A Study of

FUNDAMENTAL CHARACTERISTICS OF TRAFFIC FLOW

by

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Highway Traffic Safety Center
and
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Joint Research by
Michigan State University
and
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with participation of
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FOREWORD

This report gives the results of one of two projects which were part of a joint research program by Michigan State University and the Michigan State Highway Department with participation of the U. S. Department of Commerce Bureau of Public Roads. Financial support over three years from Highway Planning Survey funds was made possible by an agreement between the University and the Highway Department and administered by the Michigan State University Highway Traffic Safety Center. In addition to this research in traffic operations, an independent set of studies was carried on simultaneously on Economic and Social Effects of Highway Improvements. These are reported separately.

A Project Advisory Committee for the traffic flow project made advisory suggestions during conduct of the research project.

The Advisory Committee was under the chairmanship of Mr. Harold Bauerle, Director, Traffic Division, Michigan State Highway Department. To him and to the members of the Committee, it is a pleasure to express thanks for their interest and advice with the conduct of the two studies. Members of the Committee were:

Michigan State Highway Department
- Harold Bauerle
- Harry S. Bengry
- Lowell J. Doyle
- Edward F. Gervais

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- Harry Krashen
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- J. Carl McMonagle
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City of Detroit
- A. F. Malo

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FUNDAMENTAL CHARACTERISTICS OF TRAFFIC FLOW

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Synopsis

The objective of this research project was to investigate the fundamental traffic flow characteristics and the interrelationships of these characteristics on various types of heavily traveled major urban arterials.

The design of the experiment assisted in the selection for study of a wide variety of major urban highways ranging from a controlled access expressway to a surface arterial with heavy parking along commercially developed frontage.

At each of the study locations, one continuous week of data was successfully collected. This involved: (1) Detecting traffic volume, speed, and headway information for each individual lane of the direction being studied; (2) transmitting this information to a central office; and (3) summarizing the information on graphical and digital recorders. A number of analyses were performed on the data by manual and mechanical means, and some of the more important results of the analyses are outlined below, in general terms.

The more important findings with regards to traffic volume were the similarities in certain volume characteristics which were found to exist between the seven arterials studied. Ratios, in percentage form, of shorter peak period volumes to longer peak period volumes were computed, and comparisons between routes revealed surprising similarities. Similarities in the cumulative

distribution curves of one-minute traffic volume permitted devising a method for estimating percentile minute volumes for any of the seven routes studied.

The distribution of minute lane volume as related to total minute volume was investigated; and, the equation for average minute volume in the middle lane as a function of the total minute volume for three lanes in one direction, $\overline{V}2 = 0.415\ \overline{V}_t$, was formulated. Approximate confidence intervals for this relationship were computed.

The variation of 15-minute average lane speeds and the distribution of one-minute average lane speeds, for the seven study locations, were determined, and pertinent observations and comparisons were made. By combining lanes and plotting the variation of 15-minute average speeds for each of four of the facilities studied, it was found that during the period from 11 a.m. to 3 p.m. the deviations of individual 15-minute average speeds from 24-hour average speed were extremely small--smaller in fact than the normal accuracy of the speed detection instruments.

Vehicular headway distributions, under various traffic volume conditions, were determined; and, statistical analyses were undertaken in order to compare and summarize the headway distributions. Similar, definite patterns of headway distribution as affected by traffic volume were discovered at the seven study locations.

Speed-volume relationships and density related to other fundamental characteristics, for each lane, of each study location, were developed; and, linear and curvilinear equations were derived for these relationships. Means of estimating maximum volume flow and its related fundamental characteristics are included. The appropriateness of the use of the measurement, traffic density, as an indicator of the operational level of a facility is discussed.

PART ONE

INTRODUCTION

PURPOSE AND SCOPE

EXPERIMENTAL PROCEDURE

I. INTRODUCTION

The fundamental characteristics of traffic flow are volume, speed, density, and headway. These characteristics have been measured many times in the solution of everyday traffic engineering problems. However, a comprehensive determination of the critical values for each characteristic of flow and an understanding of how these variables effect each other has not been fully developed.

The fundamental characteristics are influenced greatly by the four frictions: intersectional, medial, marginal, and internal. Intersectional friction was eliminated in this project by selecting study location at a considerable distance from intersections. How medial and marginal friction affect the fundamental characteristics were important considerations in the research project. Internal friction becomes extremely important on the high density, controlled access facilities. Under low density conditions, internal friction is slight and is not an appreciable problem, but under high density conditions, internal friction may become so great as to completely stagnate traffic movement. Unfortunately, this stagnation occurs when there is the greatest need for the most efficient operation. As a result of this inefficient operation, much research is being conducted.[1,2,3,4].

Since the objectives of the study were to recognize critical values of the fundamental characteristics and the interrelationships of them, most of the analyses performed were based on one-minute intervals. Even during periods of heavy volume, the volume, average speed, and the other fundamental characteristics are quite variable. Periods with very low average speeds and low volume may be very short; and, if speeds are averaged over periods of time such as fifteen minutes, the low speeds are averaged with normal speeds, thus camoflaging the actual extent of the slowdown and resulting in intermediate values which are of little significance. It is felt that the procedure of using one-minute intervals as the basic sampling unit for most of the analyses reduced the probability of errors in interpretation which can be made when highly disperse variables are averaged over longer periods.

II. PURPOSE AND SCOPE

The purpose of this research project is to investigate the fundamental characteristics of traffic flow on urban arterial highways, and to determine their inter-relationships, with special consideration given to a determination of the effects of internal friction and of the effects of roadway features as defined by varying degrees of marginal and medial friction.

This paper presents and discusses the results of the study of the fundamental characteristics flow at study locations on seven major urban arterials. Seven study locations in urban areas were selected and represent facilities with various combinations of marginal and medial frictions. The design of experiment was based on the four friction concept[5,6], which, in essence, classifies road and traffic characteristics which resist traffic flow into four types of friction--internal, medial, marginal, and intersectional. Internal friction, defined as that friction which exists between vehicles moving in the same direction, was present at each of the study locations because of the high traffic volumes at these locations. Intersectional friction, defined as that friction between vehicles moving at right angles to one another, was eliminated by selecting study locations at considerable distances away from the influence of intersectional movement. Various degrees of medial and marginal friction were studied and are illustrated in Figure 1. Three levels of medial friction (no median, narrow median, and wide median) and three levels of marginal friction (heavy parking, no parking, and access control) were included in the design of experiment, resulting in a three by three classification table. One study location was selected for each classification, or cell, with the exception of cells eight and nine. It was anticipated that study locations could be found with these combinations of medial and marginal friction; however, locations on such facilities could not be found which were free from the effects of intersectional friction.

Each study location had the following similar characteristics: level and tangent roadways, urban environment, heavy traffic volumes, absence of intersectional friction, continuity of amount and type of medial and marginal friction some distance upstream and downstream from study locations, minimum driver visibility of survey equipment, multi-laned facilities, and minimum influence due to changing weather conditions.

DESIGN OF EXPERIMENT

MEDIAN FRICTION → / MARGINAL FRICTION ↓	NONE (WIDE MEDIAN)	MODERATE (NARROW MEDIAN)	HEAVY (NO MEDIAN)
NONE (ACCESS CONTROL)	1	2	3
MODERATE (NO PARKING)	4	5	6
HEAVY (PARKING)	7	8	9

NUMERALS REFER TO CELL NUMBERS

FIGURE I

The specific characteristics and phenomena of traffic operations obtained at the seven study locations that are included in this presentation are:

1. Traffic Volume Characteristics

2. Speed Characteristics

3. Vehicular Headway Characteristics

4. Inter-relationships of the Fundamental Characteristics of Traffic Flow.

III. EXPERIMENTAL PROCEDURE

A. Description of Study Locations

Maps showing the major street network and the study locations in the Detroit and East Lansing area are shown in Figures 2 and 3 respectively. A tabulated summary of the geometric design features of the study locations is shown in Figure 4.

The Davison Expressway is the oldest expressway in the Detroit area having been constructed in 1941. The Davison is an east-west expressway, approximately 1.5 miles in length, and located five miles north of the downtown area. The only entrances and exits to this expressway are at the terminal points. A study location was selected on the Davison so as to obtain traffic characteristics for an expressway having a narrow median and representative of the older type expressways. The exact location was thirty feet west of the Woodward Avenue overpass structure and data were obtained for westbound traffic.

The Ford is an east-west expressway approximately eight miles in length, and located two miles north of the downtown area. The geometric design features of the expressway are typical of the more recently built expressways. The study location on the Ford Expressway was at the Lonyo Street overpass and data were obtained for eastbound traffic.

The James Couzens Highway begins at the termination of the Lodge Expressway and runs to Eight Mile Road, a study location on the Couzens Highway because of the heavy parking with no medial friction.

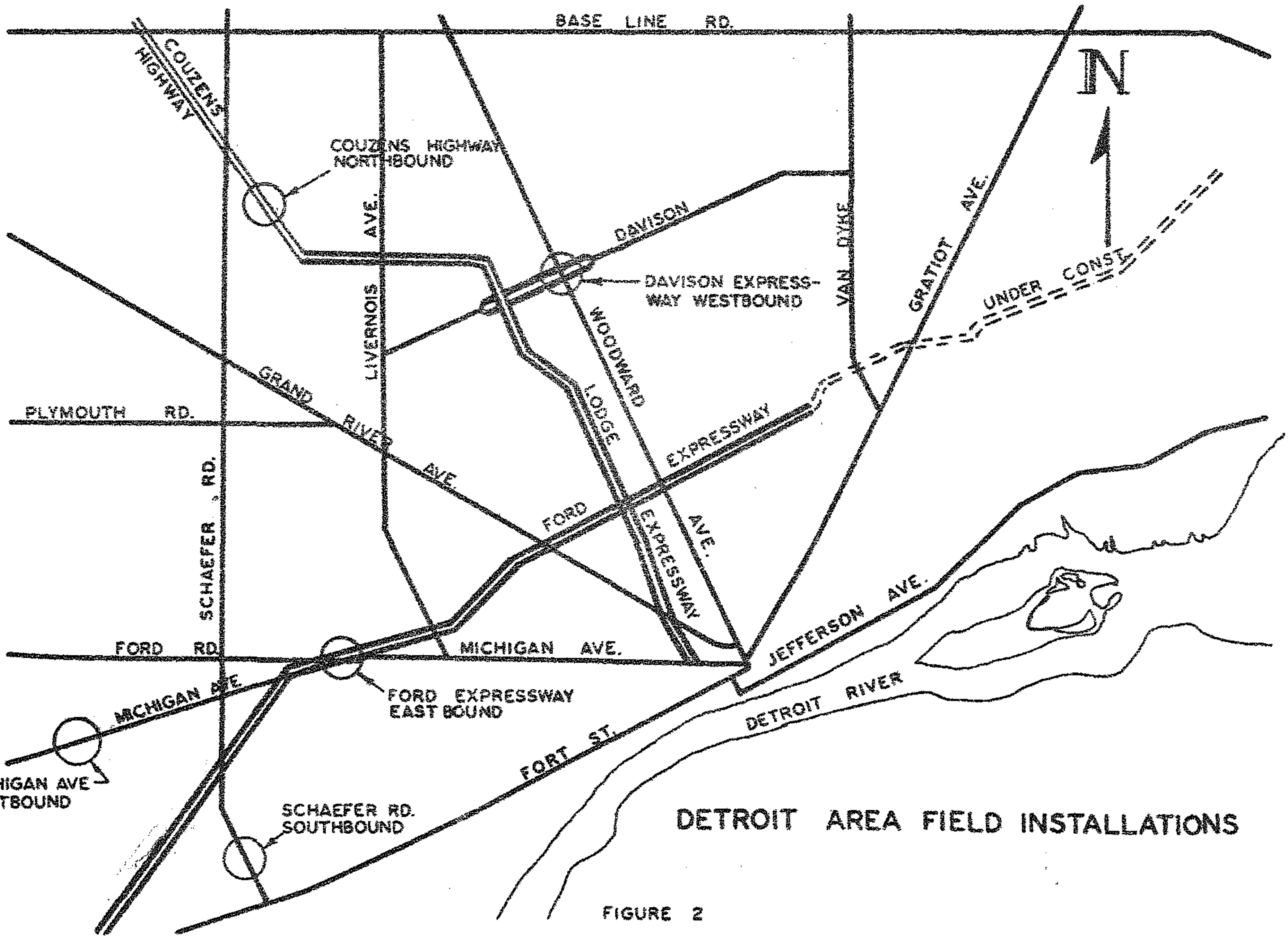
The Michigan Avenue study location was in the city of Dearborn. It represents moderate medial and marginal friction.

The study location at Schaeffer Road was also in the city of Dearborn. It had no median, and, therefore, heavy medial friction, with no marginal friction.

The East Lansing study locations were Michigan Avenue and Grand River Avenue. The Michigan Avenue location had no medial friction with moderate marginal friction. The Grand River location had heavy medial friction and moderate marginal friction.

B. Collection and Processing of Data

The processing of data at the two locations on the Detroit Expressway system has been completed. These two study locations will be discussed in this paper. The procedure used in processing the data for the remaining five study locations will be essentially



