the magnitude of the NO/NO_2 split. In order to obtain as accurate an estimate as possible, we contacted Prof. Robert Sawyer of the University of California (Berkeley), an expert in the field of combustion. We solicited his opinion as to appropriate values for the NO/NO_2 split for all categories of sources. After some discussion, we arrived at the following figures:

	% NO_2
Automobiles	1
Power Plants	5
Aircraft	1
Other fixed sources	2

However, these figures are at present uncertain and subject to revision.

Second, we wish to note that all NO_x emissions rates reported in Roberts et.al. (1971) are based on the assumption that the gases emitted are 100% NO_2. As can be seen from the preceding table, NO_x emissions from all sources range from 95 to 99% NO. If we assume in simplicity that NO_x emissions are in fact 100% NO, then reported mass rates (as NO_2) must be multiplied by the following ratio:

$$\frac{\text{molecular weight NO}}{\text{molecular weight NO}_2} = \frac{30}{46} .$$

In this report the only instance in which NO_x emissions are cited as NO is in the section dealing with automotive emissions; in all other instances, NO_x rates should be adjusted.

II. AUTOMOTIVE EMISSIONS

In this section, we describe extensions and modifications of the motor vehicle emissions inventory. Because of the length of the section, we first summarize the changes, then discuss them in detail.

A. Summary of Changes

We have modified and extended the original model describing vehicular emissions of contaminants in the Los Angeles Basin (Roberts et al. (1971)). The three major changes are (1) adoption of vehicle emissions factors Q_i based on the Federal Driving Cycle, (2) inclusion of a correlation between emissions rate and average speed to account for temporal and spatial variations in emissions from freeways, and (3) incorporation of a factor to account for variations in emissions resulting from a nonuniform temporal distribution of vehicle starts. We have also modified the treatment of emissions in the downtown area.

1. Federal Driving Cycle

We have adopted average emissions factors based on the Federal Driving Cycle. These factors, which replace those estimated using California Driving Cycle test results (as reported in Roberts et al. (1971), Table A-2), form the basis for determining emissions rates as a function of location and time, both for surface streets and freeways. Average hot and cold-start emissions factors, Q_i^h and Q_i^c respectively, are given by:

Species	(grams/mile) Q_i^h	(grams/mile) Q_i^c
CO	68.6	91.0
HC (exhaust and blowby only)	10.8	11.7
NO_x, as NO_2	4.16	4.16
as NO	2.71	2.71

where, for hydrocarbons:

molecular weight (reactive species)	= 47.8*
molecular weight (unreactive species)	= 21.1
fraction reactive (mol %)	= 67.4
fraction unreactive (mol %)	= 32.6

* We have assumed for the purposes of this inventory that methane, ethane, propane, benzene, and acetylene are unreactive. All other hydrocarbons are assumed to be reactive.

Average emissions rates for surface streets are estimated by (a) calculating

$$Q_i^s(t) = y(t)Q_i^c + (1 - y(t))Q_i^h \qquad (1)$$

where y(t) = fraction of the cars started at time t that are "cold-started"

time period	y
0:00 - 6:00	0.90
6:00 - 9:00	0.85
9:00 - 11:30	0.25
11:30 - 13:30	0.30
13:30 - 16:30	0.20
16:30 - 18:30	0.50
18:30 - 21:00	0.15
21:00 - 24:00	0.20

and (b) correcting this estimate for variations in the average emissions rate due to the nonuniform distribution of cold vehicle starts during the day. See sections in the Summary and Discussion entitled "Corrections for Nonuniform Distribution of Vehicle Starts" for details concerning the cold start corrections.

In calculating freeway emissions, we assume that all vehicles are "hot-running". Average emissions rates are estimated as a function of average vehicle speed using a relationship suggested by Rose et al. (1965). Further details are presented in sections of the Summary and Discussion entitled "Emissions/Average Speed Correlation."

2. Emissions/Average Speed Correlation

Freeway emissions rates for species i (grams/minute) for a particular grid square are given, as a function of average speed and time, by

$$E_i^f(t) = \frac{1}{60}\left\{n_f(t)\alpha_i[\bar{v}_f(t)] + n_s(t)\alpha_i[\bar{v}_s(t)]\right\} \quad (2)$$

where

$\bar{v}_f, \bar{v}_s$ = average speed in the fast and slow directions respectively (mph)

n_f, n_s = number of vehicle miles driven per hour in the fast and slow directions respectively

α_i = "hot-running" emissions rate of species i in grams per vehicle mile. α_i is a function of average vehicle speed.

(Note: "Fast" and "slow" refer to an assignment of names to the two opposing directions of flow on a freeway.) Values of α_i are computed from the following correlations, based on the work of Rose et al. (1965) and modified as described later in this text:

$$\alpha_i = a_i(\bar{v})^{b_i} \quad (3)$$

where

i	a	b
CO	295.	-0.49
HC	34.8	-0.40
NO_x	7.0	0

Values of $\bar{v}$ for each direction of freeway traffic flow, *at the particular time noted,* are given in Figures 1 through 8. ($\bar{v}$ is assumed to be 60 mph before 6 a.m. and after 9 a.m. over the daytime validation period.) Linear interpolation is used to calculate average velocities for times falling between those shown in the Figures. Finally n_f and n_s are calculated from

$$n_f = \frac{N_\ell^f}{1 + x} \; ; \; n_s = \frac{N_\ell^f x}{1 + x} \qquad (4a,\ 4b)$$

where

$N_\ell^f \quad = d_\ell^f M^f$

d_ℓ^f = fraction of daily (24-hour) freeway traffic counts assignable to hourly period ℓ (Table A-1 of Roberts et al. (1971))

M^f = freeway vehicle mileage per day for the grid square in question (Figure A-2 of Roberts et al.)

x = n_s/n_f, as given in Figures 9 through 12.

3. Correction for Nonuniform Distribution of Vehicle Starts

We have included a factor in the calculation of emissions rates to account for variations in average rates that occur when the total number of "cold-started" cars in operation changes rapidly, as during the morning rush hours. These "correction" factors, $\beta_i(t)$, which are applied to the average emissions factors for surface streets, $Q_i^s(t)$, are given by the curves shown in Figures 13 and 14. (No correction is required for NO_x .) Their entry into the calculation of emissions rates is presented in the paragraph that concludes this section. However, we strongly urge that reader refer to the Discussion section entitled "Corrections For Nonuniform Distribution of Vehicle Starts" for a full explanation of the nature of, and need for, this correction.

4. Modification in Treatment of Emissions in the Downtown Area

We have modified the treatment of auto emissions in the downtown Los Angeles area in the following manner. We have shifted the temporal distribution for surface traffic *one hour later in time* for the three grid squares having the following column and row numbers respectively: (12, 17), (11, 17), and (12, 16). (For example, the fraction of daily surface traffic assignable to the period 6 a.m. to 7 a.m. throughout the modeling region is applied to the period 7 a.m. to 8 a.m. for these three grid squares.) This shift provides a simple means to account for the fact that these squares contain few residences and thus, in the net, receive vehicles rather than discharge them during the morning hours.

Total emissions for a particular grid square, in grams/minute, are given by:

$$E_i(t) = E_i^f(t) + E_i^s(t) \qquad (5)$$

where

$$E_i^s(t) = \frac{1}{60} Q_i^s(t) d_\ell^s(t) M^s \beta_i(t)$$

and

$d_\ell^s(t)$ = fraction of daily (24-hour) non-freeway traffic count assignable to hourly period ℓ (Table A-1 of Roberts et al. (1971))

M^s = non-freeway vehicle mileage per day for the grid square in question (Figure A-3 of Roberts et al. (1971))

In conclusion, the main changes described in this section may be summarized as follows:

	Freeways	Non-Freeways
Average emissions factors	Average emissions rate based on the FDC Hot-running factors	Weighted average of cold-start and hot-running factors
Correction for nonuniform distribution included	No	Yes
Emissions/speed modification included	Yes	No

The net result, when compared to the original vehicle emissions model, is to increase emissions from surface streets, to decrease emissions from freeways (except for NO_x), to redistribute total emissions so that emissions levels are greater during periods of congestion (except for NO_x), and to maintain approximately the same total pollutant loading of the atmosphere.

Figures 1 through 14 follow

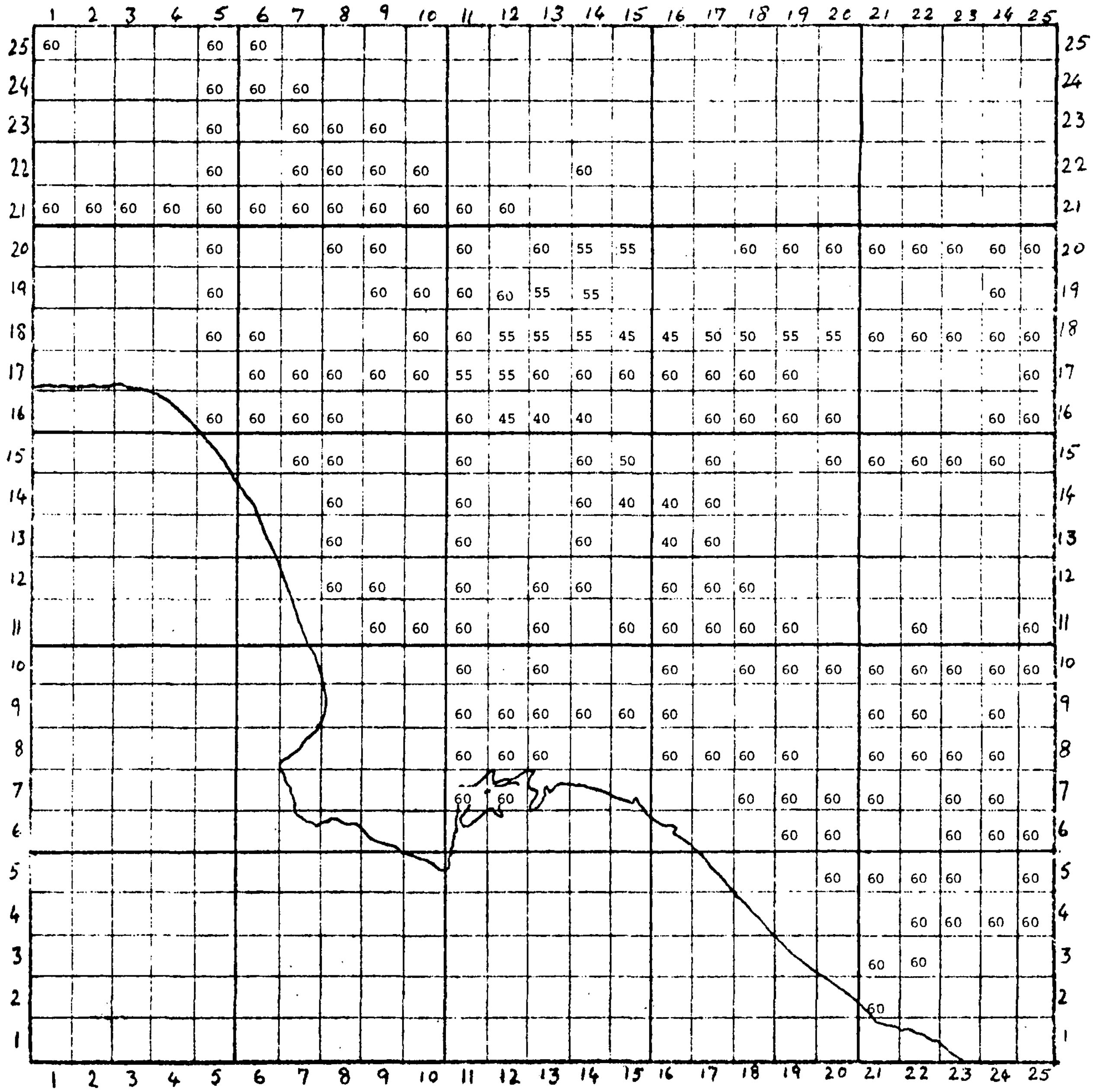


Figure 1. Average Vehicle Speed in "Slow" Direction ($\bar{v}_s$) at 6:00 a.m.

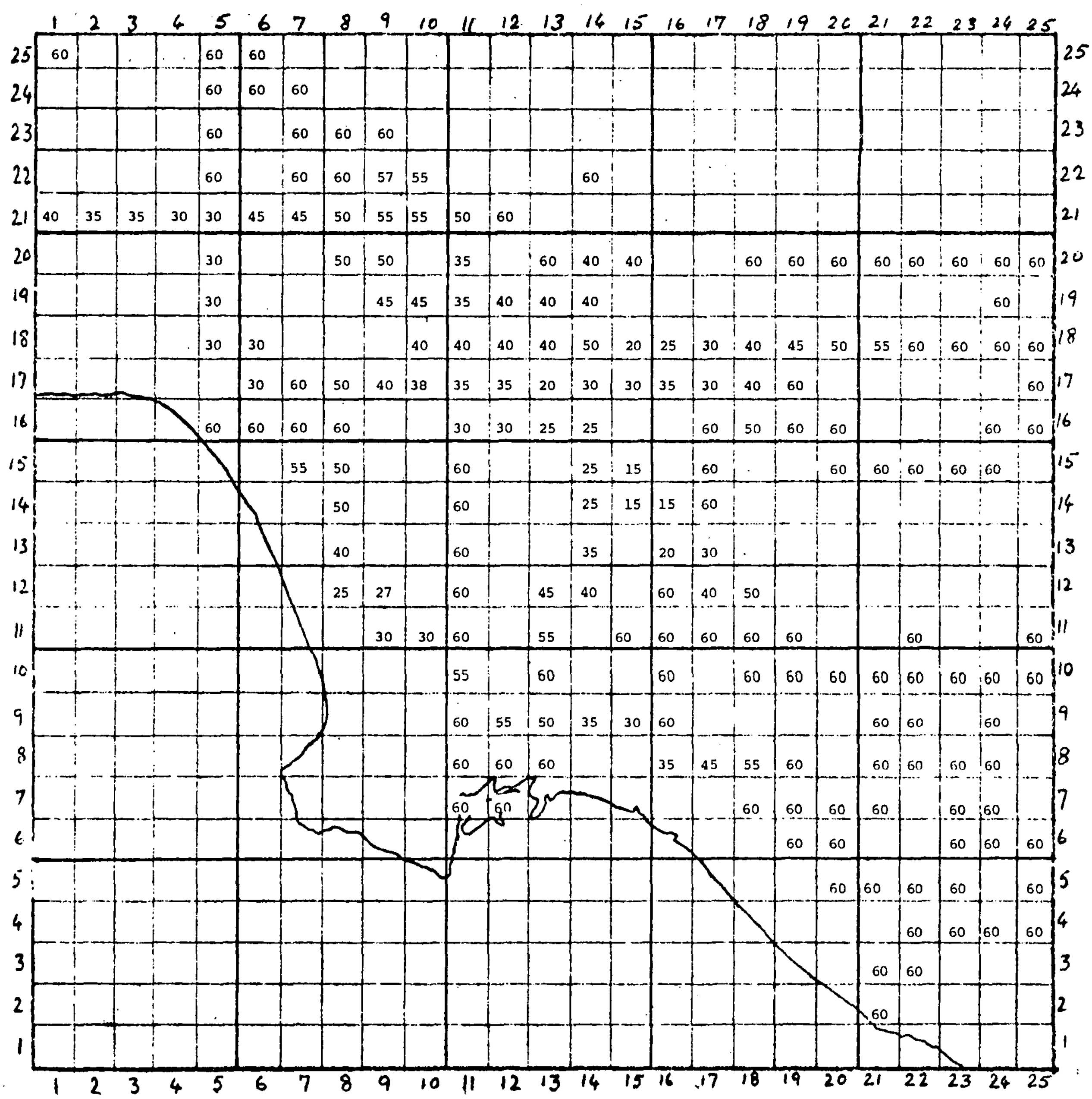


Figure 2. Average Vehicle Speed in "Slow" Direction ($\bar{v}_s$) at 7:00 a.m.

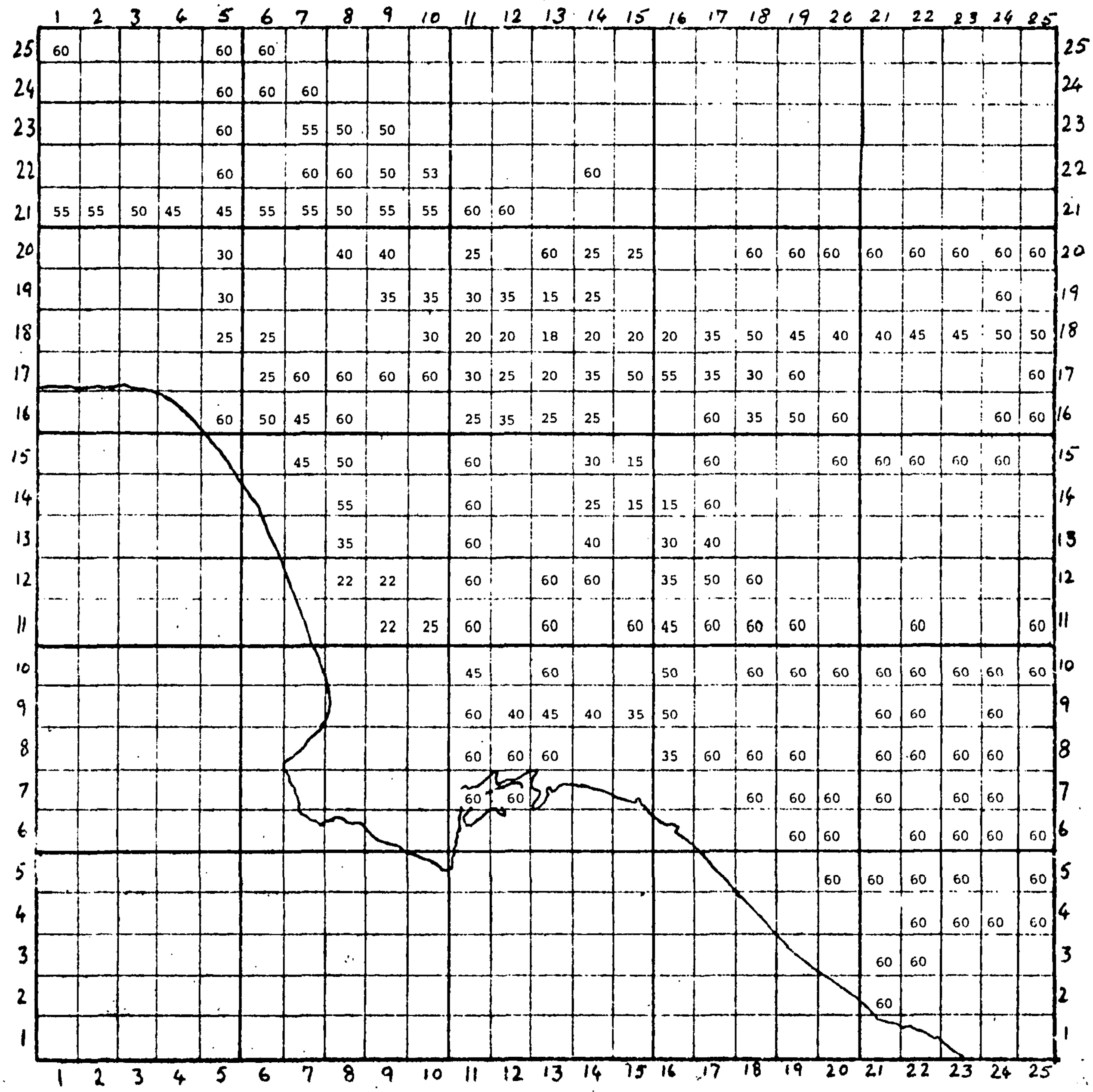


Figure 3. Average Vehicle Speed in "Slow" Direction ($\overline{v}_s$) at 8:00 a.m.

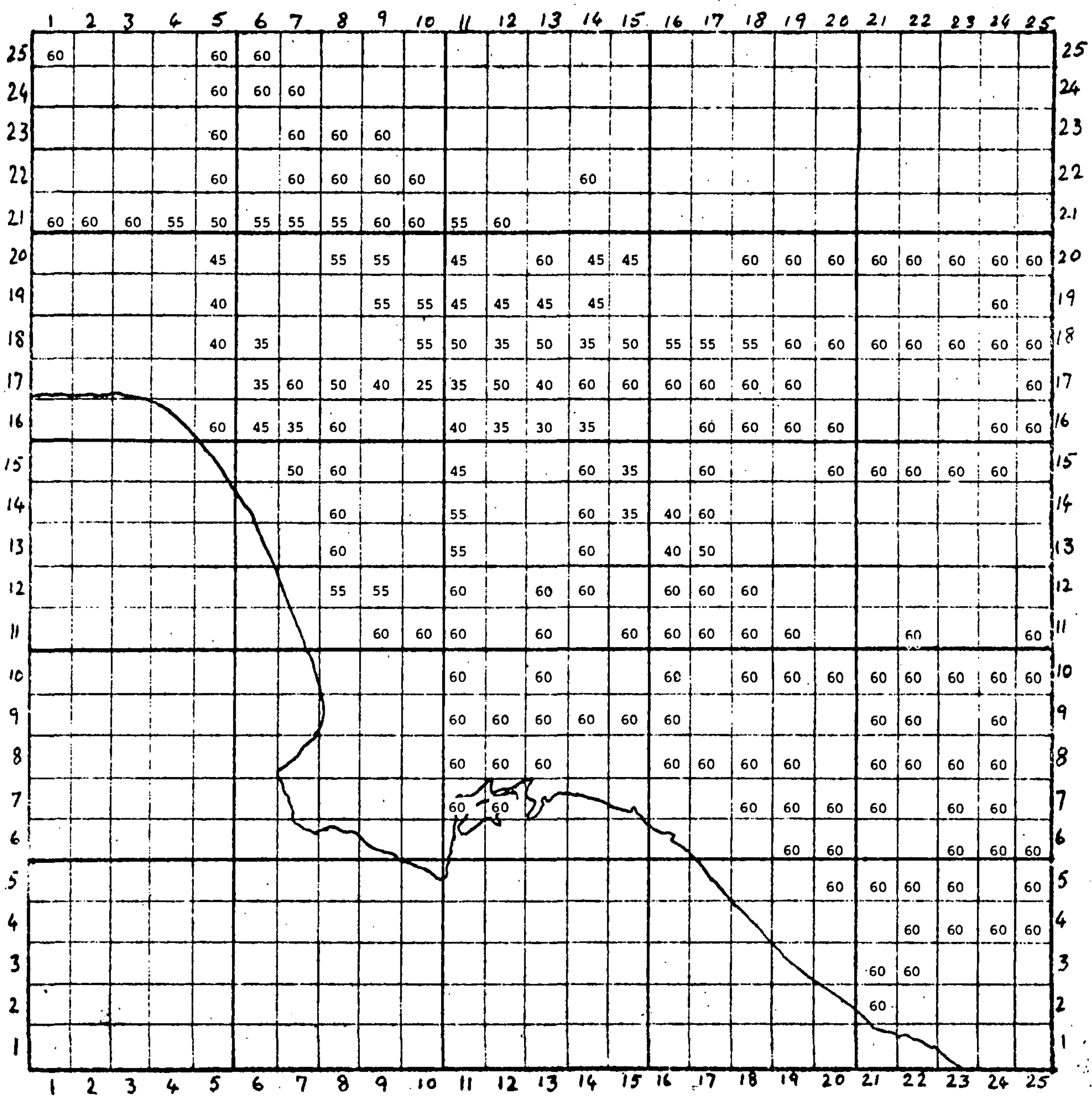


Figure 4. Average Vehicle Speed in "Slow" Direction ($\overline{v}_s$) at 9:00 a.m.

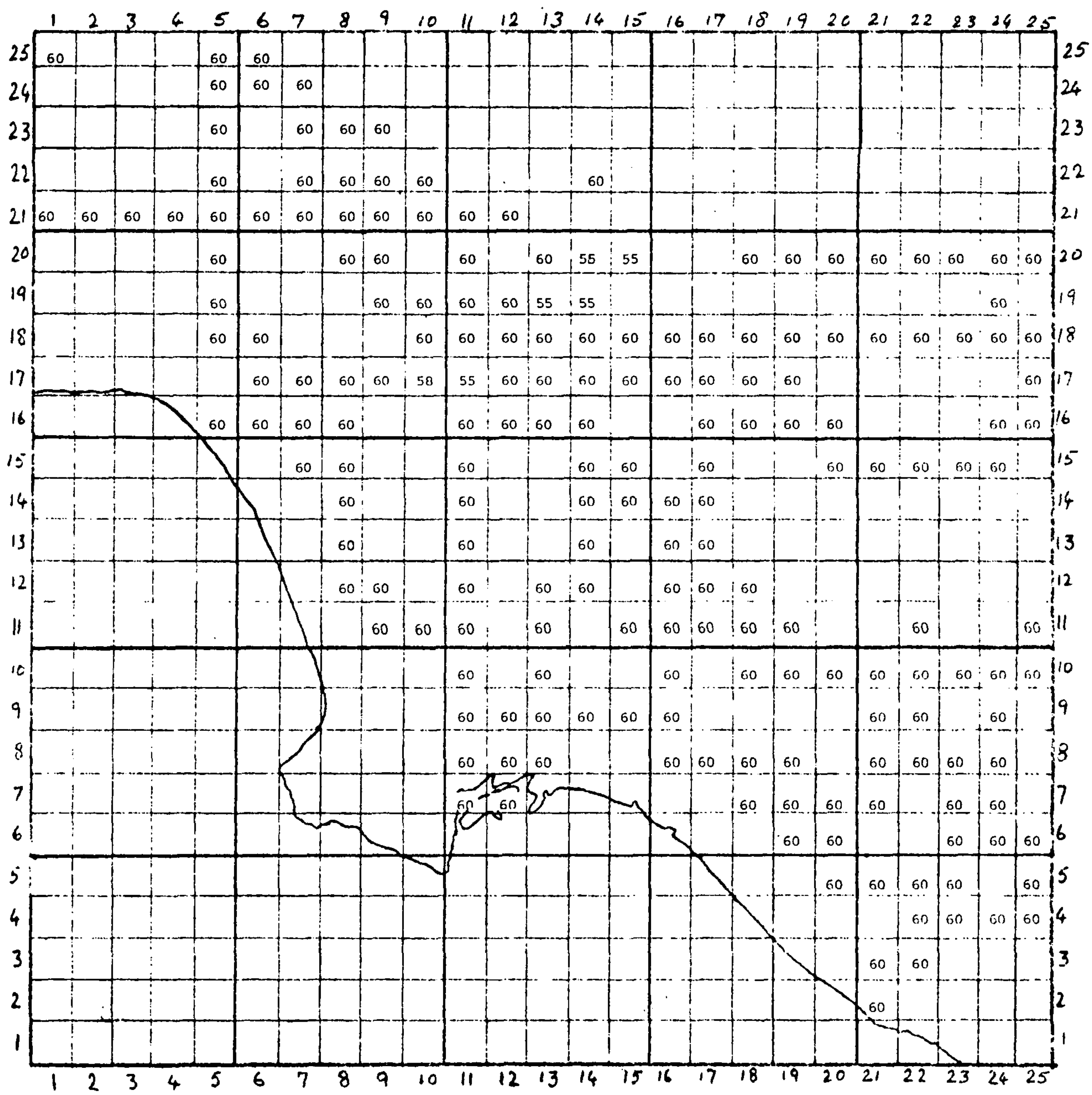


Figure 5. Average Vehicle Speed in "Fast" Direction ($\overline{v}_f$) at 6:00 a.m.