DETROIT AREA FIELD INSTALLATIONS

FIGURE 2

EAST LANSING AREA FIELD INSTALLATIONS

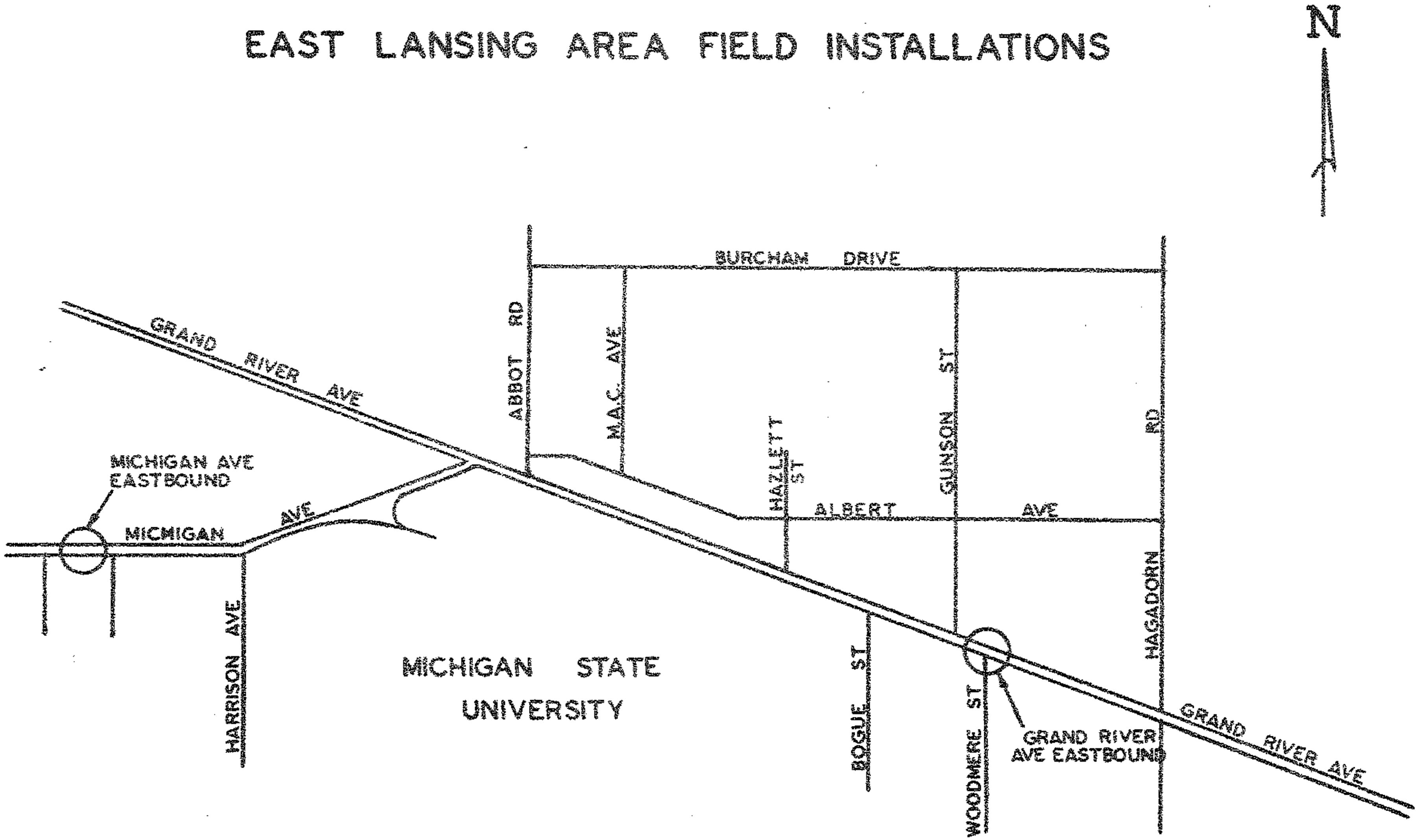


FIGURE 3

FIGURE 4

Geometric Design Features of the Study Locations

Location	Lanes		Type of Edge	Shoulder		Median		Pavement Type & Condition	Speed Limit
	Number	Width		Outer	Inner	Type	Width		
Davison	3	11-11-11	Curb & Gutter	None	None	Raised w/barrier	6'	Concrete Good	45
Ford	3	12-12-12	Curb & Gutter	8' paved	None	Raised w/barrier	12'	Concrete Excellent	40-55
James Couzens	4	11-10-10-10	Curb & Gutter	None	None	Raised	84'	Bit. Con. Good	40
Michigan Ave. (Dearborn)	3	10-10-10	Curb & Gutter	None	None	Raised	4'	Bit. Con. Good	40
Schaeffer Rd.	3	10-10-10	Curb & Gutter	None	None	None	---	Bit. Con. Good	35
Michigan Ave. (Lansing)	3	9-10-9	Curb & Gutter	None	None	Raised	40'	Bit. Con. Good	40
Grand River	2	10-10	Curb & Gutter	None	None	None	---	Bit. Con. Good	35

the same as that used on the Davison and Ford Expressways. The collection and processing of data involved: (1) detecting traffic volume, speed, and headway information; (2) transmitting these characteristics to a central office; (3) summarizing these characteristics on graphical and digital recorders; and (4) analyzing the data manually and mechanically. A radar speed detector and volume detector were installed for each lane at each site to detect speeds of each vehicle, the time headway between each pair of vehicles, and the volume of traffic for any period of time. The above mentioned variables were measured continuously for a period of seven days. The volume detectors were centered over each lane and placed approximately sixteen feet over the pavement. An external sensitivity control was placed in an accessible control box in order to adjust the sensitivity of each volume detector.

The installation of the speed detectors on the Ford Expressway and James Couzens Highway sites differed from the remaining five study locations. The lanes were identified by numbering from left to right when facing in the direction of traffic.* On the Ford Expressway, the speeds of vehicles in lane 2, the middle lane, were obtained by measuring speeds in lanes 2 and 3 combined and subtracting the speeds of vehicles in lane 3. The speed detector for the combined lanes 2 and 3 was placed on the shoulder. For detection of speeds in lane 1, the radar speed meter was placed on the median.

On the James Couzens Highway speeds in lanes 1 and 2 were determined in a manner similar to that mentioned above. One detector, placed on the median, measured speeds in lanes 1 and 2, while another one on the median detected lane 1 alone. The detector for lane 4 was placed on the shoulder. For lane 3, however, a speed meter was placed above the center of the lane and inclined at an angle of approximately twenty degrees, and was calibrated to compensate for the cosine angle error.

For all the remaining sites, speeds on each lane were detected separately with the speed meters placed on the shoulder, median, or on span wires above the lane. Using this technique greatly simplified the analysis of the recorded speed data. Photographs of the installed equipment at the study locations are shown in Figures 5, 6, 7, 8, 9, and 10.

The transmission of speed, volume, and headway characteristics from the study locations were accomplished in different manners. The

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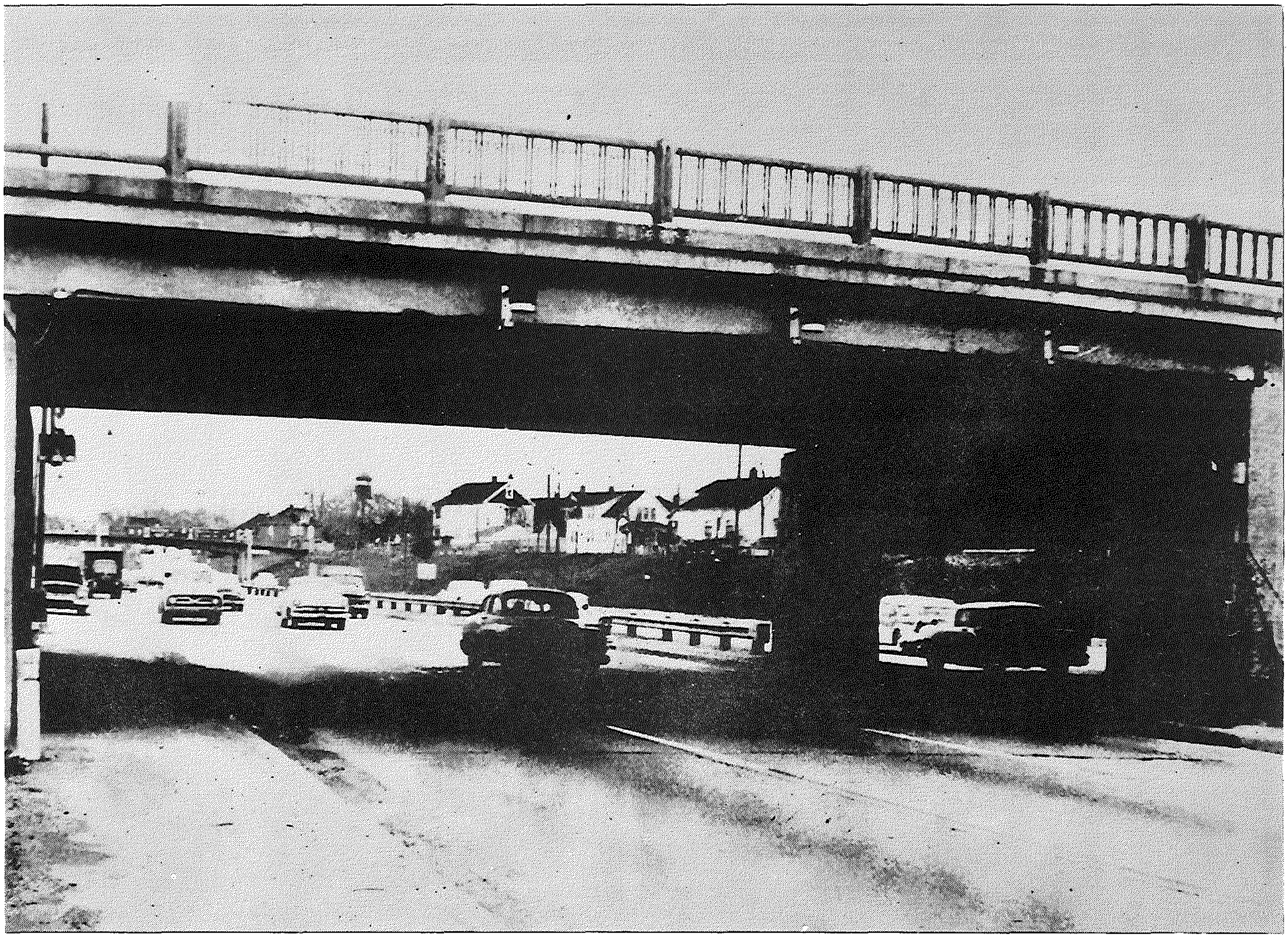
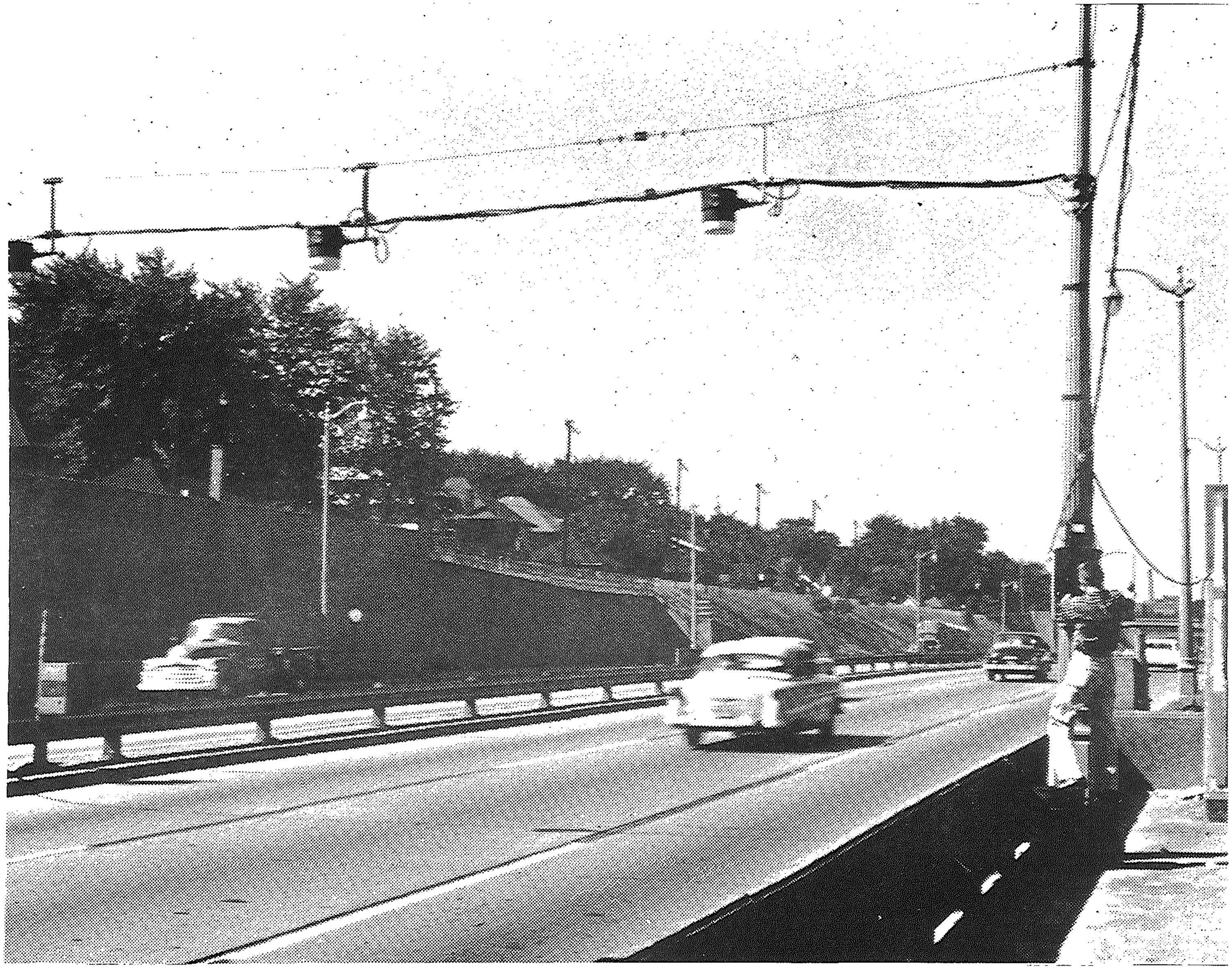
*This lane numbering system is a reversal of that used in the Highway Capacity Manual.