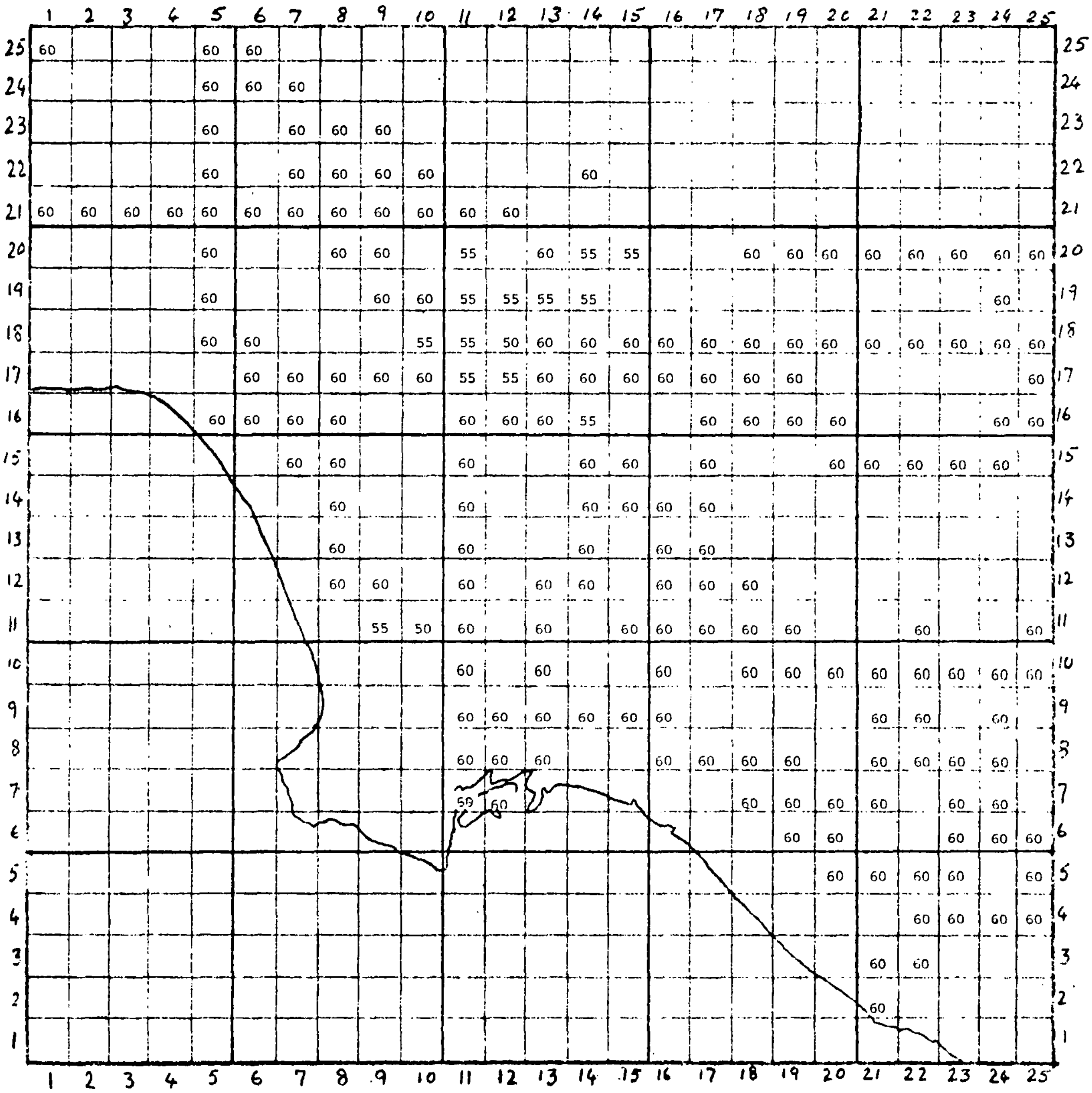


Figure 6. Average Vehicle Speed in "Fast" Direction ($\overline{v}_f$) at 7:00 a.m.

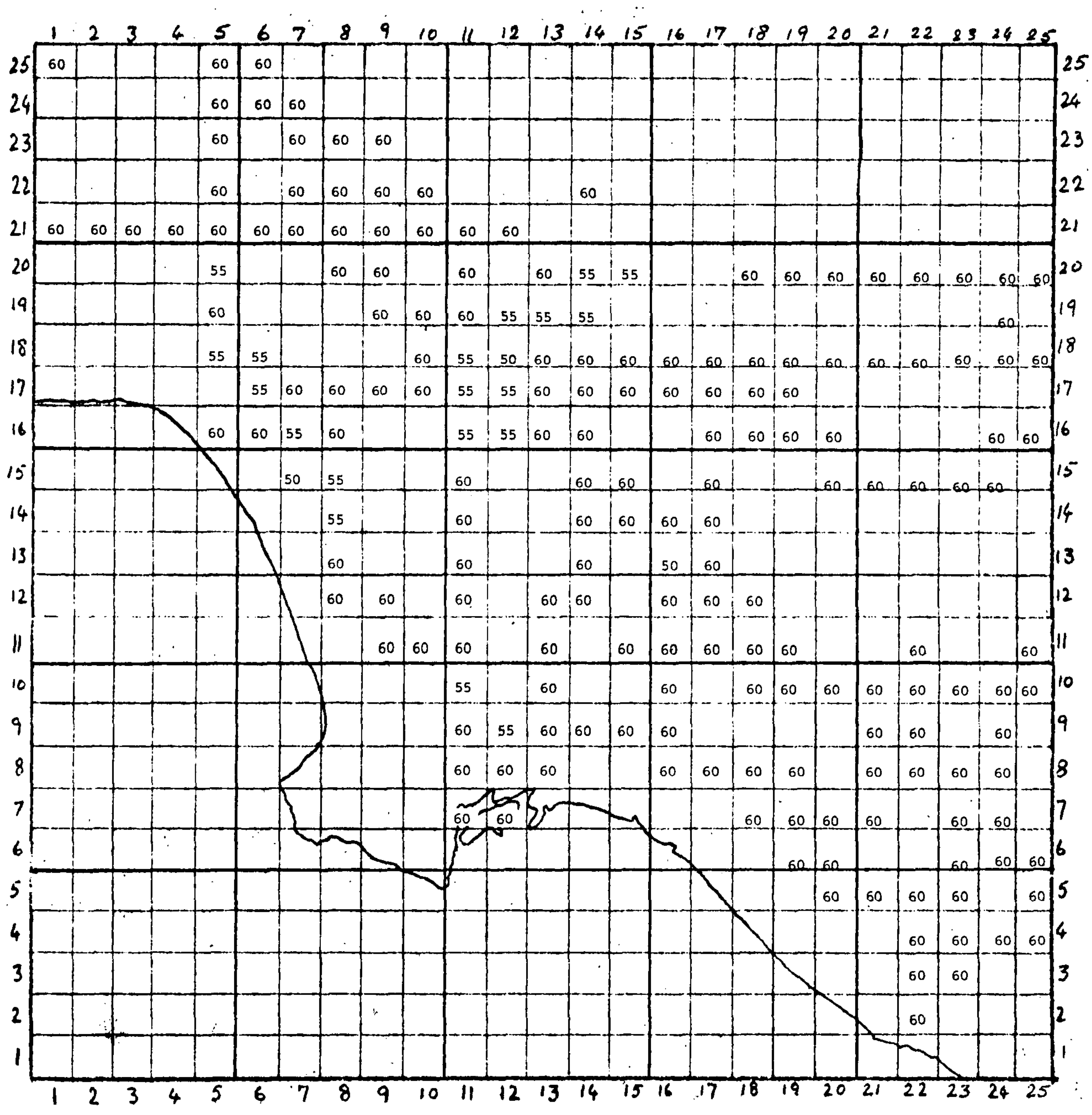


Figure 7. Average Vehicle Speed in "Fast" Direction ($\overline{v}_f$) at 8:00 a.m.

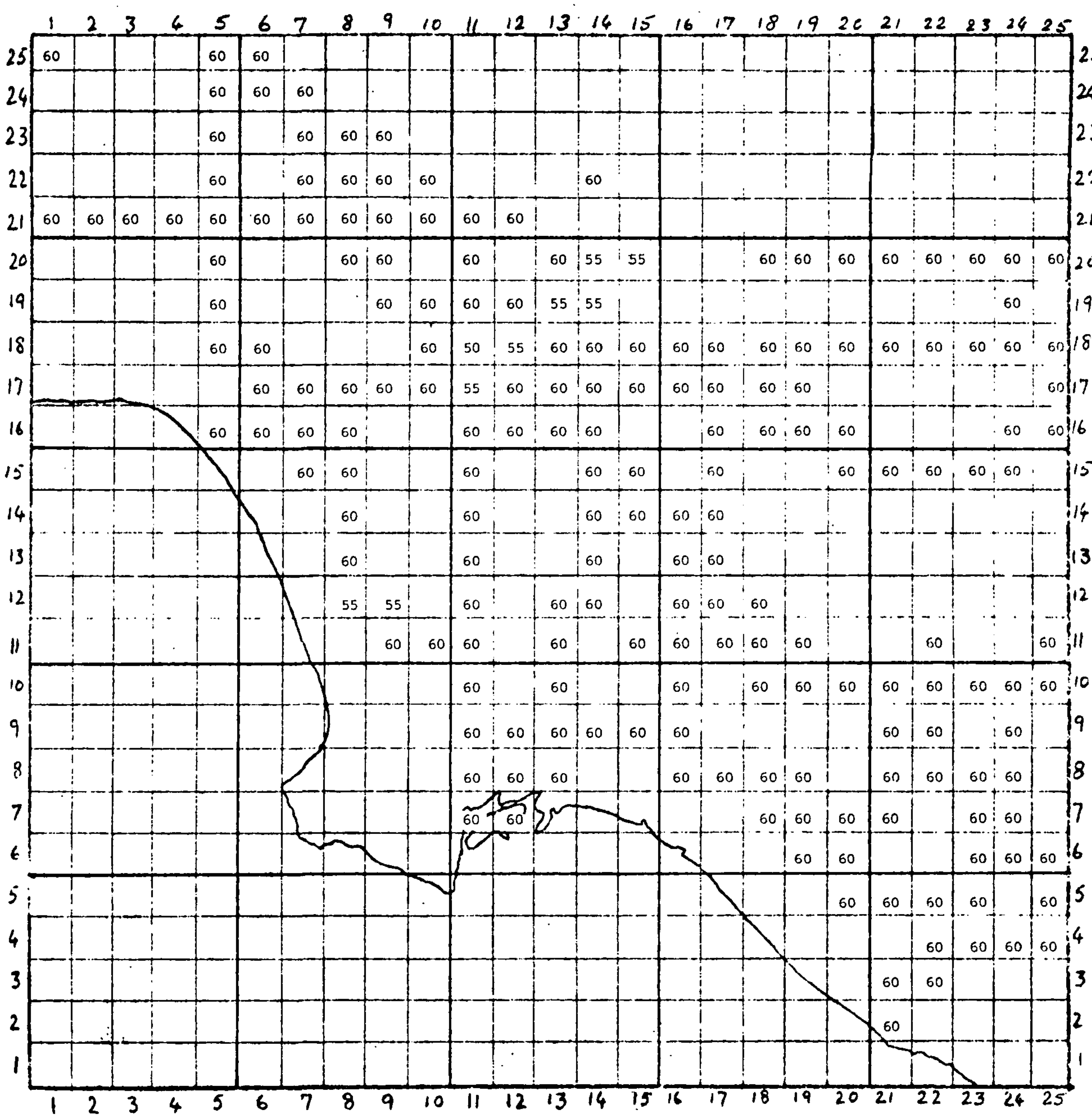


Figure 8. Average Vehicle Speed in "Fast" Direction ($\overline{v}_f$) at 9:00 a.m.

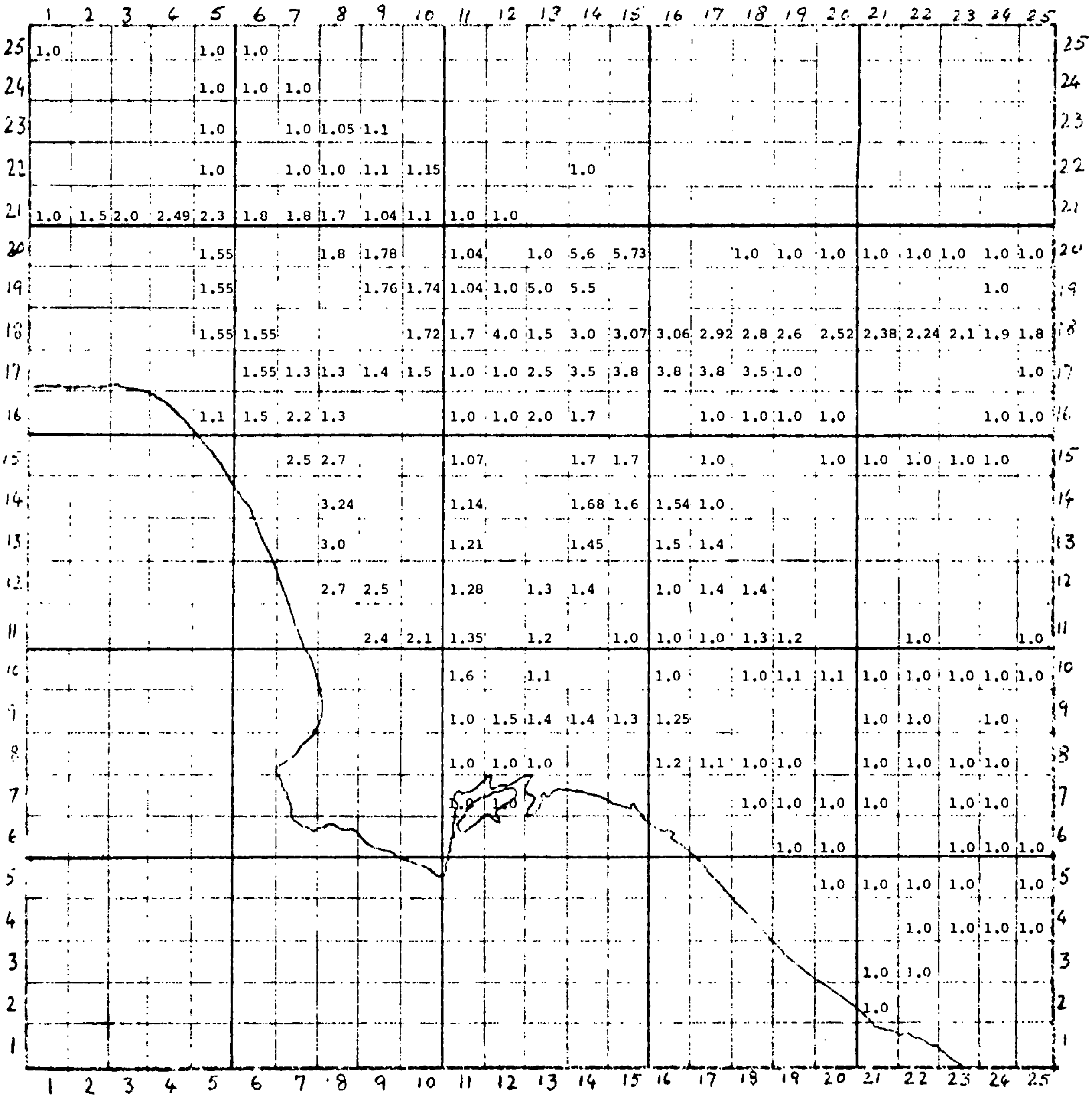


Figure 9. Ratio of Number of Vehicles Traveling in "Slow" Direction to the Number Traveling in "Fast" Direction, x $(= n_s/n_f)$, at 6:00 a.m.

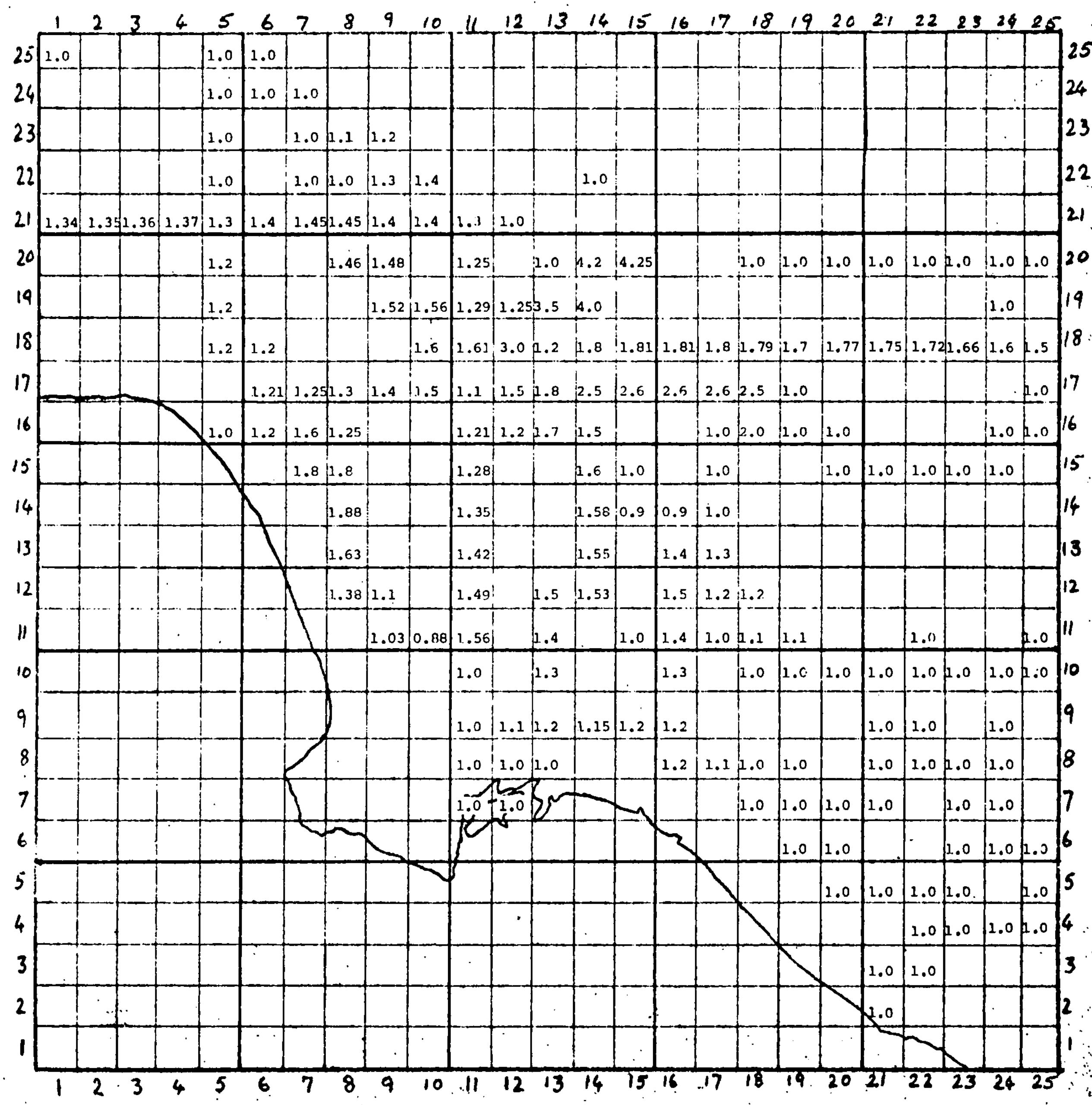


Figure 10. Ratio of Number of Vehicles Traveling in "Slow" Direction to the Number Traveling in "Fast" Direction, x (= n_s/n_f), at 7:00 a.m.

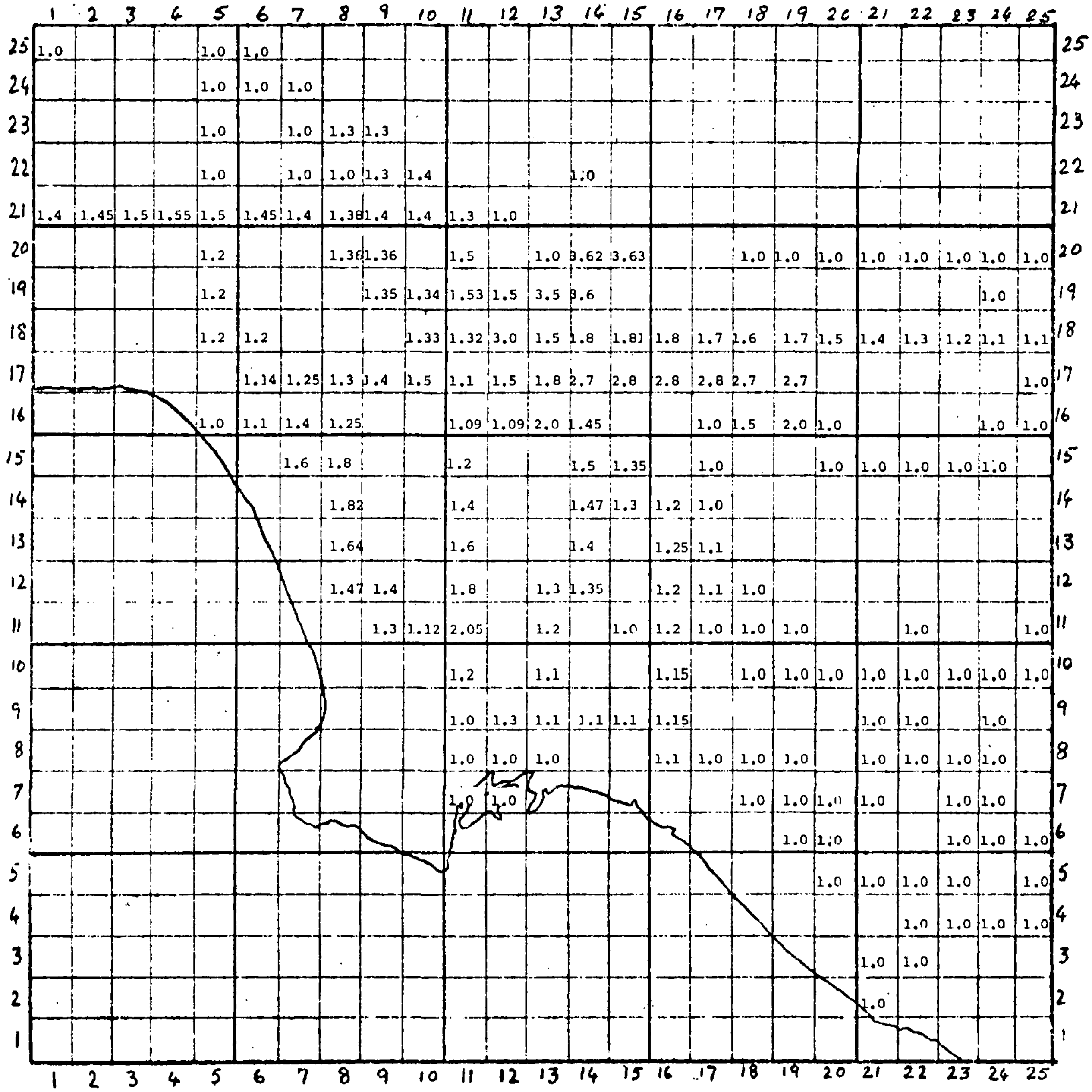


Figure 11. Ratio of Number of Vehicles Traveling in "Slow" Direction to the Number Traveling in "Fast" Direction, x (= n_s/n_f), at 8:00 a.m.

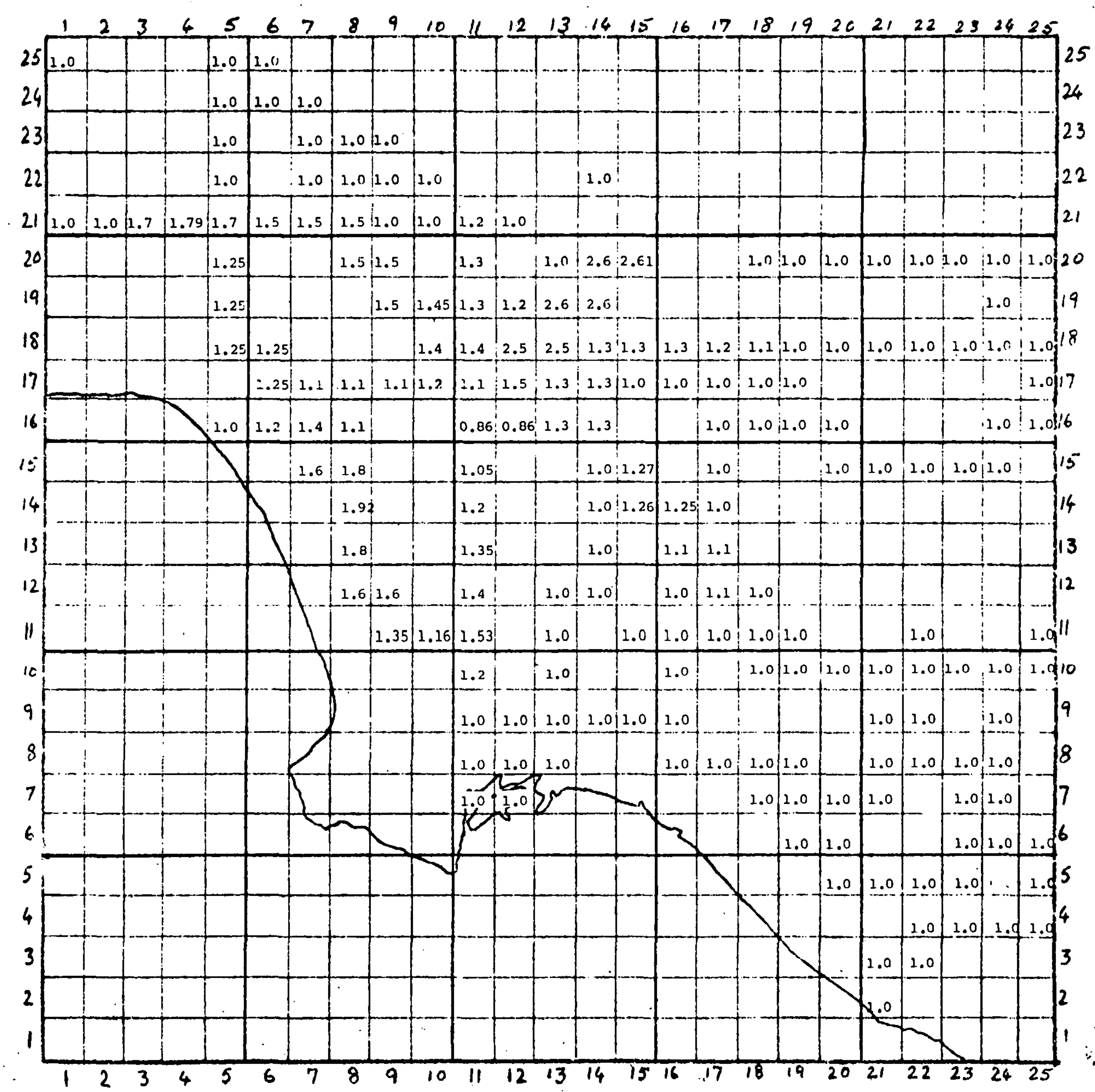


Figure 12. Ratio of Number of Vehicles Traveling in "Slow" Direction to the Number Traveling in "Fast" Direction, x $(=n_s/n_f)$, at 9:00 a.m.