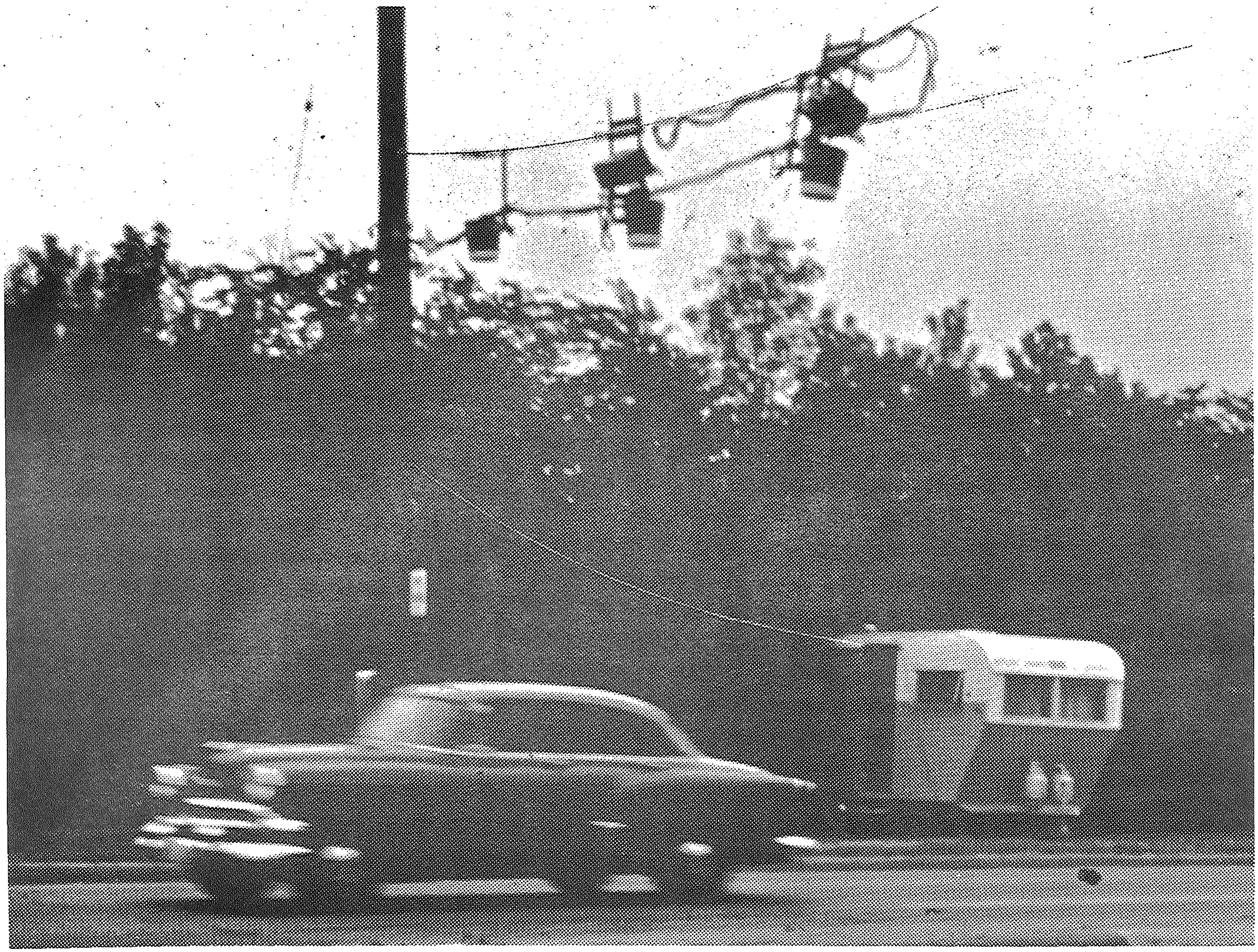
STUDY LOCATION - EASTBOUND EDSEL FORD EXPRESSWAY AT LONYO OVERPASS

FIGURE 5



STUDY LOCATION - WESTBOUND DAVISON EXPRESSWAY AT WOODWARD OVERPASS

FIGURE 6



STUDY LOCATION — EASTBOUND MICHIGAN AVENUE IN DEARBORN

FIGURE 7

STUDY LOCATION – SOUTHBOUND SCHAEFFER ROAD IN DEARBORN

FIGURE 8

STUDY LOCATION — EASTBOUND MICHIGAN AVENUE IN EAST LANSING

FIGURE 9

STUDY LOCATION — EASTBOUND GRAND RIVER AVENUE IN EAST LANSING

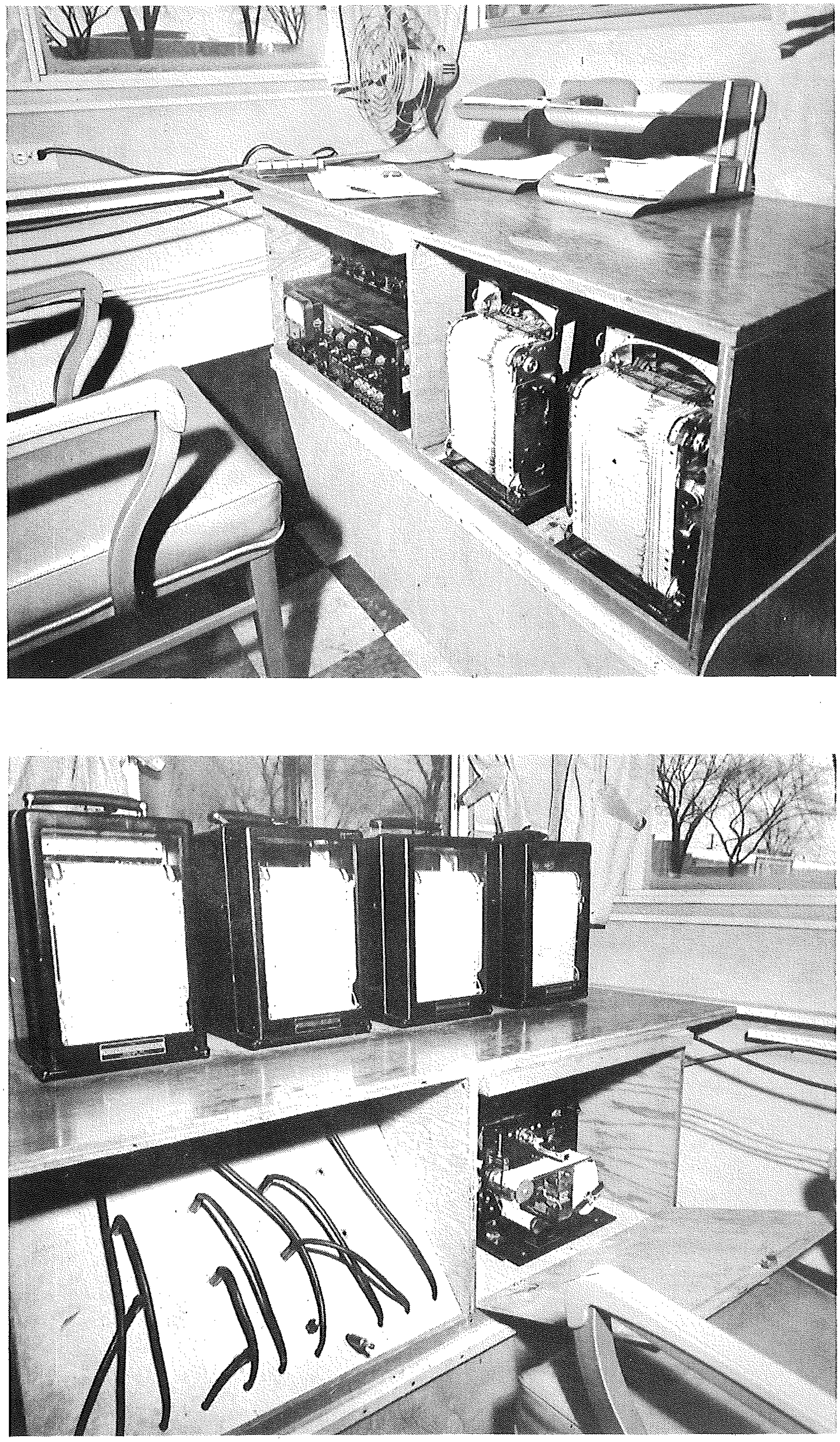
FIGURE 10

transmission of the detected characteristics on the Ford Expressway was provided by using Bell Telephone wires to a central office approximately one and one-half miles away from the study location. Although this method was satisfactory, it was deemed advisable at other sites to locate the central office at the field site in order to facilitate calibration of equipment and for checking the accuracy of the measurements. A seventeen foot trailer was used as a central office at the field site.

The measured characteristics were received at the central office and connected to a master switchboard. From the switchboard the impulses were channeled to their respective recorders. Photographs of the switchboard and recorders are shown in Figure 11. The volume impulses were passed through a relay which permitted two recordings of the same impulse -- one for headway and the other for volume. Headway was recorded on a twenty pen recorder which had four pens operating -- one for each lane and the fourth pen with manual control for daily volume checks. The chart speed of the recorder was six inches per minute which permitted obtaining headways to the nearest quarter of a second. The volume impulses for volume were connected to either a volume-density computer and then a one minute plotting graphical recorder or the impulses were transmitted to a one minute digital recorder. The headway tapes could be utilized for determining volume information for periods less than one minute. The speed impulses were routed directly to speed recorders which were operating at chart speeds of one and one half inches per minute.

A volume and speed check was made each morning and afternoon for each lane when the station was in operation. These checks indicated that the minute volumes were normally accurate to within $\pm$ 0.7% and the minute average speeds were normally accurate to within $\pm$ 1.5 miles per hour. If the minute volumes were in error in excess of $\pm$ 3% or the minute average speeds were in error in excess of $\pm$ 2.0 miles per hour, the detectors were recalibrated until the measured characteristics met the specified accuracy requirements.

The greatest difficulty encountered in this project was the summarization and analyses of data, for this operation was tedious and extremely time consuming. The speed and volume impulses were analyzed for each vehicle by lane, and summarized in one minute, fifteen minute, and one hour intervals for a typical week-day twenty-four hour period. On the Ford Expressway, speed and volume impulses of 49,731 vehicles were recorded and analyzed. On the Davison Expressway speed and volume impulses of 26,699 vehicles were recorded and analyzed. Time headways were analyzed for selected time periods only on the two controlled access facilities.



INTERIOR OF TRAILER SHOWING RECORDING EQUIPMENT

FIGURE 11

PART TWO

VOLUME CHARACTERISTICS

SPEED CHARACTERISTICS

I. VOLUME CHARACTERISTICS

Presented in this section are the results of analyses pertaining to traffic volume characteristics. The presentation is in four parts: (A) Comparison of Various Peak Period Traffic Volumes; (B) Hourly Variations of Traffic Volume; (C) Distribution of Daily Minute Traffic Volumes; and (D) Effect of Traffic Volume on Lane Distribution. Not only the characteristics on each of the seven types of facilities are evaluated, but also the similarity and differences in volume characteristics between the various types are discussed.

A. Comparison of Various Peak Period Traffic Volumes

For each of the seven facilities, the peak one minute, five minute, fifteen minute, and one hour periods were determined. The volume during these periods is shown in Figure 1. The periods indicated are consecutive but do not necessarily start and end on an hour or on an even five minutes. For example, the values shown in the "fifteen minute" row are representative of traffic volume during that consecutive fifteen minute period during which more vehicles were passed than during any other consecutive fifteen minute periods during the day.

Also shown in the figure are the daytime (6 a.m. to 6 p.m.), nighttime (6 p.m. to 6 a.m.), and total 24 hour volumes. Notice the wide range of twenty-four hour volumes--from nearly 50,000 vehicles on the Ford Expressway (Cell 1) to approximately 10,000 vehicles on the two routes in East Lansing (Cells 4 and 6). It is also interesting that Cell 7, the James Couzens Highway, which had heavy marginal friction in the form of parking, carried more traffic during the periods shown than did the Davison Expressway.

In order to determine if patterns exist in the ratios of the volumes between any of the time periods, these ratios, in percentage form, were computed and are tabulated in Figure 2. Shown in the table are the percentages that volumes during the peak periods listed across the top of the table are of the volumes during the peak periods listed along the left side of the table. For example, on the Ford Expressway the peak one minute volume (115) is 23.2 per cent of the peak five minute volume. For each of the comparisons an average percentage for all seven cells was computed. It can be seen that there does not seem to be large variations of the peak volume ratios between routes, and usually the percentage for any given cell differs very little from the average for all cells. This is of greater

FIGURE 1

PEAK PERIOD TRAFFIC VOLUMES

MARGINAL FRICTION	NONE (Access Control)			MODERATE (No Access Control-No Parking)			HEAVY (Parking)
Medial Friction	None (wide median)	Moderate (narrow median)	Heavy (no median)	None (wide median)	Moderate (narrow median)	Heavy (no median)	None (wide median)
Cell Number	#1	#2	#3	#4	#5	#6	#7
Name of Route	Ford Expressway	Davison Expressway	Schaeffer Road	Michigan Ave. East Lansing	Michigan Ave. Dearborn	Grand River E. Lansing	James Couzens Highway
One Minute	115	63	58	27	53	39	84
Five Minute	496	283	159	110	237	157	334
Fifteen Minute	1424	775	351	322	603	437	878
One Hour	5268	2763	1186	1053	2172	1423	3360
Daytime 6 a.m.-6 p.m.	37742	18812	10242	7160	14075	7008	21059
Nighttime 6 p.m.-6 a.m.	11989	7887	4218	3035	4688	3150	10014
Total 24 hour Volume	49731	26699	14460	10195	18763	10158	31073

Figure 2
Percentages That Shorter Peak Period Volumes
are of Longer Peak Period Volumes

	Cell No.	Study Location	One Minute	Five Minute	Fifteen Minute	One Hour	6 a.m. to 6 p.m.	6 p.m. to 6 a.m.
Five Minute	1	Ford	*23.2%					
	2	Davison	22.3					
	3	Schaeffer	36.5					
	4	Mich. Ave.-East Lansing	24.5					
	5	Mich. Ave.-Dearborn	22.4					
	6	Grand River-East Lansing	24.8					
	7	James Couzens	25.1					
		Average	25.5					
Fifteen Minute	1	Ford	8.1	34.8%				
	2	Davison	8.1	36.5				
	3	Schaeffer	16.5	45.3				
	4	Mich. Ave.-East Lansing	8.4	34.2				
	5	Mich. Ave.-Dearborn	8.8	39.3				
	6	Grand River-East Lansing	8.9	35.9				
	7	James Couzens	9.6	38.0				
		Average	9.8	37.7				
One Hour	1	Ford	2.2	9.4	27.0%			
	2	Davison	2.3	10.2	28.0			
	3	Schaeffer	4.9	13.4	29.6			
	4	Mich. Ave.-East Lansing	2.6	10.4	30.6			
	5	Mich. Ave.-Dearborn	2.4	10.9	27.8			
	6	Grand River-East Lansing	2.7	11.0	30.7			
	7	James Couzens	2.5	9.9	26.1			
		Average	2.8	10.7	28.5			
Twenty-four Hour	1	Ford	0.23	1.0	2.4	10.6%	75.9%	24.1%
	2	Davison	0.24	1.1	2.4	10.4	70.5	29.5
	3	Schaeffer	0.40	1.1	2.4	8.2	70.8	29.2
	4	Mich. Ave.-East Lansing	0.26	1.1	3.2	10.3	70.2	29.8
	5	Mich. Ave.-Dearborn	0.28	1.3	3.2	11.6	75.0	25.0
	6	Grand River-East Lansing	0.38	1.5	4.3	14.0	69.0	31.0
	7	James Couzens	0.27	1.1	2.8	10.8	67.8	32.2
		Average	0.29	1.2	2.9	10.8	71.3	28.7

*Example: On the Ford Expressway the peak one minute volume (115) is 23.2 per cent of the peak five minute volume (496).

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significance considering the numerical differences in 24 hour volumes, the wide variety of geometric design features, and the considerable difference in size and character of the areas from which traffic is attracted to the various routes. Another important factor is that two of the routes studied were in East Lansing while the remainder were in the Detroit area.

The ratio of one minute volumes to five minute volumes, and of one and five minute volumes to fifteen minute volumes for Schaeffer Road traffic, is much larger than for the six other routes studied. A detailed review of the minute volumes indicate that the maximum minute volume (58 vehicles) is extremely greater than the second highest minute volume of 41 vehicles. On the other hand the peak five minute volume is relatively small since it includes minute volumes as low as 12 and 13 vehicles per minute. The net result is a high one minute to five minute volume ratio and one minute to fifteen minute volume ratio. The proximity of the Ford Motor River Rouge plant may be partially the reason for the abnormal one minute and five minute peak volume periods.

Although not absolutely true in all cases, it may be generally observed that the higher volume routes (Cells 1, 2, and 7) are characterized by lower percentages in the table. This indicates that on the higher volume routes the demand is spread out over longer periods--that is the peak periods are less accentuated than on the lower volume routes. It is felt, however, that the importance of this presentation lies in the close agreement of the percentages rather than in the explanation of the relatively minor differences.

The practical use of these results is for estimating any of the peak period volumes. By entering the table with any of the listed peak period traffic volumes, any other peak period volume may be estimated.