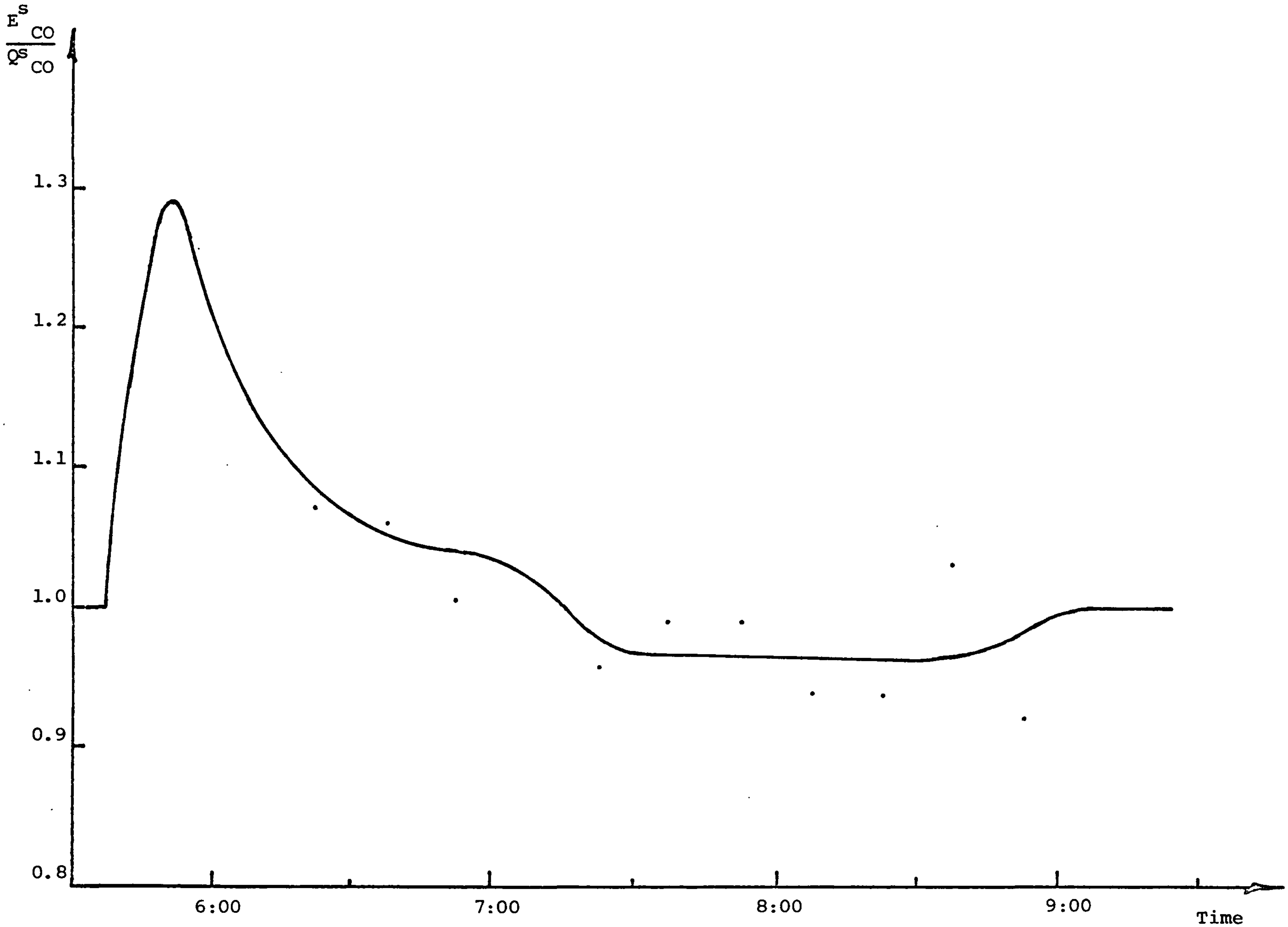


Figure 13. Correction Factor β(t) for Carbon Monoxide

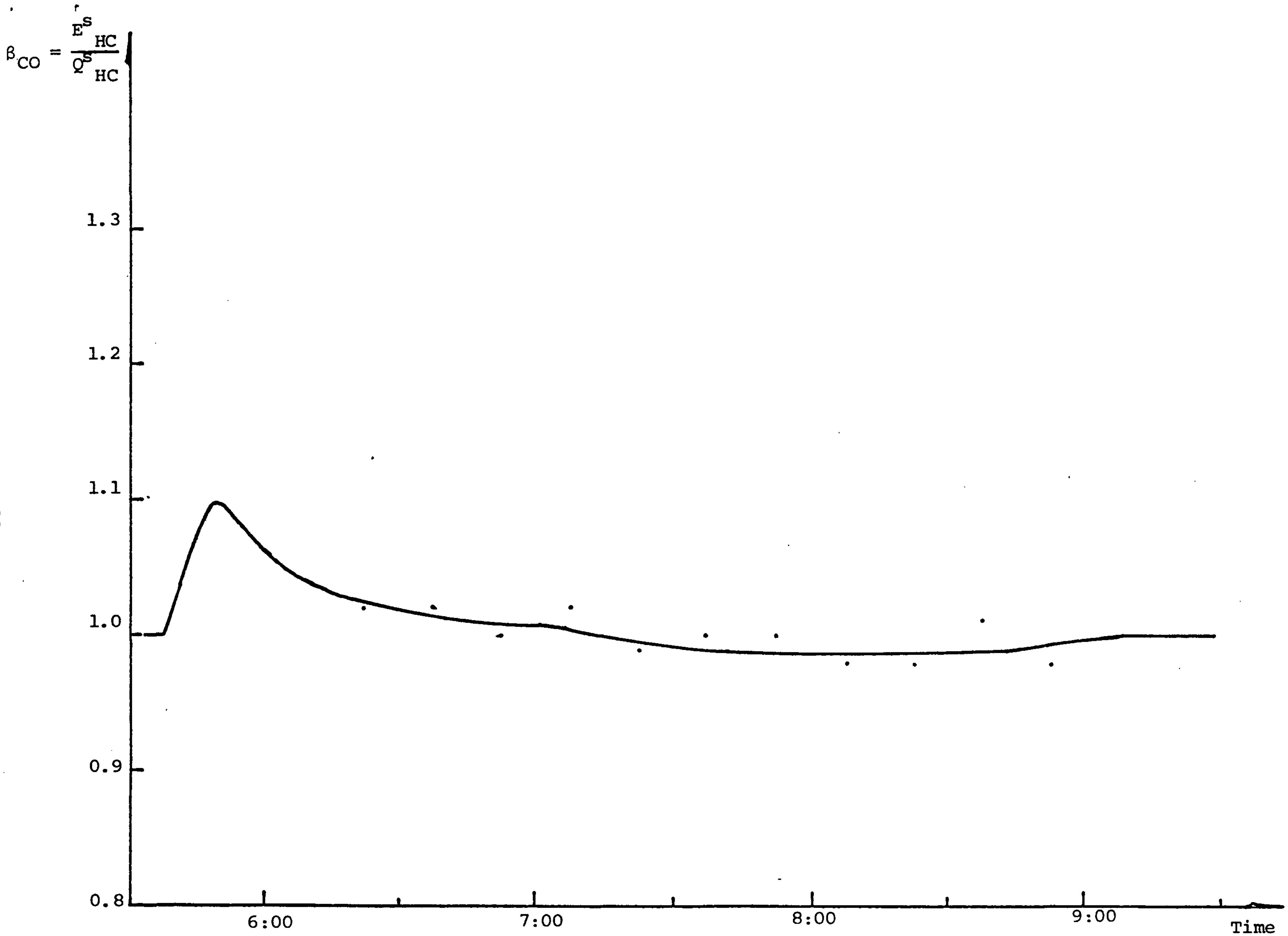


Figure 14. Correction Factor β(t) for Hydrocarbon

B. Discussion of Changes

In this section we present details pertaining to the modifications and extensions outlined.

1. Federal Driving Cycle

Quoting from Roberts et al., p. A-29, "It should be understood that while CDC (California Driving Cycle) emissions factors have been adopted for the current study, we are unable to assess the degree to which the two driving cycles* (or, for that matter, any driving cycle) are representative of actual driving performance in a particular locale. Hence, our figures may be subject to revision as more data become available."

We have very few new data that are pertinent. During the last two years, however, the Federal Driving Cycle (FDC) has come to replace the CDC as the standard emissions test procedure. We have adopted FDC-based factors in conformance with this trend. The new values adopted, with the exception of those for NO_x, have been estimated by the Environmental Protection Agency, as reported on p. A-26 of Roberts et al. (1971). Unfortunately, we are still unable to assess the degree to which these factors represent actual vehicle emissions in Los Angeles.

Establishing an emissions rate for nitrogen oxides was somewhat more involved. In carrying out a series of validation runs for the airshed model, we found to our dismay that NO emissions levels were far too high. In pursuing the possible reasons for the high NO emissions rate, we discovered that the 7.0 grams/mile figure supplied to us by EPA is based on 100% NO_2. As auto emissions are about 99% NO, the rate we have used is too high by a factor of

$$\frac{MW_{NO_2}}{MW_{NO}} = \frac{46}{30} = 1.53$$

---

* Referring to the California and Federal Driving Cycles.

Pursuing this further, we discussed the matter of NO_x emissions from automobiles with Dave Kircher of EPA. Studies carried out by him and his colleagues indicate that the emissions rate of 7.0 grams/mile, as NO_2, is also too high. To correct this, he provided us with newly available data, average emissions rates of NO_x, as measured in vehicle surveillance studies in Los Angeles in December 1971, for model years 1957 through 1971. Using his figures, we calculated the average NO_x emissions rate (as NO_2), as of September 1969, to be 4.16 grams/mile. Expressed as emissions of NO, we have 30/46 x 4.16, or 2.71 grams/mile. Undoubtedly, the fact that these measurements were made in 1971, and not in 1969, biases the result. However, we have not attempted to account for this.

Mr. Kircher also provided us with information which indicates that we had overestimated the methane content of auto emissions. We thus revised our earlier estimates for average molecular weight and fraction reactive, which were based on the distribution of hydrocarbons in auto exhaust reported by Mayrsohn et al. (1969). The figures we have adopted are as follows:

MW (reactive species)	47.8*
MW (unreactive species)	21.1
fraction reactive (mol%)	67.4
fraction unreactive (mol%)	32.6

The data that served as the basis for these calculations were taken from Papa (1967).

In our current vehicle emissions model, freeways and non-freeways (surface streets, including major and minor arterials and residential streets) are treated separately. "Hot-start" emissions factors form the basis for calculating freeway emissions rates, a weighted average of "hot" and "cold-start" factors form the basis for calculating surface street emissions rates. The cold-start emissions factors are those

* We have assumed for the purposes of this inventory that methane, ethane, propane, benzene, and acetylene are unreactive. All other hydrocarbons are assumed to be reactive.

reported by Sigworth (1971). "Hot-running" emissions factors (with the exception of NO_x*) were estimated through the following equation:

$$Q_i^h = Q_i^c \left[\frac{zP_i^h + (1 - z)T_i}{zP_i^c + (1 - z)T_i} \right] \qquad (6)$$

where

z = fraction of automobile vehicle registration (assumed equal to vehicle mileage attributable to automobile traffic) = 0.87

P_i^h, P_i^c = hot-running and cold-start emission rates, as reported by Martinez et al. (1971, p. 8, Table 5). (While the cold-start rates given in this report are less recent, and probably less representative, estimates than those adopted by us, they do permit estimation of *the ratio* of hot-running to cold-start emissions rates. Note that these figures were used to estimate only this ratio.)

T_i = emissions rates from trucks and buses (grams/mile), as reported in Roberts et al. (1971), p. A-26,

and

	CO	HC
P_i^h	82.49	16.81
P_i^c	116.60	18.25
T_i	150.	11.

* Some data indicate that NO_x emissions rates increase as a car warms up; other data indicate that they decrease. Owing to the uncertainty in available data, we have assumed for the present that NO_x emissions rates are invariant with engine operating temperature.

We emphasize that both Q_i^h and Q_i^c are based on the FDC, which is defined to simulate a trip having an average speed of about 19.6 miles/hour. We thus "assume" that vehicles travel at approximately this average speed throughout the day (and throughout the Basin) on surface streets. However, we treat freeway emissions as a function of average speed, which varies both spatially and temporally (see next section).

Finally, we shall mention two relatively minor factors that influence the estimation of non-freeway emissions of CO and hydrocarbons. First, the city traffic department estimates average surface route speeds in Los Angeles to be somewhat higher than the FDC average speed of 19.6 mph. These estimates range from 21 to 23 mph. Compensating for the decrease in emissions rate expected at these higher average speeds is the second factor, the inclusion of vehicle operations in excess of 50 mph in the FDC. If freeway emissions are to be treated separately, it is appropriate to increase average emissions values by removing the "freeway portions" of the cycle and computing a revised average emissions rate. The net effect of introducing these two modifications is to leave the initial value of Q_i^c virtually unchanged, as the effects tend to cancel each other. For this reason, and because the degree of representativeness of the Q_i^c values remains unclear, we elected to ignore these factors in estimating surface street emissions rates.

2. Emissions/Average Speed Correlation

In the original formulation of the vehicle emissions model, we assumed that emissions rates from freeways may be treated as constants, independent of driving conditions and route speeds. A major weakness of this formulation is that it fails to account for both the high emissions rates that occur during the rush hour congestion and the reduced emissions rates associated with higher average speeds. Rose et al. (1965) have shown that, while variations in emissions rates are attributable to factors such as route conditions and the percentage of time in accelerate, decelerate, idle, and cruise modes (these factors being reflected in traffic volume, average route speed, and the nature of the local terrain), average emissions rates for Los Angeles correlate well with average route speed alone. Furthermore, this single index is sufficient to provide estimates of emissions rates. Their correlations are based on a linear relationship between the logarithm of average emissions rates and the logarithm of average route speed. It is on these findings that we have based our correlations.

The following information was required to develop the emissions rate/average speed correlation presented in the summary:

1) The slopes of emissions rate/average speed curves for CO, hydrocarbons and nitrogen oxides. However, as these values are estimated from tests of vehicles of 1955 to 1963 manufacture, we have modified the a_i and b_i in a manner to be described.

2) Average emissions rates for "hot-running" conditions at a known average speed. These rates, reported in the summary, were estimated as described in the preceding section.

3) Average freeway speed as a function of time for both directions on all freeways in the Los Angeles Basin. These data were obtained from the State Division of Highways (Arcineaux (1971)).

4) Average vehicle flow as a function of time for both directions on all freeways. Individual flows were estimated from the data base discussed on p. A-18 of Roberts et al. (1971). Values of x $(= n_s/n_f)$ were computed using these data.

The data under 1) and 2) were needed to estimate emissions rate as a function of average speed, the data under 3) and 4), average speed as a function of location and time.

Emissions/average speed data are very scarce; measurements of this type are rarely made. Thus, while Rose's data are somewhat out of date (less than 50% of the vehicles on the road in September 1969 are represented by this test group), they are the best available that pertain to the period of interest. However, when correlations based on these data are used to estimate average emissions rates at high speeds under hot-running conditions, the estimates appear to be rather low. For example, while the values of 91 and 68.6 grams/mile represent FDC-based average CO emissions rates under cold and hot-running conditions respectively, we predict an average rate of only 26 1/2 grams/mile at 65 mph using a correlation based on Rose's slope ($b_{CO} = -.89$). We thus decided to modify Rose's values for use in the present work.

We have based our modifications on the premise that, since the California and the Federal Driving Cycles have been the standard for testing new emissions control systems, automobile manufacturers design their systems with the expectation that they will be tested at low average speeds (22.2 mph and 19.6 mph respectively for the two test cycles). Thus, contrasting 1963 (the last year of manufacture for Rose's test vehicles, a time during which vehicles were uncontrolled) with the present, it may be expected that average emissions rates at low average speeds have decreased more rapidly, from model year to model year, than average emissions rates at high average speeds. The net effect would be that the b_i values that were estimated for CO and hydrocarbons at the time of Rose's study would increase with each engine or exhaust system modification, becoming less negative with each succeeding year.

We have no data on which to base an estimate of a revised slope. In the absence of appropriate information, we have estimated the slopes b_i reported in the summary using two points, the hot-running emissions rates at 19.6 mph, and the rates at 60 mph, the latter computed from

$$Q_i^h(60) + 1/3[Q_i^h(19.6) - Q_i^h(60)] \qquad (7)$$

where $Q_i^h(19.6)$ are FDC values, modified for "hot-running" conditions, and $Q_i^h(60)$ are the rates computed using Rose's correlation equation and his estimates of slopes. The factor of 1/3 is a guess as to the relative decrease in emissions rates at high and low average speeds. It must be made clear that this factor might be anywhere between 0.1 and 0.5; the value of 1/3 is merely a guess and is certainly subject to revision as data become available.

3. Correction for Nonuniform Distribution of Vehicle Starts

In the original form of our model, we assumed that "hot-running" CDC tests adequately represent vehicle emissions rates. We have now adopted average emissions factors for surface streets, $Q_i^s(t)$, based on a weighted average of "hot" and "cold-running" emissions factors, as shown in equation (1). However, one further modification in the treatment of surface street emissions is required, accounting for the effect on average emissions rates of sudden variations in the number of vehicle starts. We can best illustrate the need for this modification through a simple example.

Let us assume that all vehicles on the road are operated as prescribed by the FDC, namely that they are run for 23 minutes, and that steady-state engine temperature is attained about 8-1/2 minutes after start-up. Emissions from an individual vehicle as a function of time might thus be described as shown in Figure 15. If we further assume (1) that trip starts are distributed uniformly in time, and (2) that all vehicles on the road were "cold" when started, then, at any time, about 100(8.5/23)% , or 37%, of vehicles on the road have not yet achieved steady-state operating temperature. Under these conditions the average emissions for all vehicles is given by the horizontal dotted line in Figure 15.

Suppose now that 10,000 vehicles are currently in operation, under the circumstances stated, in some region of interest. Suppose further that an additional 5000 vehicles are started in the next three minutes (all "cold"). The immediate effect of adding these additional vehicles to the pool of autos in use, each emitting at relatively high rates owing to their "cold" operation, would be to temporarily increase the average emissions of all 15,000 vehicles in operation to a value in excess of that given by the dotted line.

Suppose, however, that we maintain vehicle starts at the increased rate of 5000 starts every three minutes for the next several hours. After about 20 minutes (i.e., 23 minutes less 3 minutes), we would find that we are again terminating trips at the same rate that we are initiating them and that, as before, 37% of vehicles on the road are still in the "warm-up" period. The average emissions rate for all vehicles is once again given by the dotted line, *despite the fact that the total number of cars in operation has increased dramatically.*

Thus, we observe that the effect of suddenly increasing the rate of vehicle starts, and maintaining that rate at a constant level thereafter, is to temporarily increase the fraction of cars in warm-up to a value greater than 0.37. Since vehicles in warm-up emit carbon monoxide and hydrocarbons at a higher rate than do "hot-running" vehicles, the average emissions rate of all cars in operation increases. After sufficient time passes to equalize the rate of start-ups and trip terminations (23 minutes), the original value of average emissions rate again applies.

Figure 15 follows

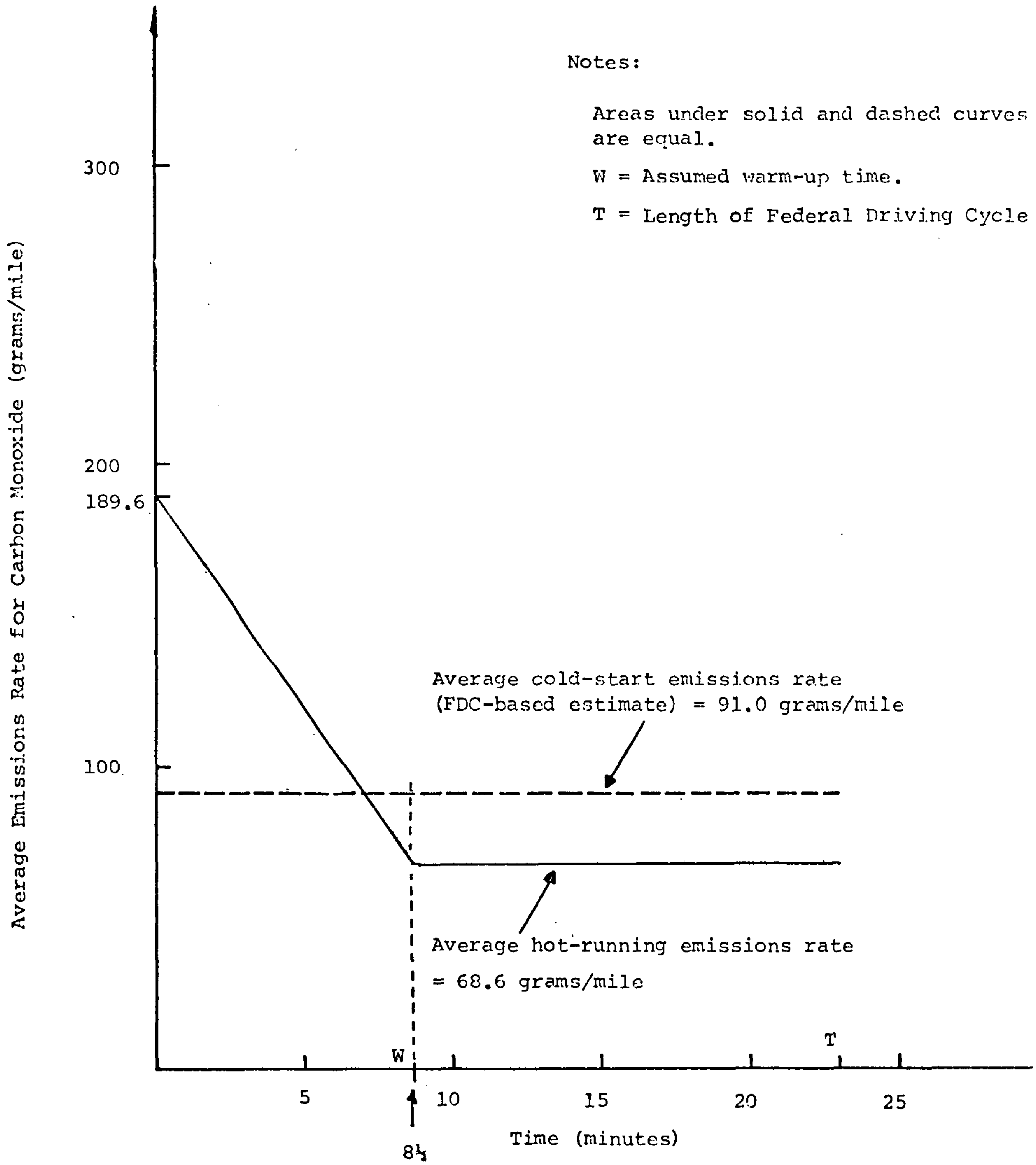


Figure 15. Estimated Variation in Emissions Rate as a Function of Time (Example: Carbon Monoxide)

The phenomenon that this example illustrates, the inducement of variations in average emissions rate due to variations in the rate of vehicle start-ups, is best exemplified during the morning rush hours. The rapidly increasing rate of vehicle starts in the early morning has the effect of increasing average emissions rates until some time when the rate of starts begins to taper off. Soon, more trips will be terminated than initiated and the average emissions rate will drop, not only returning to its original level, but falling *below* that given by the dotted line in Figure 15. Eventually, however, an approximately steady rate of vehicle starts will be attained (immediately following the "rush" period) and the average "dotted line" rate will again apply.

We have accounted for the effects of variations in the rate of vehicle starts through the correction function, $\beta_i(t)$, that appears in equation (5). The curves shown in Figures 13 and 14 describe the variation in $\beta_i(t)$ with time for carbon monoxide and hydrocarbons. The derivation of these functions is detailed in the remainder of this section. However, before turning to this discussion, we wish to note three points. First, since the "hot" and "cold-running" emissions rates for NO_x are assumed to be equal, $\beta_{NO}(t) = 1$ for all t . Second, even though the rate of trip starts varies throughout the day (as may be seen from Table 1, which is reproduced in part in Figure 16), we have considered the effect of these variations only for the period 6 a.m. to 9:23 a.m. We have not included the effect on $\beta_i(t)$ of the "midday bump" in Figure 16, as the majority of vehicles operating during that period are "hot-started"* and the bump is small compared with the rush-hour bumps. Neither have we included the effect of the "evening bump", as we do not plan to validate our model for that time period. Third, it should be evident that, in order to properly evaluate $\beta_i(t)$, large quantities of data are needed. Pertinent data include those involving driving patterns in the Los Angeles area, trip length, average speed, time between trips, etc. Also needed are emissions data as functions of time for both "cold" and "hot-starts". As such data are, for the most part, unavailable, we have based our model on what data we were able to obtain. In the absence of full information, we have made what we believe are reasonable simplifying assumptions in deriving $\beta_i(t)$.

---

* Note that if all vehicles are "hot-running", and there is a sudden increase in vehicle starts (all "hot"), there will be no effect on the average emissions rate. For the effect to be noticeable, a reasonable percentage of vehicle starts must be "cold".

Figure 16 follows

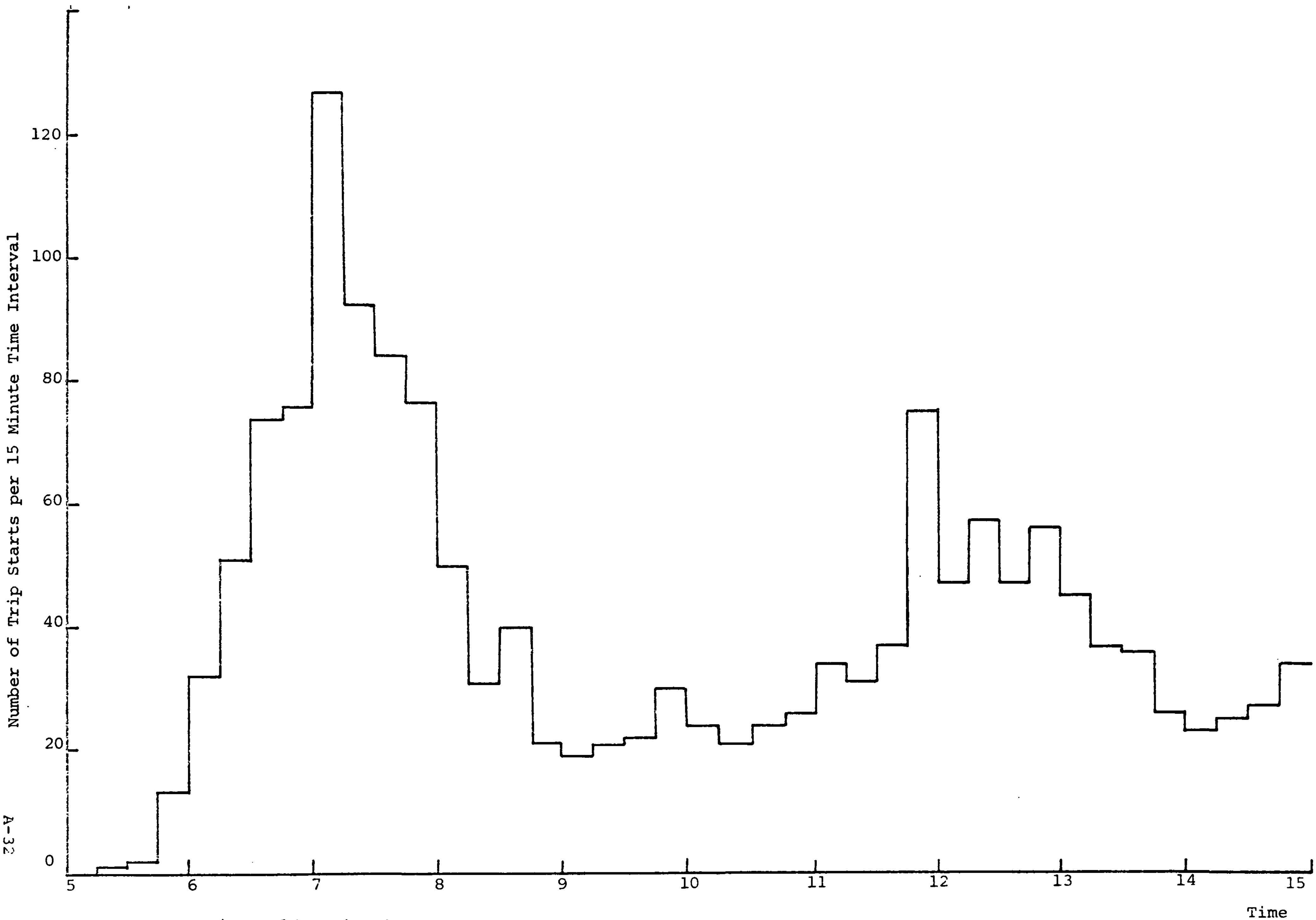


Figure 16. Distribution of Weekday Trip Start Times in Los Angeles (Kearin, et al. (1971))

a. General Mathematical Statement of Problem

The relationship for $\beta_i(t)$ was derived in the following manner: Let

t = time of day

T = length of FDC (minutes)

$c(t)$ = distribution of vehicle trip-start times, such that the number of vehicles started between times t and $t + dt$ equals $c(t)dt$

τ = time elapsed after vehicle start-up (minutes)

$\varepsilon_i^c(\tau)$ = emissions from a vehicle at time τ after a cold-start (grams/mile)

$\varepsilon_i^h(\tau)$ = emissions from a vehicle at time τ after a hot-start (grams/mile)

$y(t)$ = ratio of cold-starts to total starts during time interval dt

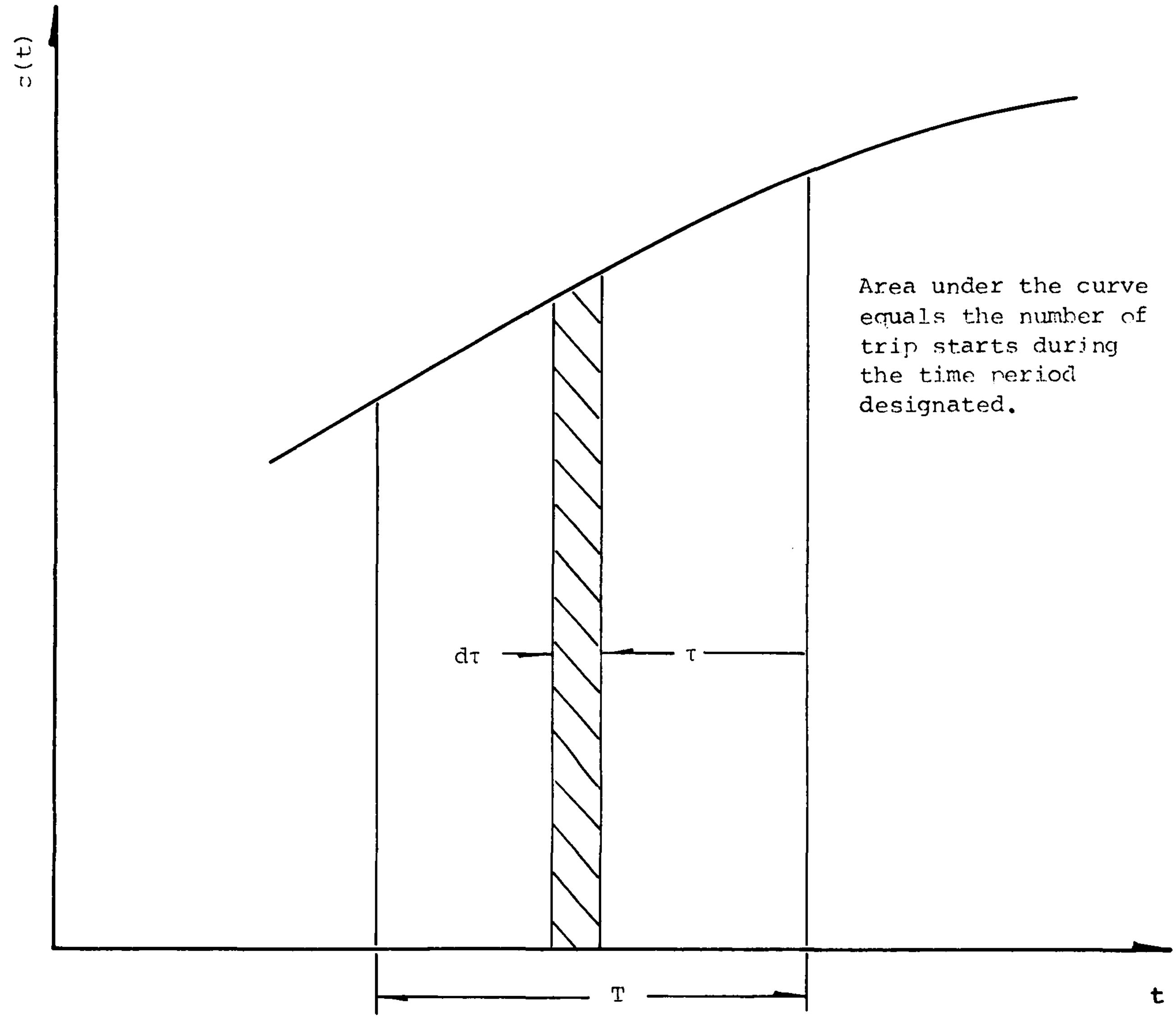
The number of vehicles started between time $t-\tau-d\tau$ and $t-\tau$ is given by $c(t-\tau)d\tau$ (see Figure 17). The emissions rate of species i from a vehicle at time t, cold-started at the time $t-\tau$, is $\varepsilon_i^c(\tau)$. Assuming that the average trip length for all vehicles is T, the total emissions rate of species i at time t is given by