B. <u>Hourly Variations of Traffic Volume</u>

In order to obtain a pictorial view of the variations of traffic volume during the day in each of the cells, and to compare the cells with each other, a plot was made of hourly volume--as a percentage of 24 hour volume (one direction)--versus time of day. This plot is shown in Figure 3. The hourly variation for each of the seven cells is shown by a different type of line as indicated by the key. Before discussing the variations, it should once again be noted that traffic in one direction only was observed. Consequently, it can be seen that some of the facilities depicted have peak periods during the morning, while others have their peaks during the afternoon. Regardless of this fact, there is

HOURLY TRAFFIC VOLUME FLUCTUATIONS

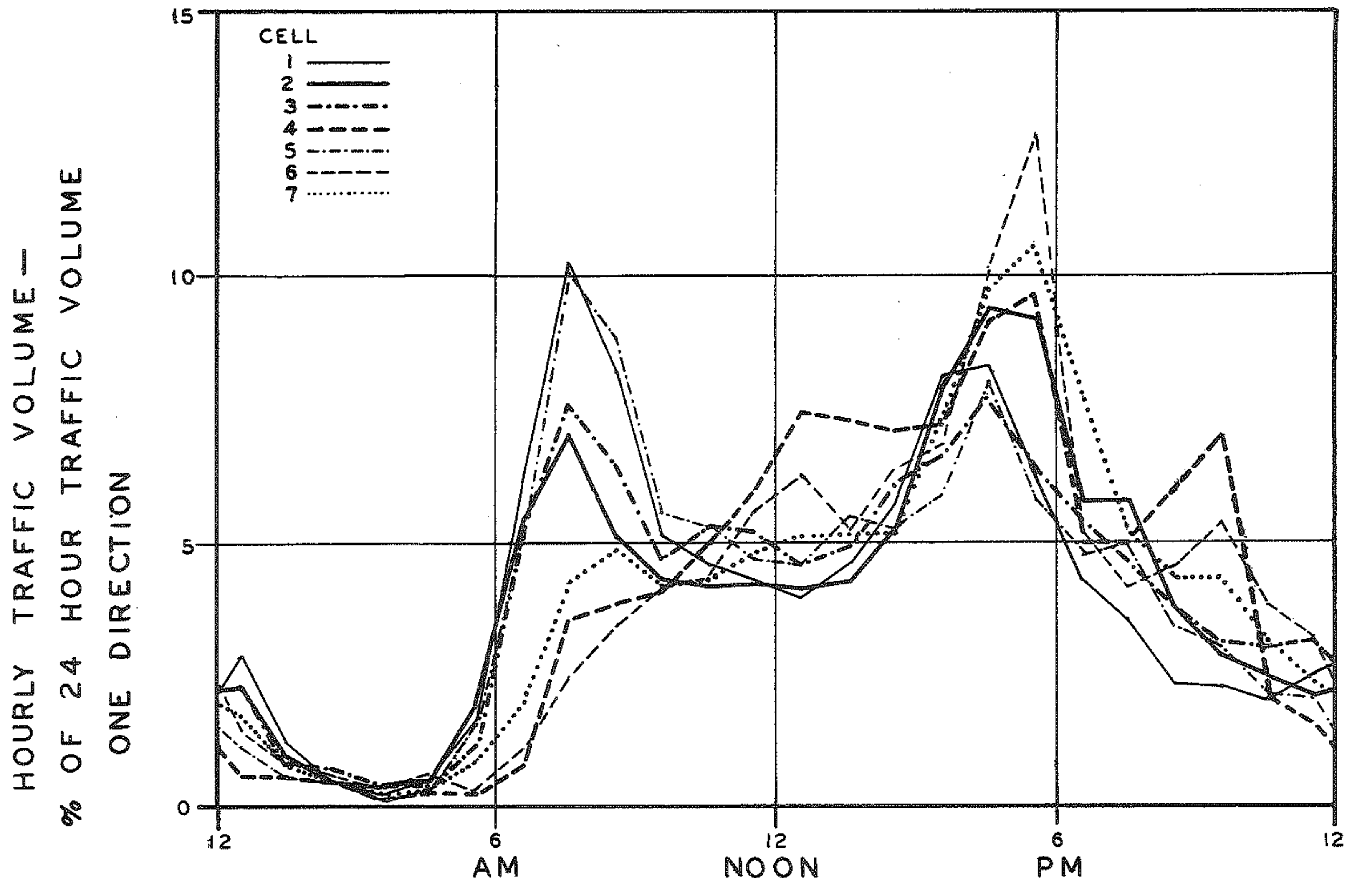


FIGURE 3

recognizable similarity in the traffic volume variations from cell to cell. The cell which seems to deviate farthest from the general pattern is Cell 4 (Michigan Avenue, East Lansing). The hourly volumes during early afternoon, on this facility, are a considerably higher percentage of 24 hour volume than on the other facilities. Notice, also, the sharp evening peak for Cell 4 reaching a maximum of 7.0 per cent of the 24 hour volume between 9 and 10 p.m. Much of the traffic contributing to this peak originated from a nearby shopping center which remained open until 9 p.m.

It can be generally observed in the figure that those routes with comparatively high peaks in the morning had comparatively low peaks during the afternoon, and vice versa. There is nothing startling about this, but the results do follow an expected pattern.

One result which was being sought from this analysis was to determine whether some period during the day was particularly well suited as a volume estimating period. In other words, it would be desirable to select a period when the percentage of the hour volume to the 24 hour volume was relatively uniform for all the cells studied. By inspecting Figure 3 it seems that the most uniform period is from 10 to 11 a.m. For this hour the range of values for the seven cells is from 4.2 to 5.3 per cent of 24 hour volume, and the average value is 4.73 per cent. If then it is desired to make a hour directional volume count and to estimate the 24 hour directional volume, our data indicates that the best period for the short count would be from 10 to 11 a.m. For the data presented, an estimate based upon the 10 to 11 a.m. volume will yield a smaller range of per cent differences from the actual 24 hour volume than will estimates based upon any other one hour period.

The figure also reveals that the peak hour expressed as a percentage of the 24 hour volume for the seven cells was 10.3%, 9.3%, 7.8%, 9.6%, 10.2%, 12.7%, and 10.7%. The hour volumes selected in computing the percentages began on the hour and consequently are slightly lower than similar percentages shown in Figure 2.

C. Distribution of Daily Minute Traffic Volume

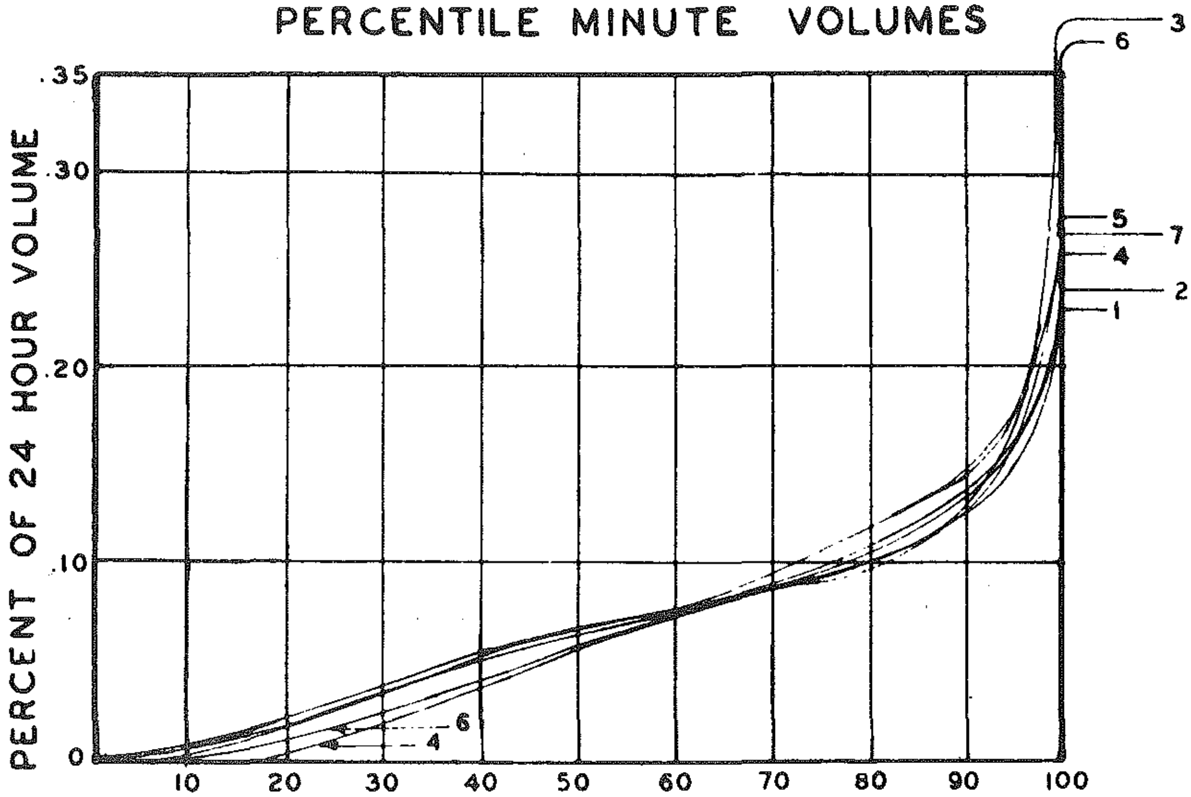
Traffic volume for each minute of the selected 24 hour period was measured; therefore, it was possible to determine the distribution of the minute volumes for each cell. Since volume is more commonly expressed in terms of 24 hours rather than as minute volumes, it was felt desirable, in this case, to do so.

The procedure used was to plot 24 hour percentile minute volume versus the per cent that these minute volumes were of the 24 hour volume. Two such graphs are shown in Figure 4--the upper graph indicating the accumulative minute volume distribution for each of the cells, and the lower graph with an "average" curve representing the distribution of minute volume for all seven cells. It is of significant value to note the high degree of similarity between the cells, and it was for this reason that the average distribution was plotted.

The title of Figure 4, "Method of Estimating Various Percentile Minute Volumes", implies the usefulness of the relationship. That is, by entering the lower graph with any desired percentile minute volume, the per cent that volume is of the 24 hour volume can be determined. As an example, consider a study of traffic flow on an urban arterial highway where the 24 hour traffic volume was determined to be 20,000 vehicles. Suppose it is desired to determine the value of the 24 hour 90 percentile minute volume (that volume which is exceeded by 10 per cent of the minutes during the day and is greater than the remaining 90 per cent of the minutes). Entering the graph with 90 percentile minute volume we find that it is 0.135 per cent of the 24 volume. Hence, the 90 percentile minute volume equals 0.00135 times 20,000 or 27 vehicles per minute. When the per cent that a certain minute is of 24 hour volume is known, the percentile rank of that minute volume can be determined from the graph.

Returning the attention to the upper graph of Figure 4, a number of interesting observations concerning the differences in the accumulated distributions of minute volume can be made. First note that in the middle percentile range the seven distribution curves form a very narrow band. However, the curves spread out considerably in the lower and higher percentile ranges. There does seem to be a pattern in the way in which the curves spread out. First, remember that the two lowest volume routes were Cells 4 and 6 (Michigan Avenue and Grand River in East Lansing respectively), and the three highest routes were Cells 1, 2, and 7 (Ford, Davison, and James Couzens). Then note that in the low percentile ranges the curves for Cells 4 and 6 are lowest; and, in the upper percentile ranges, the Cells 1, 2, and 7 curves are among the lowest four. This indicates that the low 24 hour volume routes have a greater number of minutes whose volumes are a small percentage of 24 hour volume than do the higher 24 hour volume routes. The 95 to 100 percentile minute volumes on the high volume routes are not generally as large a per cent of the 24 hour volume as on the lower volume routes. More simply stated, it was generally the case on the routes studied that the lower volume routes had a higher number

METHOD OF ESTIMATING VARIOUS PERCENTILE MINUTE VOLUMES



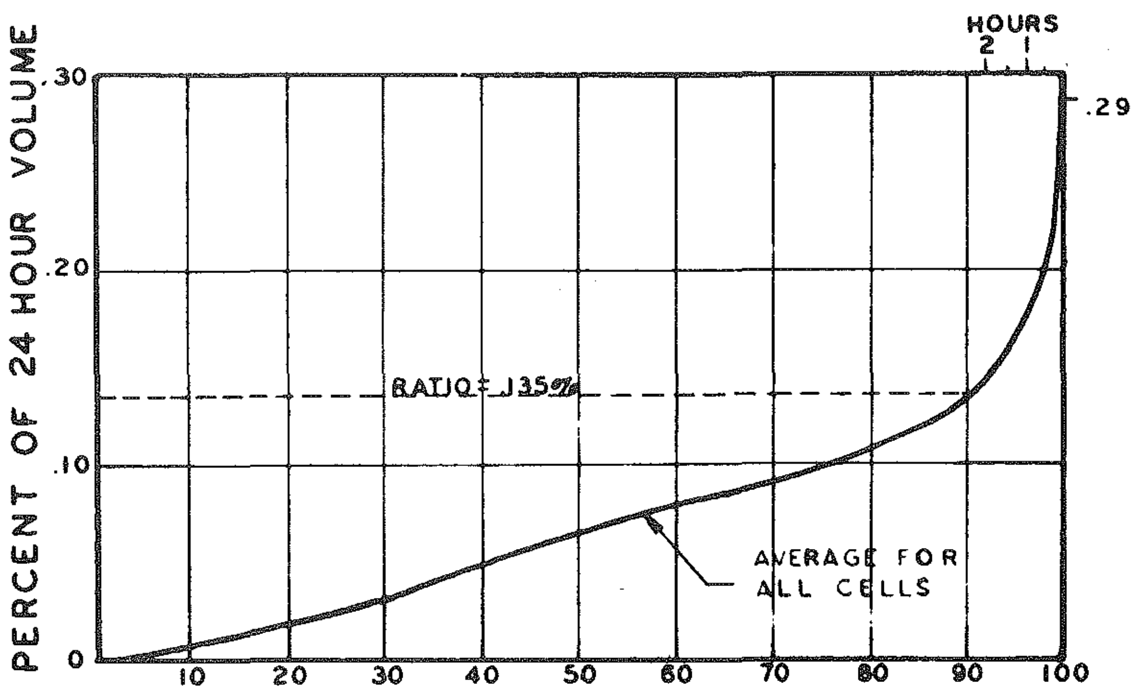


FIGURE 4

of low minute volumes and also had relatively larger peak minute volumes. This observation reinforces the statements and observations made earlier in Part A. The 100 percentile minute volumes are the same as that indicated in Figure 2 relating the peak minute to the 24 hour volume.

An analysis was made in order to determine where each distribution curve departs from the approximately linear path that it follows in the lower percentile ranges. It is felt that this point demarks what can be considered as the separation between peak minute volumes and non-peak minute volumes. Finding this point on each of the curves then was a matter of determining the point following which an increased rate of change (or slope) occurs. The rate of change is determined on the basis of the ratio of vertical to horizontal rate of growth

$$\left(\frac{\Delta V}{\Delta H}\right)$$

which is the tangent of the angle between the curve segment and the horizontal axis. In order to determine the point following which a rapid increase in slope is noticeable, attention was also given to the rate of change of this ratio. Based on both of these considerations, the points were found after which a departure from the linear rate of growth occurs, and these are listed below.

Cell	Cumulative Percentage
1 - Ford Expressway	84
2 - Davison Expressway	82
3 - Schaeffer	92
4 - Michigan (East Lansing)	88
5 - Michigan (Dearborn)	89
6 - Grand River (East Lansing)	82
7 - James Couzens	80
Average	85.3

The 85.3 per cent indicates that the peak minute volumes extend for about three hours and thirty-two minutes. Again we can notice the fair degree of similarity between cells with regard to the location of this point. This analysis also indicates that, generally speaking, the peak periods last longer on the high volume routes (Cells 1, 2, and 7) than on the lower volume routes.

There also seems to be a point higher up on each of the distribution curves where another rapid rate of change of slope occurs and the curves become nearly perpendicular. Using the same technique, the following points were found after which the most rapid rate of change occurs:

Cell	Cumulative Percentage
1 - Ford Expressway	98.9
2 - Davison Expressway	97.6
3 - Schaeffer	99.4
4 - Michigan (East Lansing)	98.9
5 - Michigan (Dearborn)	98.0
6 - Grand River (East Lansing)	98.4
7 - James Couzens	95.6
Average	98.1

The 98.1 per cent indicates that this minute volume level is exceeded approximately 27 minutes per day. These percentiles are analogous to the thirtieth highest hourly volume in that they have a possible use as design volumes. It is economically unfeasible to design the road so that it will have sufficient capacity during every single minute. It can be seen on the lower graph of Figure 4 that 98 percentile corresponds to a minute volume which is approximately 0.20 per cent of 24 hour volume. The 100 percentile minute volume is approximately 0.29 per cent of 24 hour volume. Consequently, if the road is to satisfy the requirements of the highest 2 percentile of the 24 hour period (in other words the highest 29 minutes), it must be designed to carry nearly 50 per cent more traffic.

D. The Effect of Traffic Volume On Lane Distribution

For an analysis of the relationship between total volume and lane usage for each of the cells, the graphs shown in Figures 5 and 6 were constructed. On each of the graphs the vertical scale is lane minute volume, and the horizontal scale is total minute volume. There is one graph for each cell, with the exception of Cell 7, the James Couzens Highway, which is depicted in two graphs--one for the normal periods when there are three moving traffic lanes, and one for the period from 4 to 7 p.m. when parking is prohibited and there are four moving traffic lanes. The graphs are constructed in such a way that a point on a curve represents the average minute lane volume for a given total minute volume.

A definite pattern exists between lane usage and traffic volume and can be seen from Figures 5 and 6. In each of the seven graphs, beginning with the lowest minute volume and proceeding to the largest minute volume, there is an apparent interplay

LANE USAGE ON TEST ROUTES

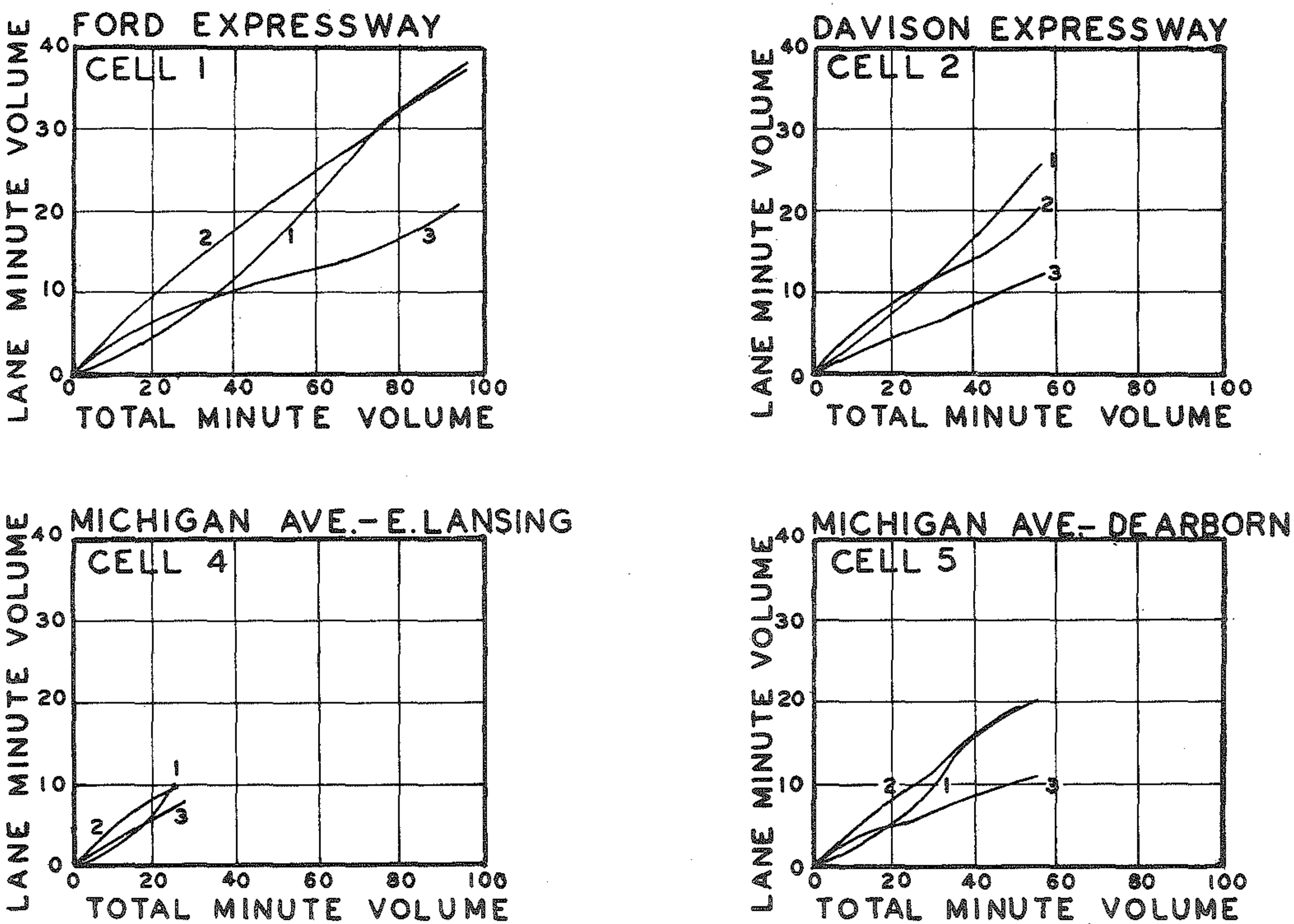


FIGURE 5

LANE USAGE ON TEST ROUTES

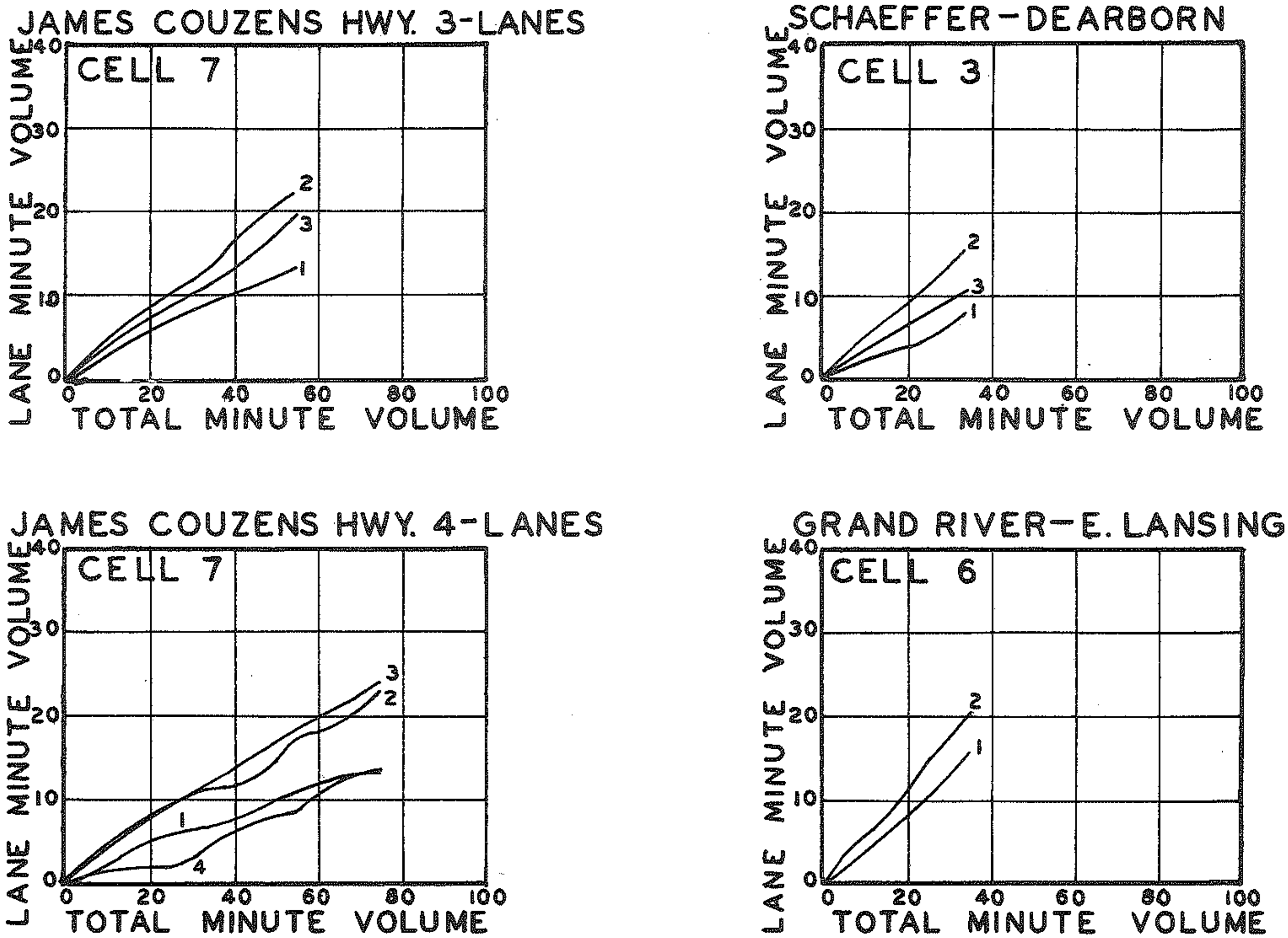


FIGURE 6

between the usage of the lanes. First, lane 2 (middle lane) carries the greatest lane volume with lane 3 (curb lane) carrying the second highest lane volume. As the minute volume increases lane 2 continues to carry the highest lane volume, while the usage of lane 1 increases faster than lane 3, and in several of the cells lane 1 begins to exceed lane 3. At the highest minute volume ranges the volumes in lane 1 approach or, in several cases, exceeds the volume in lane 2 while the volume in lane 3 is approximately only one-half as great as in either lanes 1 or 2.

There are two additional observations that can be made in regards to the general pattern of volume distribution between lanes: (1) For any total minute volume, the average minute volume in lane 3 is never greatest; and (2) for any total minute volume, the average minute volume in lane 2 is never smallest. Another factor which is apparent in Figure 5 is that when total volume is high, lane 3 is carrying a considerably lower volume than either of the other two lanes. In other words, when it is really needed, the lane next to the shoulder is not carrying its share of the load.

To be able to better compare cells with each other, the curves were plotted in a slightly different manner as is shown in Figure 7. Each lane was plotted separately so that we have three graphs, and the lane volume curve for the cells is shown on each graph. Cell 6 (Grand River in East Lansing) was omitted in this case because it has only two lanes in the direction studied, whereas all the other cells had three lanes.

Note the very narrow band formed by the cell curves in the lane 2 graph, and also that the slopes of the curves are relatively constant. The lane 3 and particularly lane 1 curves, however, are decidedly more spread out and have more fluctuating slopes. Because of the close agreement of the lane 2 curves, a statistical analysis was performed to determine an average line for all six cells.

The average volume for lane 2 of all six cells under scrutiny, and for total minute volumes varying from 0 to 60, is represented by a nearly straight line. The equation

$$\overline{\overline{V}}_2 = 0.415\ V_t$$

representing a straight line passing through the origin closely approximates the values determined from the collected data. The constant 0.415 implies that 41.5 per cent of the total minute volume utilizes lane 2.

COMPARISON OF LANE USAGE BY LANE

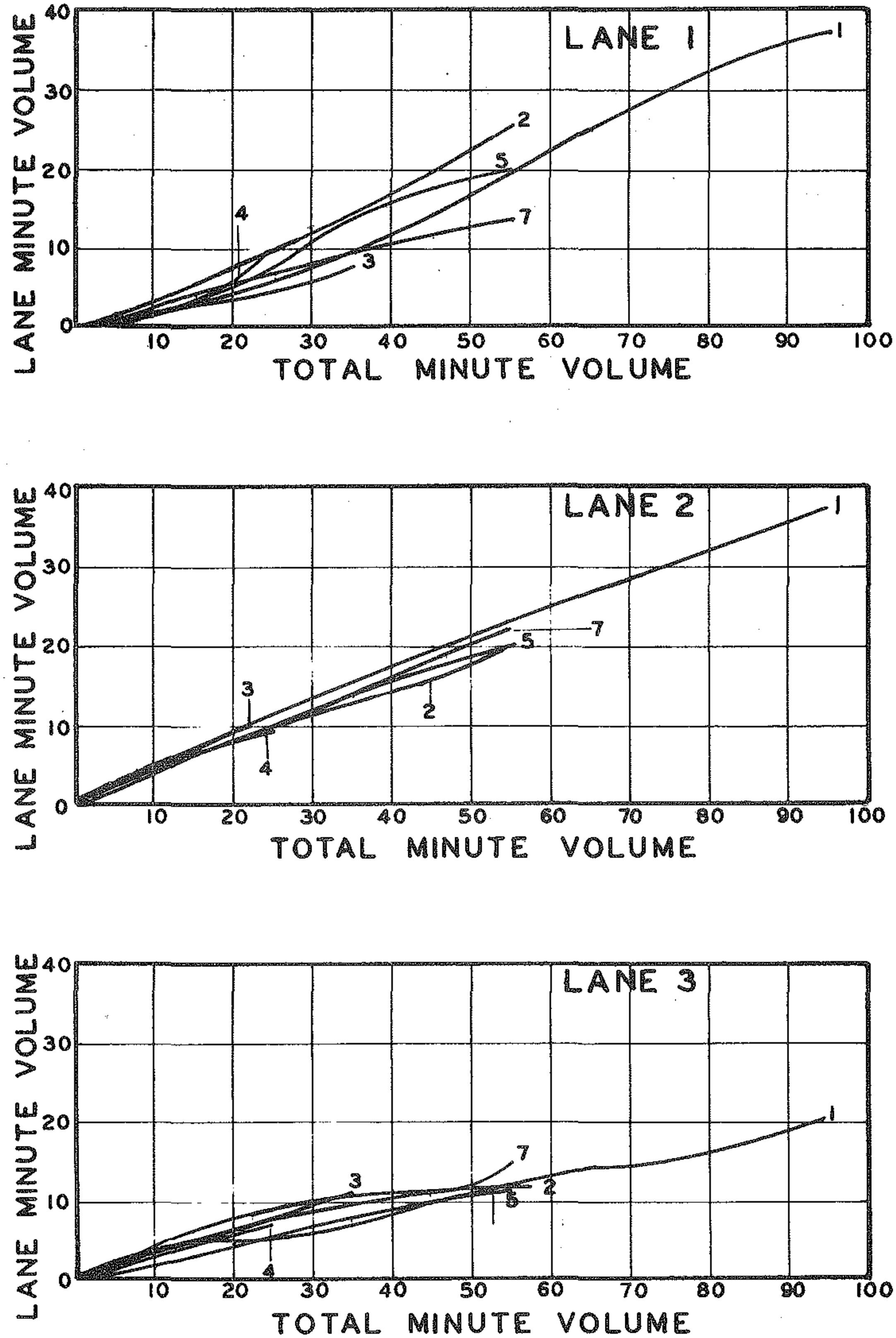


FIGURE 7

Where:

V_t = total minute volume

$\overline{\overline{V}}_2$ = the mean of the average lane 2 minute volumes.

Assuming that the average volumes for the individual facilities represented a random sample from a population of such facilities, and assuming that the variables are normally distributed, 95 per cent confidence intervals for the mean were computed for certain levels of the traffic volume. These confidence intervals lie in the range as indicated in the table below.

Range of V_t	Range of the 95% confidence interval
5 - 25	$\overline{\overline{V}}_2 \pm 0.5$
25 - 45	$\overline{\overline{V}}_2 \pm 1.5$

For V_t's higher than 45 vehicles per minute, the 95 per cent confidence interval is considerably wider. For example, when V_t = 53, the 95 per cent confidence interval on $\overline{\overline{V}}_2$ is $\pm$ 4.19.

For a given lane 2 average minute volume, $\overline{V}_2$, between 1 and 10, a reasonable estimate of the total minute volume, based on the present data, is

$$V_t = \frac{\overline{V}_2}{0.415} \pm 2.$$

For values of $\overline{V}_2$ between 11 and 15 inclusive, the estimated total minute volume is

$$V_t = \frac{\overline{V}_2}{0.415} \pm 3.$$

Beyond a value for $\overline{V}_2$ of 15, the spread is considerably wider.