$$\int_0^T [y(t-\tau)\varepsilon_i^c(\tau) + (1-y(t-\tau))\varepsilon_i^h(\tau)]c(t-\tau)d\tau$$

and the average emissions rate from each vehicle by

$$E_i^s(t) = \frac{\int_0^T [y(t-\tau)\varepsilon_i^c(\tau) + (1-y(t-\tau))\varepsilon_i^h(\tau)]\ c(t-\tau)d\tau}{\int_0^T c(t-\tau)d\tau} \qquad (8)$$

Figure 17 follows



c(t) is defined such that the number of trips started between times t and t + dt equals c(t)dt.

T is the length of the Federal Driving Cycle (23 minutes) assumed equal to the average trip length.

τ is a dummy variable of integration but is also equal to the length of time a car has been running at time t which was started at time t-τ.

Figure 17. Explanatory Diagram for Derivation of Equation 8.

The correction factor is then defined as

$$\beta_i(t) = \frac{E_i^s(t)}{Q_i^s(t)} \qquad (9)$$

where $Q_i^s(t)$ is given in equation (1).

b. <u>Evaluation of β_i</u>

In order to integrate equation (8), it is necessary to establish a functional form for $\varepsilon_i^c(\tau)$ and $\varepsilon_i^h(\tau)$. Recent data obtained from the EPA (Sigworth (1972)) show that engine operating temperatures reach steady-state levels about 7-1/2 minutes after a "cold-start". Based on this information, we have assumed that a simple relationship exists between $\varepsilon_i^c(\tau)$ and time, as shown in Figure 15. We have postulated a linear decrease in emissions rate during the first 7-1/2 minutes of operation and a constant emissions rate thereafter. This rate is equal to $\varepsilon_i^h(\tau)$, and, being constant over time is also equal to Q_i^h. The slope of the $\varepsilon_i^c(\tau)$ curve during the warm-up period is calculated by equating the area under the solid line to the average "cold-start" emissions rate, given by the dotted line.

In order to calculate $\beta_i(t)$ for carbon monoxide and hydrocarbons using equations (8) and (9), we also need to know the temporal dependence of $c(t)$. Kearin et al. (1971) recently carried out a survey of average driving patterns for six urban areas in the United States. In their survey, based on a sample of 946 drivers (169 drivers in the Los Angeles area)*, they

* Kearin, et al. note that "...when one considers the number of automobile trips made daily in even the smallest of the cities sampled, it becomes clear that our sample sizes are puny...". Thus, while the statistics employed in this analysis are the most useful available, their reliability is clearly subject to question and they must be used with caution.

Table 1 follows

Table 1.

Distribution of Weekday Trip Start Times in Los Angeles, c_n.

Time period, n		No. of Trips	Time period, n		No. of Trips	Time period, n		No. of Trips
From	To		From	To		From	To	
0001	0015	15	0901	0915	19	1801	1815	69
0016	0030	5	0916	0930	21	1816	1830	78
0031	0045	4	0931	0945	22	1831	1845	74
0046	0100	4	0946	1000	30	1846	1900	66
0101	0115	1	1001	1015	24	1901	1915	58
0116	0130	1	1016	1030	21	1916	1930	62
0131	0145	2	1031	1045	24	1931	1945	63
0146	0200	1	1046	1100	26	1946	2000	52
0201	0215	2	1101	1115	34	2001	2015	50
0216	0230	4	1116	1130	31	2016	2030	53
0231	0245	2	1131	1145	37	2031	2045	58
0246	0300	4	1146	1200	75	2046	2100	51
0301	0315	2	1201	1215	47	2101	2115	22
0316	0330	2	1216	1230	57	2116	2130	31
0331	0345	0	1231	1245	47	2131	2145	21
0346	0400	3	1246	1300	56	2146	2200	35
0401	0415	1	1301	1315	45	2201	2215	21
0416	0430	3	1316	1330	37	2216	2230	17
0431	0445	1	1331	1345	36	2231	2245	14
0446	0500	1	1346	1400	26	2246	2300	9
0501	0515	0	1401	1415	23	2301	2315	16
0516	0530	1	1416	1430	25	2316	2330	10
0531	0545	2	1431	1445	27	2331	2345	11
0546	0600	13	1446	1500	34	2346	0000	7
0601	0615	32	1501	1515	38			
0616	0630	51	1516	1530	44			
0631	0645	74	1531	1545	39			
0646	0700	76	1546	1600	48			
0701	0715	127	1601	1615	45			
0716	0730	92	1616	1630	83			
0731	0745	84	1631	1645	155			
0746	0800	77	1646	1700	128			
0801	0815	50	1701	1715	119			
0816	0830	31	1716	1730	147			
0831	0845	40	1731	1745	105			
0846	0900	21	1746	1800	97			

The calculation of $\beta_i(t)$ was carried out as follows. Let the total number of trips started in the fifteen minute interval denoted by n equal c_n. If we assume the trip start rate to be uniform during each fifteen minute interval, then we can approximate the integral of equation (8) by:

$$E_i^s(t_n) = \frac{\frac{c_{n-2}}{30}\varepsilon_i^h + c_{n-1}\{(1 - y_{n-1})\varepsilon_i^h + y_{n-1}\bar{\varepsilon}_i\} + \frac{c_n}{2}\{1 - y_n)\varepsilon_i^h + y_n\tilde{\varepsilon}_i\}}{\frac{c_{n-2}}{30} + c_{n-1} + \frac{c_n}{2}} \qquad (10)$$

where:

n = denotes a fifteen minute time interval

$E_i^s(t_n)$ = Average emissions rate of species i evaluated at the mid-point of time interval n .

$\bar{\varepsilon}_i$ = Average emissions rate of species i from an automobile over the time period between 7-1/2 and 22-1/2 minutes after a cold-start.

$\tilde{\varepsilon}_i$ = Average emissions rate of species i from an automobile over the time period between zero and 7-1/2 minutes after a cold-start.

Using the emissions factors given earlier we have estimated $\bar{\varepsilon}_i$ and $\tilde{\varepsilon}_i$ as:

Species	$\bar{\varepsilon}_i$ (grams/mile)	$\tilde{\varepsilon}_i$ (grams/mile)
CO	69.1	136.2
HC	10.82	13.52

In using the results of Kearin et al., we elected to segment the weekday into eight time periods, as suggested by the slope of the curve in Figure 16. We assigned to each period a constant value of y , the ratio of cold starts to total starts. These values of y given in Table 2, the values of $Q_i^s(t)$ given in the same table, the emissions curve of Figure 15, and the distribution of vehicle start-ups C_n shown in Figure 16 form the basis for evaluating equation (10) to obtain $\beta_{CO}(t)$ and $\beta_{HC}(t)$. The results of these integrations are given in Figures 13 and 14. Note, again, that $\beta_{NO_x}(t) = 1$, as $Q^h_{NO_x} = Q^c_{NO_x}$.

Table 2 follows

TABLE 2. TEMPORAL DISTRIBUTION OF "COLD-STARTS"

n	Time Period	c_n^* % of daily trips started	y_n fraction of cold starts to total starts	Q_{CO}^{s**}	Q_{HC}^{s**}
				$[= (1-y)Q_i^h + yQ_i^c$ grams/mile]	
1	0:00 - 5:59	2.0	0.90	88.8	11.61
2	6:00 - 8:59	21.0	0.85	87.6	11.57
3	9:00 - 11:29	6.9	0.25	74.2	11.03
4	11:30 - 13:29	10.7	0.30	75.3	11.07
5	13:30 - 16:29	12.1	0.20	73.1	10.98
6	16:30 - 18:29	24.7	0.50	79.8	11.25
7	18:30 - 20:59	16.1	0.15	72.0	10.94
8	21:00 - 23:59	6.5	0.20	73.1	10.98

Note: Kearin, et al. (1971) have estimated that a vehicle in Los Angeles makes an average of 4.66 trips per weekday. Of these 4.66 trips, we have estimated that 2 are "cold-started" and 2.66 are "hot-started". Thus:

$$\sum_{n=1}^{8} y_n c_n = 42.92, \text{ and } \sum_{n=1}^{8} (1-y_n)c_n = 57.08$$

Using the figures from the above table:

$$\sum_{n=1}^{8} y_n c_n \approx 43\%, \text{ and } \sum_{n=1}^{8} (1-y_n)c_n \approx 57\%$$

---

* Estimated from Figure 16.

** These figures should be multipled by $\beta_i(t)$ (Figures 13 and 14) to obtain the surface street emissions factors, $E_i^s(t)$. ($\beta_i(t) = 1$, except for the period 6:00 - 9:23 a.m.)

III. REVISIONS OF THE AIRCRAFT EMISSIONS INVENTORY

Since the completion of the original emissions inventory, the results of two studies dealing with the emissions from aircraft have become available.

(1) Emissions tests of reciprocating aircraft engines were performed recently by Scott Research Labs (1970). Based on their findings, entries in Table A-14 of Roberts et al. (1971), have been updated. Changes are shown in Table 3.

(2) New information involving the average number of jet aircraft flights per day at Los Angeles International Airport has been reported by the Los Angeles APCD (1971). We have correspondingly altered the appropriate statistics in Table A-18 of Roberts et al. (1971), as shown in Table 4.

The change in total emissions from each square as reflected by these alterations is very small; the revisions are made primarily for the sake of completeness and consistency.

Finally, we have assumed, for lack of better information, that aircraft exhaust has approximately the same hydrocarbon composition as automobile exhaust, and thus the same molecular weights for the reactive and unreactive groupings.

The inventory, as reported by Roberts et al. (1971) and herein, should be considered representative of airport and aircraft emissions. However, we note here that we do not include emissions released from elevated sources, i.e., from aircraft during ascent and descent, in the airshed model due to the small contribution of these sources to the total emissions load in cells adjacent to the airports.

Tables 3 and 4 follow

Table 3. Corrections to Table A-14 of Roberts et al. (1971), Emissions Factors, f^k_{gu} and f^k_u (Northern Research (1968))

Aircraft Class	Operating Mode	Emission factors, f^k_{gu} and f^k_u (pounds/1000 pounds of fuel) CO	Organics	NO_x
u = 1	Idle & Taxi	174	75	2.0
	Approach	8.7	16	2.7
	LTC*	0.7	0.1	4.3
2	Idle & Taxi	50	9.6	2.0
	Approach	6.6	1.4	2.7
	LTC	1.2	0.6	4.3
3	Idle & Taxi	118	11.5	2.0
	Approach	11	0.6	2.7
	LTC	4	0.3	4.3
4	Idle & Taxi	24.8	8.1	3.7
	Approach	1.6	0	2.9
	LTC	2.3	3.2	3.1
5	Idle	~~600~~ 896	~~160~~ 32	~~0~~ 7
	Taxi	~~900~~ 910	~~90~~ 43	~~3~~ 2
	Approach	~~800~~ 825	~~60~~ 104	~~5~~ 3
	LTC	1250	190	0
6	Idle	~~600~~ 896	~~160~~ 32	~~0~~ 7
	Taxi	~~900~~ 910	~~90~~ 43	~~3~~ 2
	Approach	~~800~~ 825	~~60~~ 104	~~5~~ 3
	LTC	1050	110	1
7	Idle & Taxi	118	11.5	2.0
	Approach	11	0.6	2.7
	Climb-out	4	0.3	4.3

*Land, Take-Off and Climb-Out

Table 4. Corrections to Table A-18 of Roberts et al. (1971), Average Number of Aircraft Flights Per Day at Los Angeles Basin Airports[1,2]

Airport \ Aircraft Class	1	2	3	4	5	6	7
Brackett	0	0	6(1.5)	0	0	288(1.0)	10(1.0)
Compton	0	0	0	0	0	191(1.0)	0
Culver City	0	0	12[5](1.0)	0	0	21(1.9)	20(1.0)
El Monte	0	0	0	0	0	700(1.0)	0
Hawthorne	0	0	0	0	0	428(1.0)	0
Hollywood/Burbank	0	47(2.5)	19(2.0)	4(2.8)	25(4.0)	225(1.6)	10(1.0)
Long Beach	0	0	2(2.0)	0	67(4.0)	591(1.4)[3]	25(1.0)
Los Alamitos[4]	0	0	300[5](1.0)	0	50(2.0)	0	0
Los Angeles Int'l.	264 ~~331~~(4.0)	249 ~~196~~(2.9)	9(1.0)	57(2.9)	21(3.2)	159(1.4)[3]	58(2.0)
Orange County	0	12(2.0)	0	0	0	850(1.4)[3]	0
San Fernando	0	0	0	0	0	100(1.1)	0
Santa Monica	0	0	3(2.0)	0	0	525(1.1)	25(1.0)
Torrance	0	0	0	0	0	500(1.1)	0
Van Nuys	0	0	25(2.0)	0	14(4.0)	720(1.0)	125(1.0)
Whiteman	0	0	0	0	0	200(1.1)	0

[1] 1968 data.