Transferring attention now to the lane 3 and lane 1 graphs of Figure 7, a few more interesting observations may be made. It appears that for a total volume of from 0 to 30 vehicles per minute, lane 3 carries on the average 30.5 per cent of the total volume. For a total volume of 30 to 50, lane 3 carries on the average only 23.5 per cent of the total volume, and, furthermore, the percentage decreases even more with larger total minute volume. Conversely, since the proportion carried by lane 2 remains relatively constant, the percentage of vehicles carried by lane 1 increases with increased total minute volume. Using the above mentioned percentages for lanes 2 and 3, and knowing the total volume, the amount of traffic using lane 1 can be estimated.

II. SPEED CHARACTERISTICS

Presented in this section of the report are the results pertaining to the speed characteristics on the seven facilities which were studied. The presentation is separated into the following parts: (A) Variation of Average Speed by Time of Day; and (B) Distribution of Minute Average Speeds.

In a manner similar to Section I, on volume characteristics, first comparisons are made within each individual cell, and then the results of investigations of similarities and differences between cells are discussed.

A. Variation of Average Speed by Time of Day

For all seven facilities studied, at least 24 consecutive hours of individual vehicle speed detection in each lane was recorded. The individual speeds were averaged for one minute and 15 minute intervals. Because of the small number of vehicles during the one minute intervals, rather large fluctuations occur from minute to minute (particularly during early morning hours), and it was decided not to attempt to plot the minute to minute variation in average speed for the 24 hour period but 15 minute average speeds.

Figures 8 and 9 include the variation of 15 minute average speed, by lane, for each of the seven cells. For four of the cells (1, 2, 4 and 6) the 15 minute average speeds for the total 24 hour period were computed and plotted on the graphs shown. Notice the relatively large fluctuations which occur during the early morning hours, mainly a result of the low volumes during these periods. Since the analysis of individual speeds from the graphical recorder tape is so time consuming (5 minutes of analysis for each one minute of data per lane), it was necessary to eliminate those analyses which were felt to be relatively unimportant. Consequently, for the remaining cells (3, 5, and 7) only the periods from 6 a.m. to 6 p.m. have been analyzed. For these three cells, additional time saving procedures were employed. First, five 30- minute periods were selected, and these were completely analyzed--every individual speed observation being considered. Then, for the remaining 30-minute periods, a sampling technique (one minute sample for each 30-minute period) was utilized to compute estimates of average speed. If the average speeds computed from the one minute samples were 5 per cent greater or less than the composite average obtained from the five 30-minute samples, a second one sample was taken and considered in computing the average speed.

VARIATION OF AVERAGE LANE SPEED BY TIME OF DAY

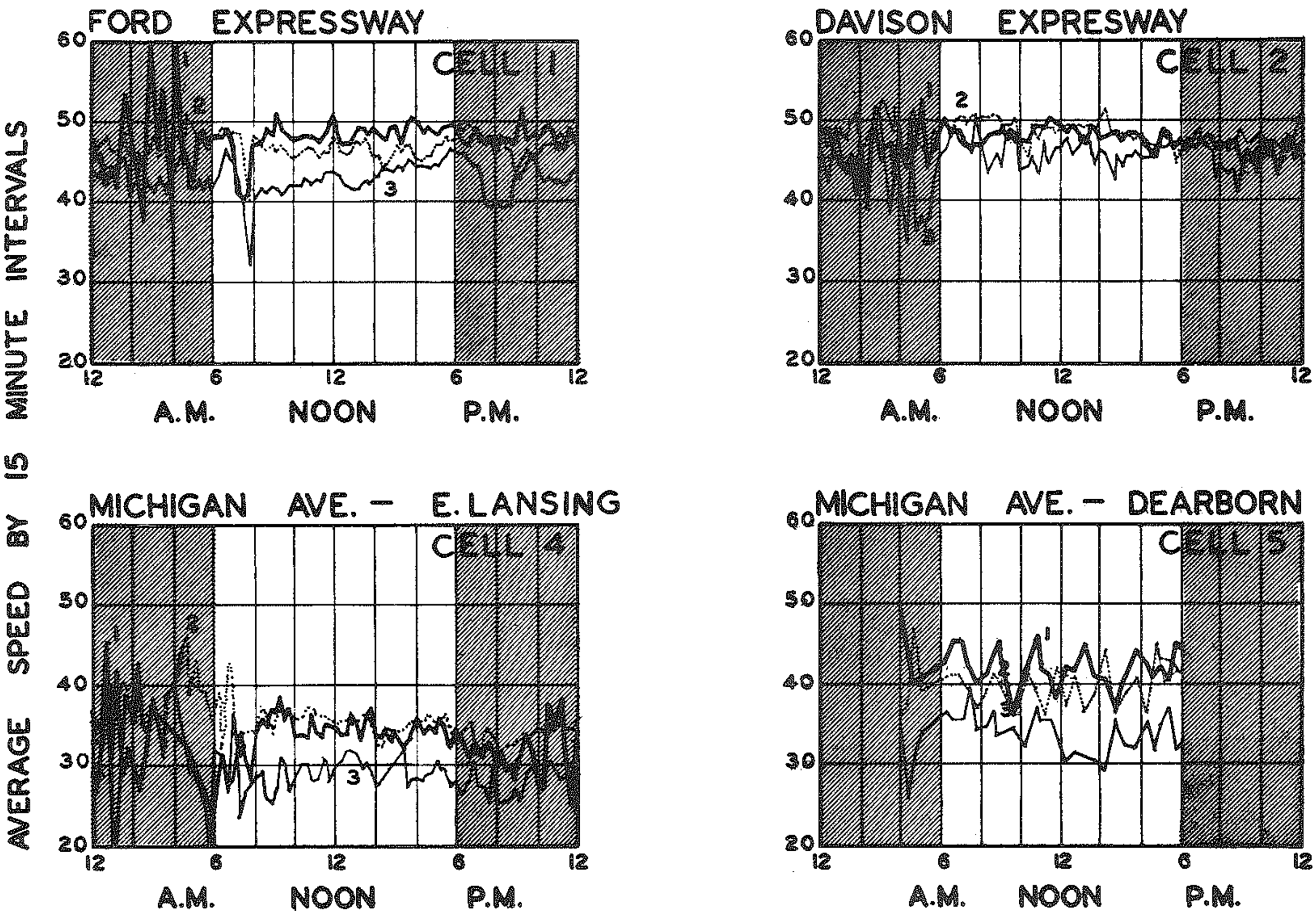


FIGURE 8

VARIATION OF AVERAGE LANE SPEED BY TIME OF DAY

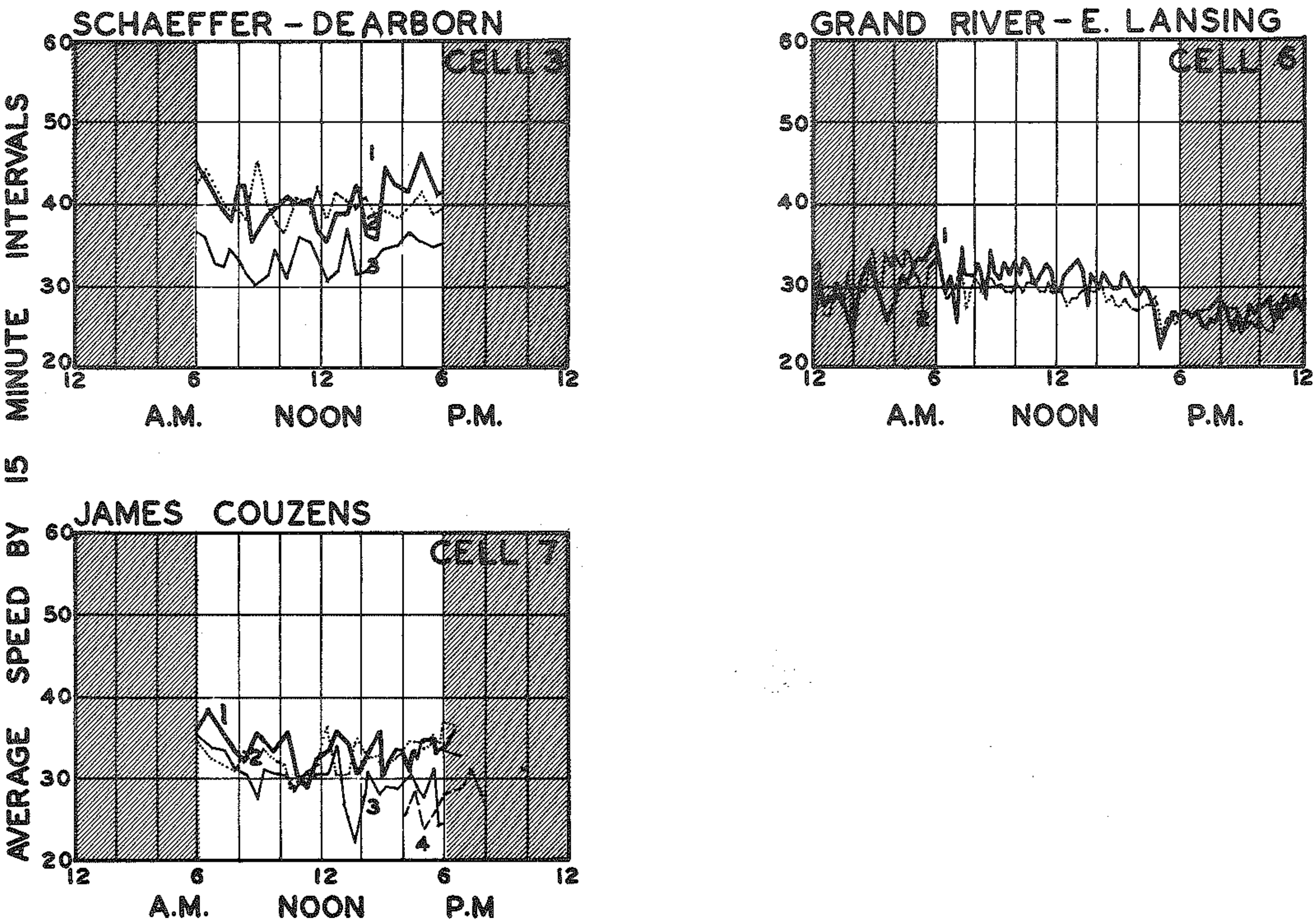


FIGURE 9

More careful scrutiny of each of the graphs allows a number of observations to be made. Notice, for example, the magnitude of the fluctuations in 15 minute average speeds for the daytime period (6 a.m. to 6 p.m.). Particularly in Cells 1, 2, 4, and 6 these fluctuations are very small for all lanes of the facilities. Note in Cell 1 (Ford Expressway) the one large drop in average speed between 7 and 8 a.m., which, unlike the very early morning fluctuations, is caused by an excessive volume. For Cells 3, 5, and 7 the average speeds plotted have slightly greater fluctuations from period to period. This was expected, however, because of the sampling procedure which was used to analyze the data.

Another interesting observation which can be made is a comparison of the average speeds between lanes for a given cell. Notice, for all cells, that lane 3 is characterized by lowest average speed, and lane 1 is generally characterized by highest average speed. The mean average lane speed for the total period analyzed was computed for each cell, and it was found that: (1) In all cases, without exception, lane 3 had the lowest mean average speed; and (2) in nearly all cases (excluding Cells 2 and 4) lane 1 had the highest mean average speed.

In order to better compare the magnitude and variability of 15 minute average lane speed between cells, three graphs were plotted, see Figure 10, one for each lane. On each graph all the cells with the exception of Cell 6 were plotted as indicated by the key at the top of the page. The reason for not plotting Cell 6 on this figure was that it had only two traffic lanes in the direction studied while all the other cells had three lanes. Because of the less important random fluctuations during much of the low volume "nighttime" period, only the period of 6 a.m. to 6 p.m. is shown on the graphs.

It seems that the most important observation to be derived from Figure 10 is that for all cells, and for each lane, the 15 minute average speed variations generally form a series of parallel, horizontal lines. This is especially noticeable from 9 a.m. to 6 p.m. Of course there are upward and downward fluctuations from period to period, but the magnitude of the fluctuations seems to be fairly constant from 9 a.m. to 6 p.m. For those cells (1, 2, 4, and 6) in which every individual speed observation was included in the analysis the lines appear to be extremely horizontal; whereas, for the cells which were analyzed on a sampling basis, the fluctuations are slightly larger as would be expected.

For the period from 6 a.m. to 9 a.m. most of the lines still appear to be of the same character as for the rest of the day. As discussed previously, the only major exception seems to be the Ford Expressway (Cell 1) which has a large drop in average speed

VARIATION OF AVERAGE LANE SPEED BY TIME OF DAY FOR ALL CELLS

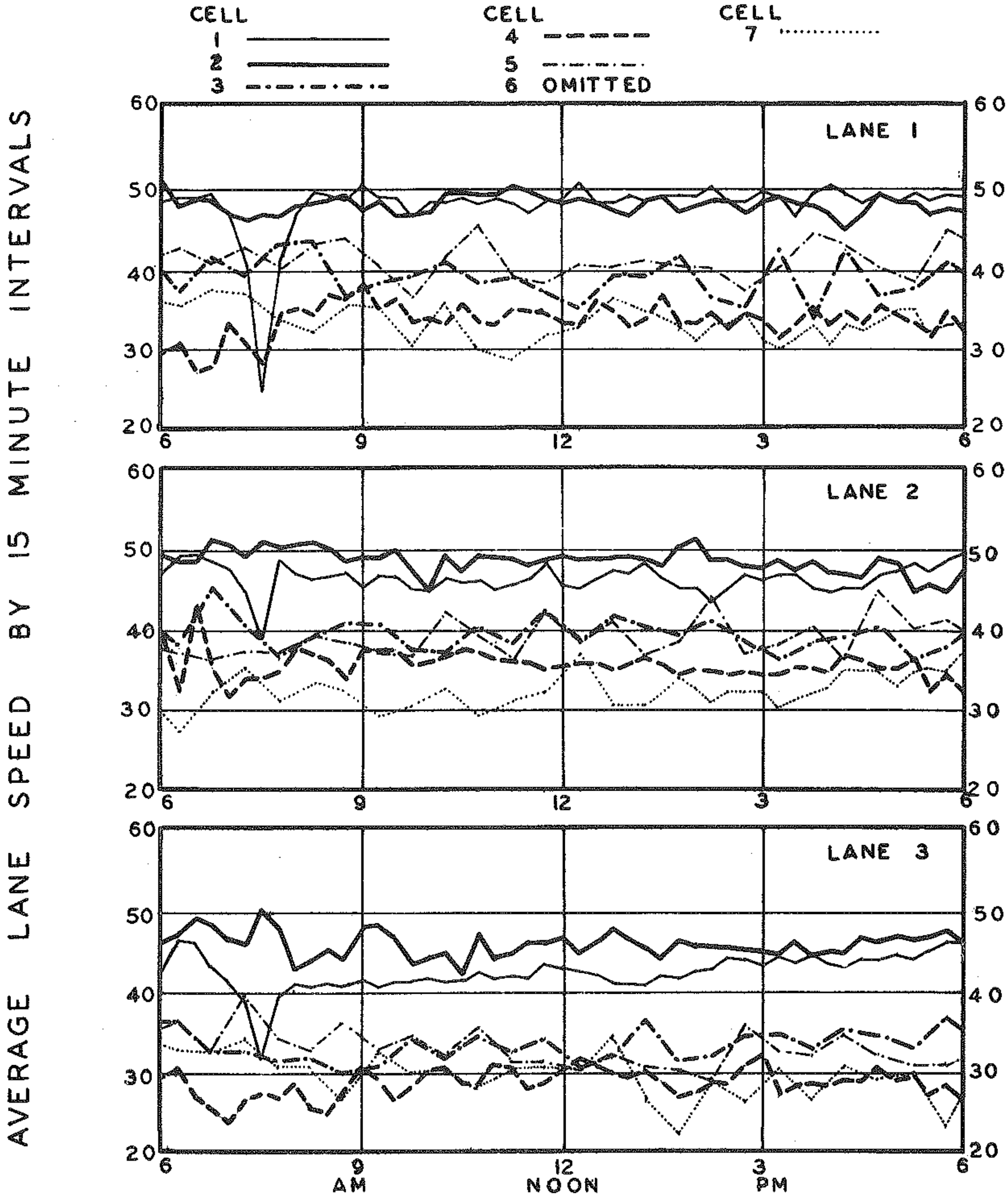


FIGURE 10

in all three lanes caused by congestion of traffic during the morning peak period (7 to 8 a.m.).

The last investigation in regards to speed variations was an attempt to determine if there were small intervals of time during which speeds could be measured, and this average speed thus computed to estimate the 24 hour average speed. In order to perform this investigation lane speeds were averaged for 15 minute periods and then lane average speeds were combined resulting in 15 minute average speeds for each of the facilities. Only those facilities (Cells 1, 2, 4 and 6) where the speed of each vehicle was determined are included in this analysis and only the period from 6 a.m. to 6 p.m. was studied.

The results of this investigation are graphically depicted in Figure 11. It is observed that averaging the lane speeds has the effect of eleminating incidental variations which were very pronounced in the graphs of average 15 minute speeds for each lane separately. As a result, it is noted that there are several long periods during which the variation in 3 lane-15 minute average speed does not differ from the overall 24 hour average by more than ± 1 mile per hour. The period between 11 a.m. and 3 p.m. seems to be especially well suited to the determination of the daily average speed. The ± 1 mile per hour confidence limits for each of the four facilities from 11 a.m. to 3 p.m. are indicated on the figure. The practical significance of this result is that by measuring the speeds for any period of 15 minutes between 11 a.m. and 3 p.m. an estimate of the 24 hour average speed can be made, and it would be accurate to within ± 1 mile per hour.

B. Distribution of Minute Average Speeds

The distribution of minute average speeds at each of the seven locations were determined and are graphically presented in Figures 12 and 13. Cells 1, 2, 4, and 5 are depicted in Figure 12, while Cells 3, 6, and 7 are included in Figure 13. The horizontal scale of each graph is one minute average speed while the vertical scale is an accumulative per cent of minutes with average speeds less than indicated on horizontal scale. First comparisons between lanes on the same facility will be discussed and then followed by a discussion comparing similar lanes of all the cells.

In each of the graphs depicted in Figures 12 and 13, the distribution curve of minute average speeds for lane 3 for all cells is offset to the left 2 to 7 miles per hour, while the distribution curves for lanes 1 and 2 for each of the cells are quite similar. For five of the cells (excluding Davison Expressway

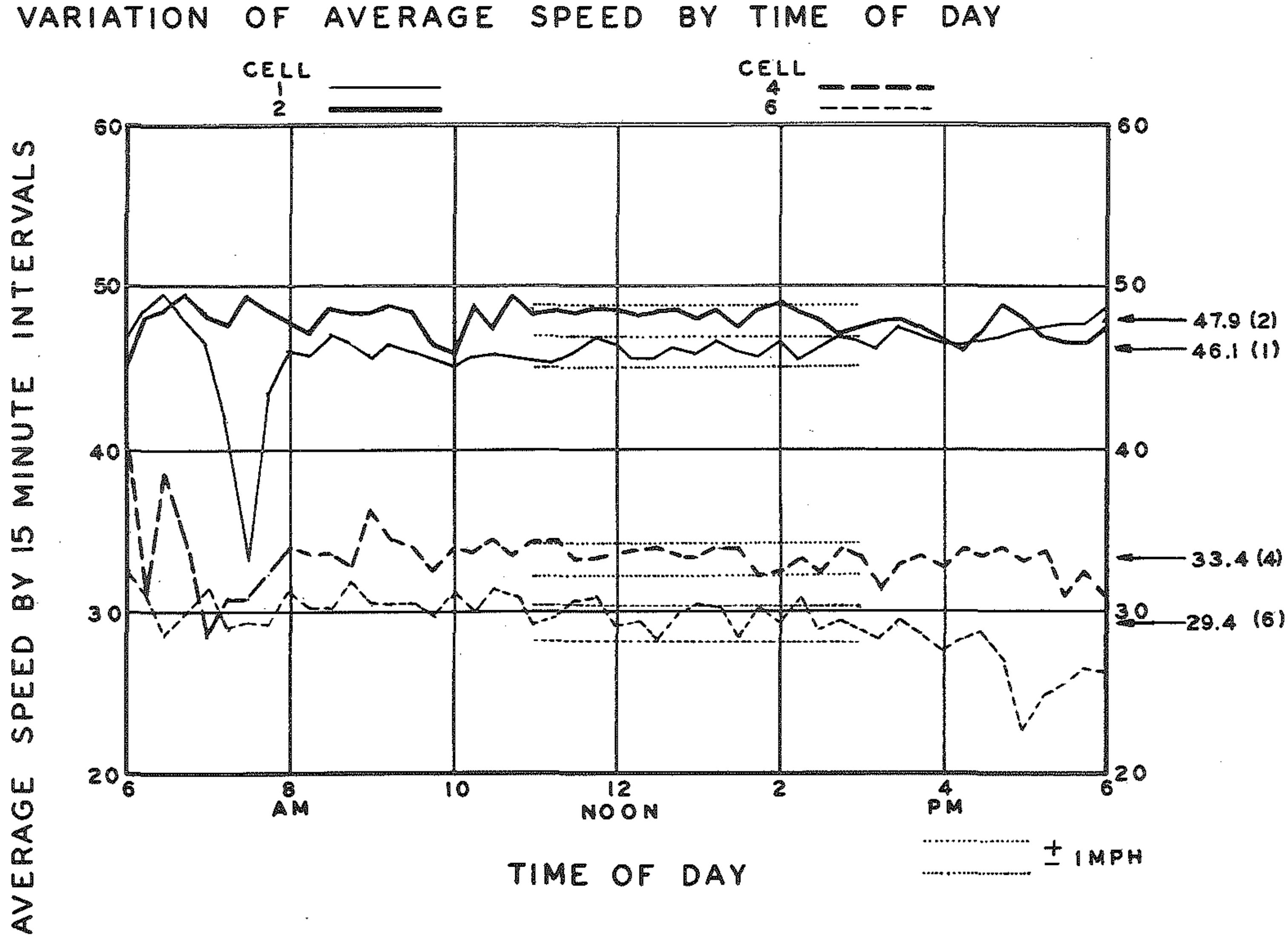
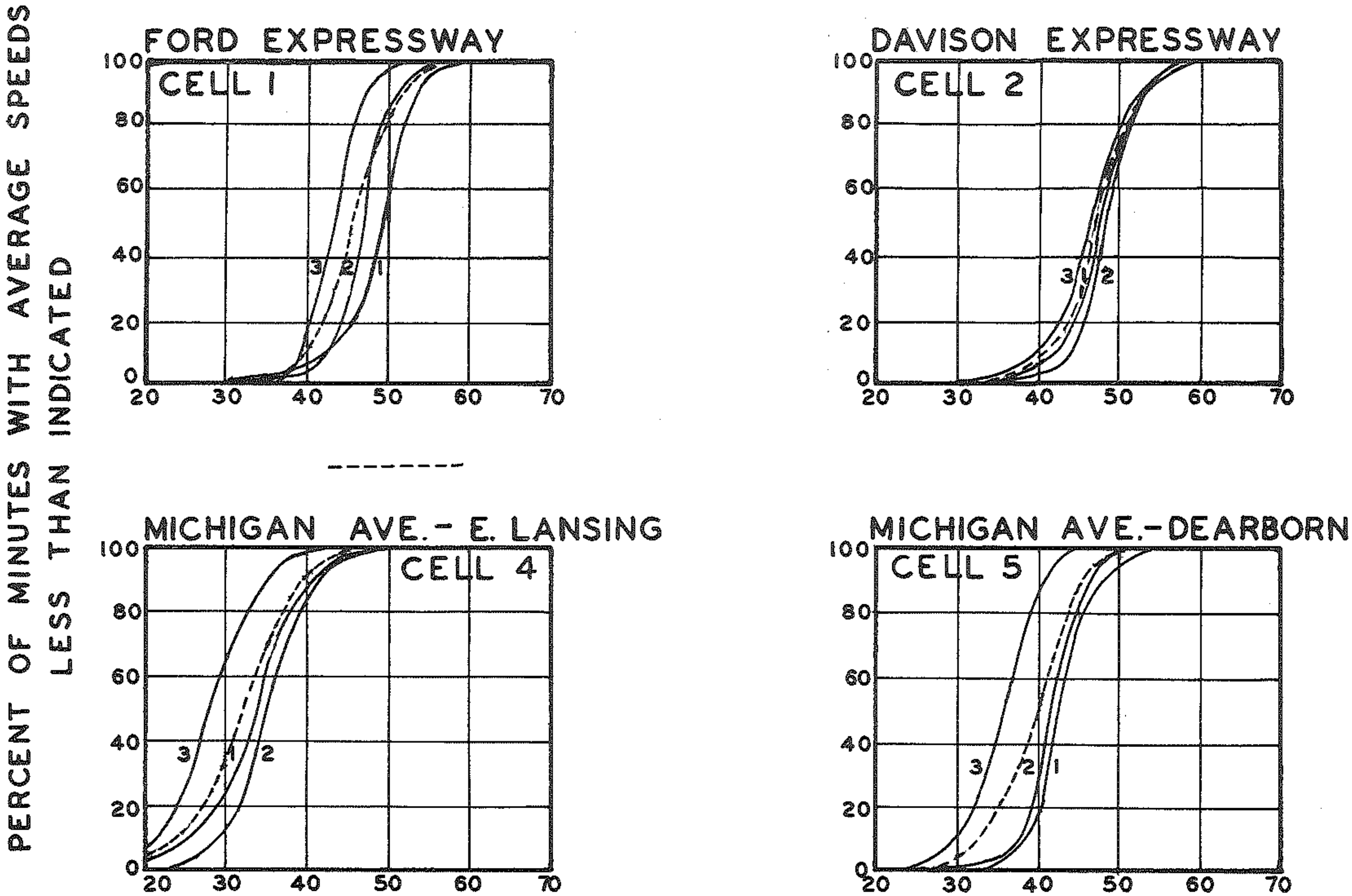

VARIATION OF AVERAGE SPEED BY TIME OF DAY
CELL
1
2
CELL
4
6
60
50
40
30
20
AVERAGE SPEED BY 15 MINUTE INTERVALS
6
8
AM
10
12
NOON
2
4
PM
6
47.9 (2)
46.1 (1)
33.4 (4)
29.4 (6)
± 1MPH
TIME OF DAY

FIGURE 11

DISTRIBUTION OF MINUTE AVERAGE SPEEDS



ONE MINUTE AVERAGE SPEEDS

FIGURE 12

DISTRIBUTION OF MINUTE AVERAGE SPEEDS

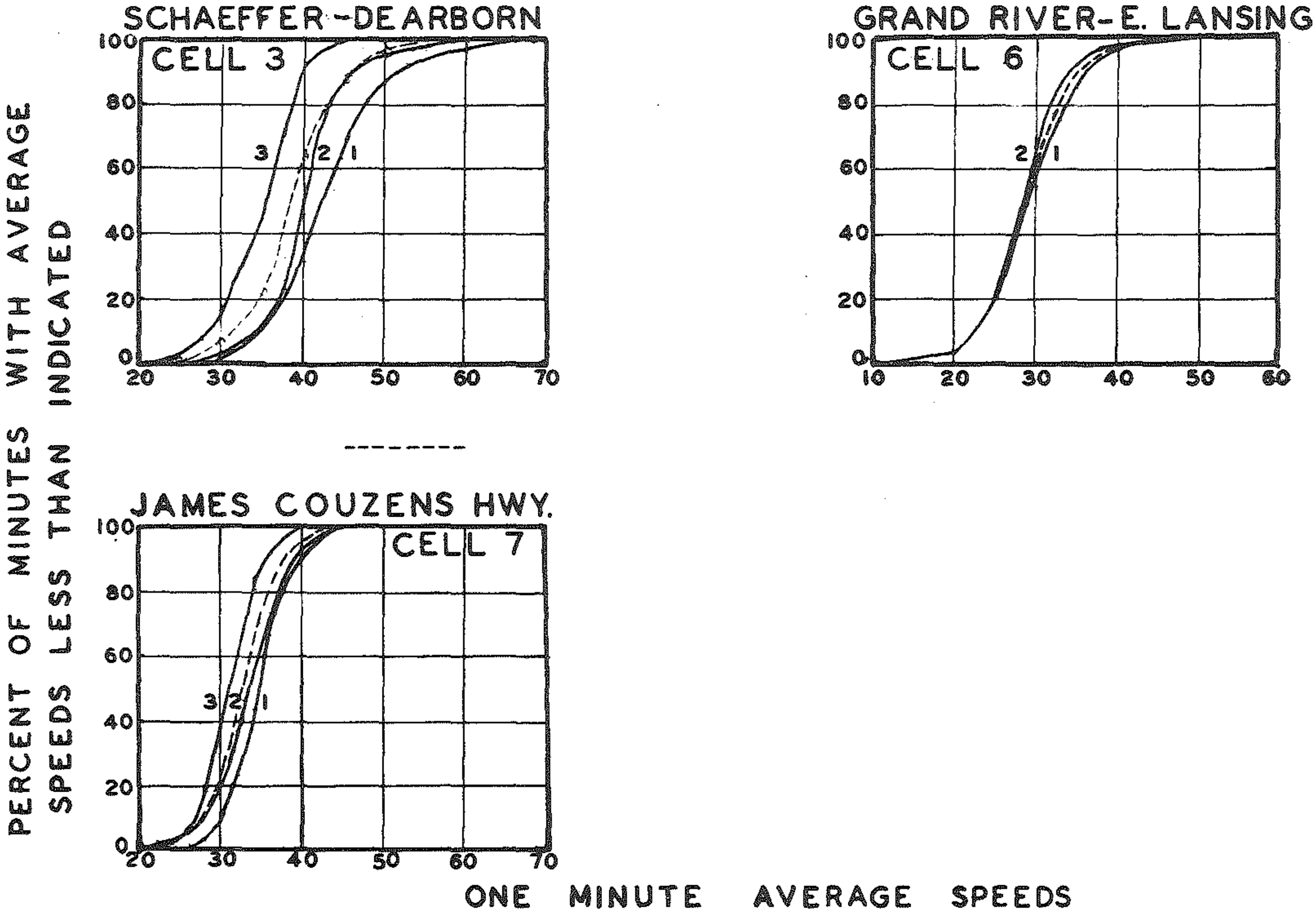


FIGURE 13

and Michigan Avenue in East Lansing), the distribution curve for lane 1 is offset to the right indicating a higher average speed. The distribution curves for the lanes for Davison Expressway and Grand River are close together indicating little difference in speed distributions between lanes.