[2] Numbers in parentheses are average number of engines per aircraft.

[3] Total national average--FAA controlled terminals (Northern Research (1968)).

[4] Airport closed March 1, 1971.

[5] Class 3 activity at this terminal is mostly military aircraft. Military engines are estimated to be equivalent to six Class 3 aircraft engines. Thus, numbers of flights shown are actual flights multiplied by six.

IV. FIXED SOURCE EMISSIONS - POWER PLANTS

We carried out a thorough review of the inventory and model of pollutant emissions from power plants in the Los Angeles Basin. Based in this review, we felt that the emissions model needed both revision and extension, particularly with regard to

- the apportionment of emissions from a power plant among cells downwind of the source
- the inclusion of temporal variations in emissions rates
- the treatment of "inversion penetration"
- the calculation of the average molecular weight of emitted hydrocarbons

The original model and inventory for power plant emissions is discussed in Chapter III of Roberts et al. (1971). We describe only the modifications to that model and inventory in the presentation that follows.

A. Apportionment of Emissions

The original model for apportioning emissions among downwind squares can be summarized as follows:

1. Draw a straight line, beginning at the source, in the downwind direction parallel to the direction of wind flow.

2. Continue the line until it passes through portions of no more than three squares including the square in which the source is located (only two if it passes through a corner).

3. Apportion emissions among the three squares in proportion to the length of the segment passing through each square

See p. A-49 of Roberts et al. (1971) for a full description of the model.

While the model was intended to be simple and therefore could be expected to provide only a rough basis for allocating emissions, it nevertheless displayed a major defect. Under low wind conditions--say, one to two mph--emissions were advected too far and too quickly by the model, thus providing estimates that were too low near the source and too high downwind.

To rectify this flaw in the model, we now apportion power plant emissions in the following manner. The fraction $r_i/(r_1 + r_2 + r_3)$ of power plant emissions is allocated to each of the three downwind grid squares, where

$$r_1 + r_2 + r_3 \leq 3.5 \text{ miles} \tag{11}$$

and

$$r_1 + r_2 + r_3 \leq (60 \text{ minutes}) \times (\text{wind speed in ft./min.}) \tag{12}$$

(See Figure 18a.) If the situation depicted in Figure 18b. occurs, the segment r_4 is ignored, and apportionment is carried out in proportion to the lengths r_1 , r_2 , and r_3 . Note that inequalities (11) and (12) both must apply.

B. Temporal Distribution of Emissions

We found in reviewing data obtained from the Southern California Edison Company, that diurnal temporal variations in NO_x emissions are substantial and must be taken into account in our airshed model. Inclusion of these variations is particularly important in the vicinity of the Pasadena, Burbank, and Haynes plants, as each is located in immediate proximity, and often upwind, of a LAAPCD monitoring station.

After analyzing the Southern California Edison data, we contacted the Los Angeles Department of Water and Power, and the Cities of Pasadena, Burbank, and Glendale to obtain the additional data needed. The data, summarized in Table 5 are of somewhat varying specificity and reliability. Yet, be believe the improvement in accuracy realized by their inclusion far outweighs the inconsistencies introduced--say, by including data for one day in the case of the SCE plants, and data averaged over a season for the remaining plants.

Figure 18 and Table 5 follow

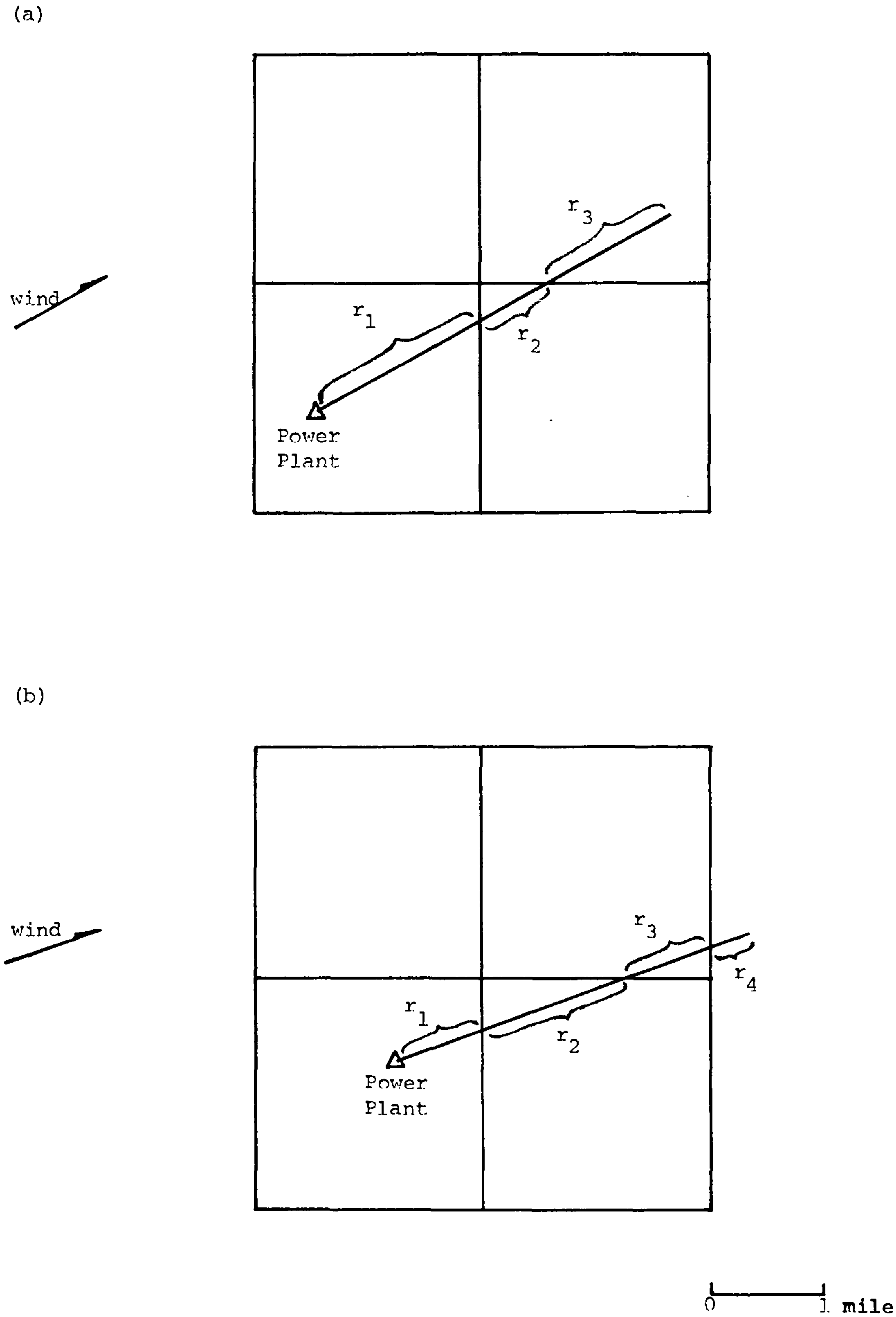


Figure 18. Apportionment of Power Plant Emissions

TABLE 5 - TEMPORAL DISTRIBUTION OF POWER PLANT EMISSIONS

TIME (LOCAL)	5	6	7	8	9	10	11	12	13	14	15	16	REMARKS
Southern Cal. Edison													
Los Alamitos	44.3	48.9	43.7	59.7	78.9	71.3	86.9	100.8	113.0	121.3	123.9	121.7	September 30, 1969
El Segundo	51.4	56.8	52.3	63.2	82.7	79.5	84.1	75.9	96.8	105.9	110.5	108.2	September 30, 1969
Redondo Beach	65.2	77.3	65.6	85.4	94.4	90.8	93.9	90.3	97.5	102.0	106.5	104.3	September 30, 1969
Huntington Beach	38.9	38.9	74.4	82.2	100.0	98.3	98.3	98.3	102.2	102.2	104.4	104.4	September 30, 1969
LA Dept. of Water	59.1	60.5	69.6	81.9	91.3	96.8	100.4	100.8	104.0	104.4	105.1	103.7	Summer
and Power	55.1	62.7	71.0	81.6	85.5	87.0	86.3	86.3	87.4	87.4	85.9	84.1	Winter
City of Pasadena	33.9	33.9	34.8	40.9	51.3	61.3	67.0	70.4	72.2	74.8	76.5	76.1	Summer
	25.7	22.2	29.6	35.7	42.2	47.0	47.8	47.0	46.5	46.5	46.1	45.7	Winter
City of Burbank	44.8	46.6	56.9	70.1	77.6	83.9	88.5	90.2	96.6	97.7	100.6	98.3	Summer
	41.4	47.1	58.0	69.0	71.3	71.8	71.8	69.0	70.1	70.7	67.0	65.5	Winter
City of Glendale	35.9	37.3	42.5	51.0	60.1	68.6	74.5	78.4	81.0	86.3	89.5	91.5	Summer
	32.0	35.9	46.4	55.6	59.5	62.1	62.1	62.1	60.1	60.1	58.8	57.5	Winter

NOTE: The entries are percentages of nominal hourly emission rates estimated in Appendix A. The distribution for the LA Department of Water and Power is the average for their four power plants -- Harbor, Haynes, Scattergood, and Valley -- and, as such, is applied to each.

C. Penetration of the Inversion Layer by a Plume

Oftentimes, during the early morning hours, the base of the inversion overlying the Los Angeles Basin is sufficiently low that it can be penetrated by plumes emenating from tall stacks. In order to include this phenomena in an airshed model, it is necessary to specify the conditions under which penetration will occur.

The maximum height of the base of an elevated inversion above a stack, Δh , that a buoyant plume can penetrate is expressed by

$$\Delta h = 1.128 \left(\frac{Q_H}{u \rho C_p \Delta T_i} \right)^{1/2} \quad \text{(moderate wind)} \qquad (13)$$

where Q_H = heat emissions from the stack

u = average wind speed at the stack height

ρ = average density of ambient air

C_p = specific heat of air at constant pressure

ΔT_i = temperature difference between top and bottom of the elevated inversion

as given by Briggs (1971). For calm conditions Briggs suggests the use of

$$\Delta h = 4 \left(\frac{g Q_H}{\pi \rho c_p T} \right)^{2/5} \left(\frac{g \Delta T_i}{T} \right)^{-3/5} \quad \text{(low wind)} \qquad (14)$$

If $\Delta h + H$ is less than the local mixing depth, where H is the stack height, emissions are apportioned as described in part A of this section. If $\Delta h + H$ is greater than the local mixing depth, emissions are assumed to be injected into or above the inversion layer and are thus not apportioned below the inversion base.

In order to implement these formulae, we need to establish a critical wind speed, u_c, to determine which of these two formulae will apply under specific conditions. To estimate u_c, we have equated ΔT_i in equations (13) and (14),

$$(\Delta T_i)_{\text{moderate wind}} = (\Delta T_i)_{\text{low wind}}$$

By doing thus, we obtain the relationship,

$$u_c \simeq 0.4 \left(\frac{g Q_H}{\pi c_p \rho T Z} \right)^{1/3}$$

where Z is the range of elevation of interest. Hence the following classifications will be made,

$u > u_c$	moderate wind
$u < u_c$	low wind

For a typical power plant in Los Angeles, $Q_H = 10^7$ cal/sec. Assuming that the elevation of the inversion base is 400 ft.,

$$u_c \simeq 1.9 \text{ ft/sec}$$

$$\simeq 1.25 \text{ mph.}$$

D. Calculation of Average Molecular Weight of Emitted Hydrocarbons

Since power plants burned natural gas during the validation period, we have assumed that the molecular weight of unreactive species is between that of C_1 and C_2 hydrocarbons, but much closer to that of C_1 (about 18). For reactive hydrocarbons, we have assumed the molecular weight to lie between that of C_4 and C_5 hydrocarbons, but closer to C_4 (about 60).

V. FIXED SOURCE EMISSIONS - DISTRIBUTED SOURCES AND REFINERIES

We have reviewed the treatment of fixed source emissions rates (from sources other than power plants) and their spatial and temporal distribution, as reported in Roberts et al. (1971). The only source of the data on which the inventory is based is the LAAPCD's published emissions profile, in which only total emissions rates for a 5 mi. x 5 mi. grid are reported. With the exception of hydrocarbon emissions, which we will discuss shortly, we found no reason to alter the treatment of these emissions, given the limitations in accuracy inherent in the inventory due to the spatial "lumping" process. However, it would be most helpful if the APCD would furnish emissions data (locations, rates and temporal distributions) for

(1) large sources, such as steel and aluminum plants

(2) sources located near monitoring stations.

With respect to hydrocarbon emissions from fixed sources, the LAAPCD has classified these as follows:

Unreactive (U) - all paraffins

Reactive (R) - all aromatics, olefins, and acetylenes

We, in contrast, have classified C_1 to C_3 paraffins, benzene, and acetylene as unreactive, all other hydrocarbons as reactive. In order to place hydrocarbons emissions from all sources on the same basis in terms of reactivity, we have re-evaluated previously estimated HC emissions rates from (1) refineries (Tables A-15 and A-16 of Roberts et al. (1971)) and (2) other distributed fixed sources (Tables A-20 and A-21). Emission rates in tons per day from these sources, based on classifications of the APCD (old) and ourselves (new), are given in Table 6. The net result is that entries in the tables in Roberts et al. (1971) must be multiplied by the following factors to convert from the APCD classification system to our classification system:

Figure (in Roberts et al. (1971))	Source	Reactivity	Multiplier
A-15	Refineries	R	5.000
A-16	Refineries	U	0.555
A-20	Petroleum marketing and organic solvents	R	3.233
A-21	Petroleum marketing and production and organic solvents	U	0.355

Finally, since refineries and other fixed sources primarily burned natural gas during the validation period, we have assumed that the molecular weight of unreactive species is the same as that for unreactive hydrocarbons emitted from power plants, i.e., between C_1 and C_2, but much closer to C_1 (about 18), and that of reactive species between C_4 and C_5, but closer to C_4 (about 60).

Table 6 follows

TABLE 6. Hydrocarbon Emissions From Fixed Sources

	Source	Old (APCD)		New (SAI)		Total
		U	R	U	R	
	Refineries	45	5	25	25	50
Other Distributed Fixed Sources	Petroleum Production	60	0	60	0	60
	Petroleum Marketing	60	50	0	110	110
	Solvent Evaporation	400	100	125	375	500
	Total	520	150	185	485	670

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