The construction of such graphs permits the measurement of certain statistical characteristics, such as the median, 15 percentile, 85 percentile, 15-85 percentile range, 10 mile per hour pace, and per cent of vehicles within the 10 mile per hour pace. These statistical characteristics are summarized in tabular form in Figure 14. Additional analyses were made in order to summarize the speed distributions for daytime (6 a.m. to 6 p.m.) and nighttime (6 p.m. to 6 a.m.) for the Ford and Davison Expressways. The minute average speed distributions at the James Couzens location were determined for the period when three lanes are used for traffic movement and also for the period (4 to 7 p.m.) when four lanes are used for traffic movement.

Although there is little difference between daytime and nighttime average speeds (45.3 and 45.4 miles per hour on the Ford Expressway; and 47.4 and 46.3 miles per hour on the Davison Expressway), the daytime minute average speeds are much more uniform. For example, the 15-85 percentile range on the Ford and Davison Expressways during the daytime was 5 to 6 and 6 to 9 miles per hour while during the nighttime the 15-85 percentile range was 8 to 11 and 9 to 13 miles per hour. Another method that can be used to show the difference between speed distributions is to compare the per cent of vehicles included within the 10 miles per hour pace. This per cent on the Ford and Lodge Expressways during the daytime was 89 to 93 and 77 to 88 per cent while the similar per cent for nighttime was 68 to 80 and 60 to 72 per cent.

In comparing the speed distributions of the seven cells many similarities exist. Note in Figure 14 that the average median and mode for each lane for all seven facilities are within two miles per hour of one another. The 15-85 range for each lane for all seven facilities is always between 7 and 13 miles per hour. This means that 70 per cent of the minutes have an average speed never greater than ± 6.5 miles per hour from the 24 hour average speed and on some lanes of some facilities never greater than ± 3.5 miles per hour. A review of the per cent of vehicles included in the 10 mile per hour pace indicates that the per cent varies from 58 to 88 which means that the average speed during 58 to 88 per cent of minutes during the 24 hour period is never greater than ± 5.0 miles per hour from the 24 hour average speed.

FIGURE 14
SUMMARY OF MINUTE AVERAGE SPEED DISTRIBUTIONS

Speed Characteristics	FORD EXPRESSWAY - CELL 1								
	Day Time			Night Time			24 Hour		
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
Average	47.7	46.0	42.4	47.0	46.6	42.6	47.4	46.3	42.5
Median	48	45	42	47	46	42	48	46	42
Mode	50	46	41	48	48	41	50	46	41
15 percentile	45	43	39	41	42	38	48	46	42
85 percentile	50	48	45	52	51	46	51	49	46
15-85 percentile Range	5	5	6	11	9	8	8	7	7
10 mph pace	44-53	42-51	38-47	44-53	42-51	38-47	44-53	42-51	38-47
Percent included in 10 mph pace	89.5	93.3	90.5	68.4	74.5	80.4	80.7	85.3	85.5
Overall Average	45.3			45.4			45.4		

Speed Characteristics	DAVISON EXPRESSWAY - CELL 2								
	Day Time			Night Time			24 Hour		
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
Average	47.9	48.3	46.1	46.1	47.8	45.0	47.1	48.2	45.5
Median	47	48	46	46	47	45	47	48	45
Mode	48	49	45	47	47	45	47	49	45
15 percentile	43	45	41	40	43	38	43	44	40
85 percentile	51	51	50	51	52	51	51	51	50
15-85 percentile Range	8	6	9	11	9	13	8	7	10
10 mph pace	44-53	44-53	41-50	41-50	42-51	42-51	43-52	44-53	42-51
Percent included in 10 mph pace	88.4	90.6	77.0	66.5	72.6	60.8	78.0	84.5	70.5
Overall Average	47.4			46.3			46.9		

FIGURE 14 (Concl.)
SUMMARY OF MINUTE AVERAGE SPEED DISTRIBUTIONS

Speed Characteristics	Shaeffer Rd. Cell-3			Michigan Ave., E. Lansing Cell-4			Michigan Ave., Detroit Cell-5		
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
Average	42.8	40.0	34.5	33.1	35.3	29.1	42.3	41.6	35.1
Median	43	40	35	34	35	29	42	42	35
Mode	41	42	34	34	34	30	42	43	34
15 Percentile	37	37	30	27	31	23	38	38	31
85 Percentile	49	44	39	40	41	34	47	45	40
15-85 Percentile Range	12	7	9	13	10	11	9	7	9
10 mph pace	38-47	35-44	32-41	30-39	31-40	25-34	38-47	36-45	31-40
Percent Included in 10 mph pace	58.9	80.2	74.3	62.2	70.9	64.9	77.0	88.6	78.8
Overall Average	39.1			32.5			39.4		

Speed Characteristics	Gr.Rv.,E.Lansing Cell-6		James Couzens (3 Lane) Cell-7			James Couzens (4 Lane) Cell-7			
	Lane 1	Lane 2	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3	Lane 4
Average	28.8	27.9	34.1	32.9	30.5	34.2	34.7	30.8	26.0
Median	29	28	34	33	31	35	35	32	26
Mode	28	27	34	32	31	37	37	31	26
15 Percentile	24	24	31	29	27	32	31	28	23
85 Percentile	35	33	38	38	35	37	40	34	30
15-85 Percentile Range	11	9	7	9	8	5	9	6	7
10 mph pace	23-32	23-32	29-38	29-38	26-35	29-38	29-38	26-35	22-31
Percent included in 10 mph pace	64.3	74.8	86.3	76.8	84.4	96.7	75.0	86.7	85.0
Overall Average	28.3		32.5			31.4			

Another area in the investigation of speed distributions was to compare the minute average speed distributions of similar lanes on the seven different facilities. Figure 15 was prepared in order to present this analysis. Again the horizontal scale is minute average speed, and the vertical scale is per cent of minutes with average speeds less than indicated minute average speed. The numbers (1 thru 7) positioned near each curve refers to the cell number. The top diagram is for lane 1, the middle diagram for lane 2, and the lower diagram for lane 3.

The lane speed distributions of the seven facilities appear to be in pairs from left to right: Cells 4 and 7, Cells 3 and 5, and Cells 1 and 2. The speed distribution curves for Cell 6 (Grand River in East Lansing) only appear in the upper two diagrams since there are only two lanes. The curves in the lower diagram are positioned slightly to the left indicating a lower average speed in lane 3. Note the parallel position of the curves for lane 2 which implies that the 15-85 percentile ranges are approximately equal. The curves in the two top diagrams have steep slopes indicating greater uniformity in speed.

In summary those cells with a combination of minimum marginal and median friction (Cells 1 and 2) have distribution curves furthest to the right and have steep slopes. Those facilities (Cells 6 and 7) with the combination of greatest median and marginal friction have distribution curves furthest to the left and have relatively flat slopes. It would appear from the study data that as traffic friction increases, average speed decreases and the speeds become less uniform.

DISTRIBUTION OF MINUTE AVERAGE SPEEDS BY LANE

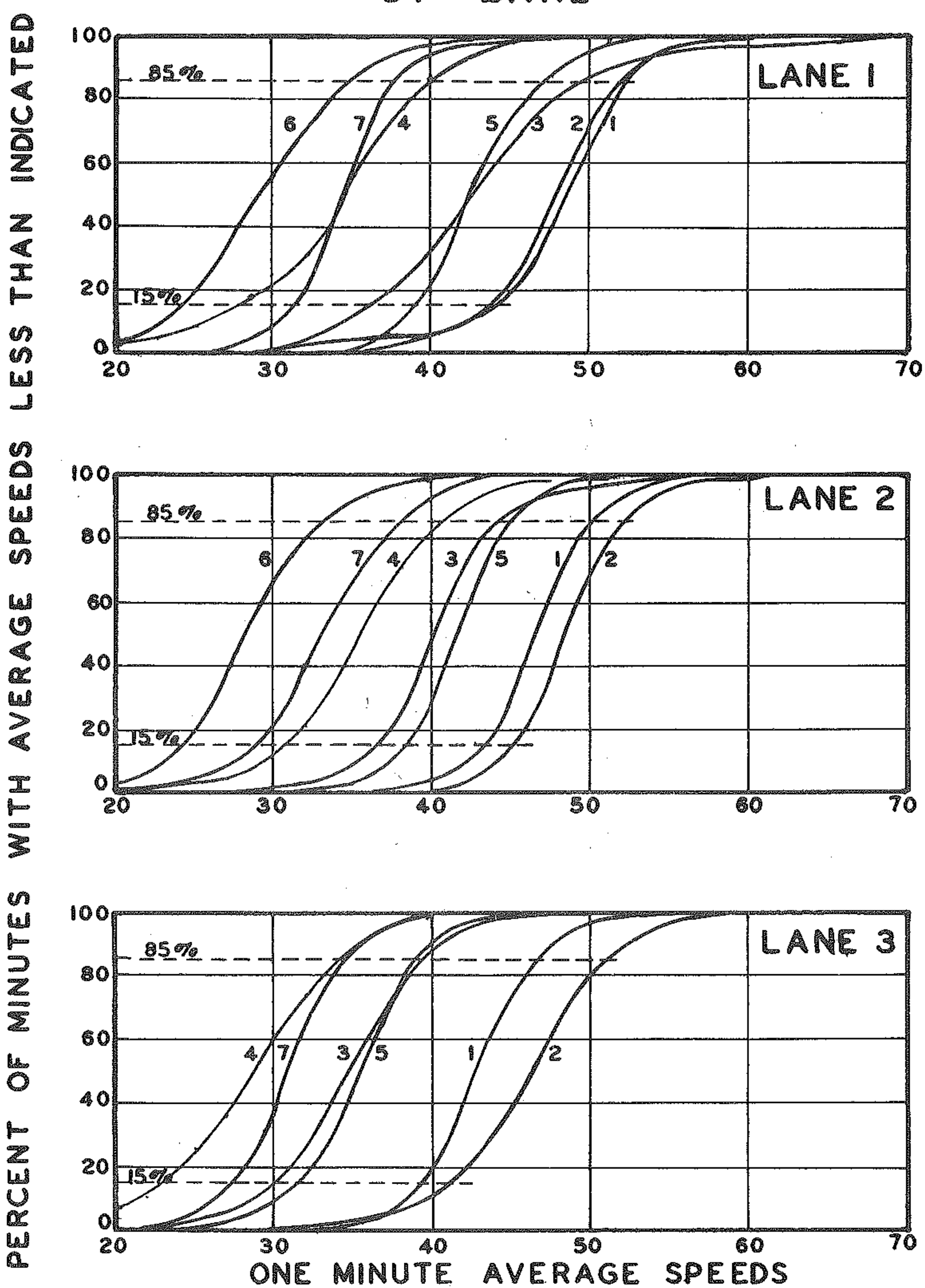


FIGURE 15

III. SUMMARY

The more important findings pertaining to the volume and speed characteristics of the seven locations on major urban arterials are summarized below.

1. The ratio of various peak traffic volumes for different intervals of time for the seven locations are similar.

2. A method of estimating various 24 hour percentile minute volumes when applied to the seven locations give similar satisfactory results.

3. Traffic volume affects lane usage and distribution of traffic volume between lanes follows very definite patterns.

4. The shoulder lane (lane 3) at each of the seven locations at the lowest average lane speed, while the median lane (lane 1) at five of the seven locations at the highest average lane speed.

5. The variations in average lane speeds between 9 a.m. and 4 p.m. at the seven locations were extremely small.

6. The average speed determined for any 15 minute period between 11 a.m. and 3 p.m. was within ± 1 mile per hour of the 24 hour average speed.

7. There was no significant difference between daytime and nighttime average speeds at the locations on the Ford and Davison Expressways. Nighttime average speeds were more dispersed.

8. The average minute lane speeds are quite uniform throughout the 24 hour period with 70 per cent of the minutes having average speeds within ±3.5 to ±6.5 miles per hour of the 24 average speed.

9. Routes having greater medial and marginal friction generally have lower average speed and speeds which are less uniform.

PART THREE

HEADWAY CHARACTERISTICS

INTER-RELATIONSHIPS OF FUNDAMENTAL CHARACTERISTICS

I. HEADWAY CHARACTERISTICS

The headway or time interval between vehicles is one of the most interesting fundamental characteristics of traffic flow. It is relatively simple to compute the average headway for a given time interval since it is equivalent to the number of seconds in the time interval divided by the traffic volume during the selected time interval (assuming the desired units of headway are seconds. As an example, if a lane of a highway has a volume of 25 vehicles in one minute, then the average time headway is 60 divided by 25 or 2.4 seconds.

However, in order to better understand the phenomena of traffic flow, it is of value to know how headways are distributed under various traffic volumes and on the several lanes of the facilities studied. The following paragraphs will be presented in two parts: Presentation of the Headway Distributions at each Location; and Comparison of the Headway Distributions between Locations.

A. Presentation of the Headway Distributions

An attempt will be made in this report to graphically present the analyzed headway characteristics in a rather unique manner. One Figure will be presented for each of the seven locations and each Figure include the headway distributions on a per lane basis.

The construction of the graphs will now be discussed. Each of the seven Figures are similar. The vertical scale is time headway ranging from 0 to 10 seconds. The horizontal scale is minute volume ranging from 0 to 30 vehicles (the Ford expressway-cell one has a range of 0 to 40 vehicles). The heavy curved line on each graph indicates the average time headway at the various minute volume levels. For example, at a minute volume of 10 vehicles, the average time headway is 60 divided by 10 or 6 seconds.

The minute volumes per lane were placed into five volume groups: 6-10, 11-15, 16-20, 21-25, and 26-30 vehicles per minute. Since the traffic volume on the Ford expressway was heavier, the minute volumes per lane were placed into two additional volume groups: 31-35 and 36-40 vehicles per minute. The time headways for thirty individual minutes for each volume group and for each lane of each facility were analyzed. The average distribution for each volume group was determined and is presented as a cross-hatched area at the average minute volume of each volume group.

The horizontal measurement of the cross-hatched area indicates the per cent of vehicles having that particular headway.

The last step of the construction of these Figures was the establishment of the 15, 50, 85, and 100 percentile levels for each lane of each facility. This was accomplished by determining these five percentile levels for each volume group, and then connecting these points for the various volume groups of each lane.

The results obtained for each facility will be presented. The Figure numbers are the same as the cell numbers and will be discussed in numerical order. A later section of the report will discuss similarities and differences between facilities.

The headway distribution for each volume group and each lane for the Ford Expressway (cell 1) is depicted in Figure 1. The top graph is for lane 1 (median lane), the middle graph is for lane 2 (middle lane), and the lower graph is for lane 3 (curb lane). The volume group up to 40 vehicles per minute is presented for lanes 1 and 2, while the highest minute recorded on lane 3 was 30 vehicles per minute. For each of the three lanes the headway distributions at the lower volume groups are well dispersed, while as the minute volumes increase the dispersion is less and a mode between 0.5 and 2.0 seconds becomes more pronounced. Note that the mode for each of the three lanes remains almost identical over the volume range. For lane 1 the mode is always between 0.6 and 1.0 seconds. The mode for lane 2 for minute volumes over 16 vehicles per minute is between 1.1 and 1.5 seconds. The mode for the lower volume groups is between 1.6 and 2.0 seconds while for the higher volume groups is between 1.1 and 1.5 seconds. The 15, 50, 85 and 100 percentile curves are shown on the three graphs and generally are parallel to the average headway curve (heavy curved line). These curves can be used in the following manner. Take for example lane 3 with the volume group of 26-30 vehicles per minute. The following characteristics of headway distribution can be surmised.

(a) 15 per cent of the vehicles are traveling at headways equal to or less than 1.1 seconds.

(b) 50 per cent of the vehicles are traveling at headways equal to or less than 1.9 seconds.

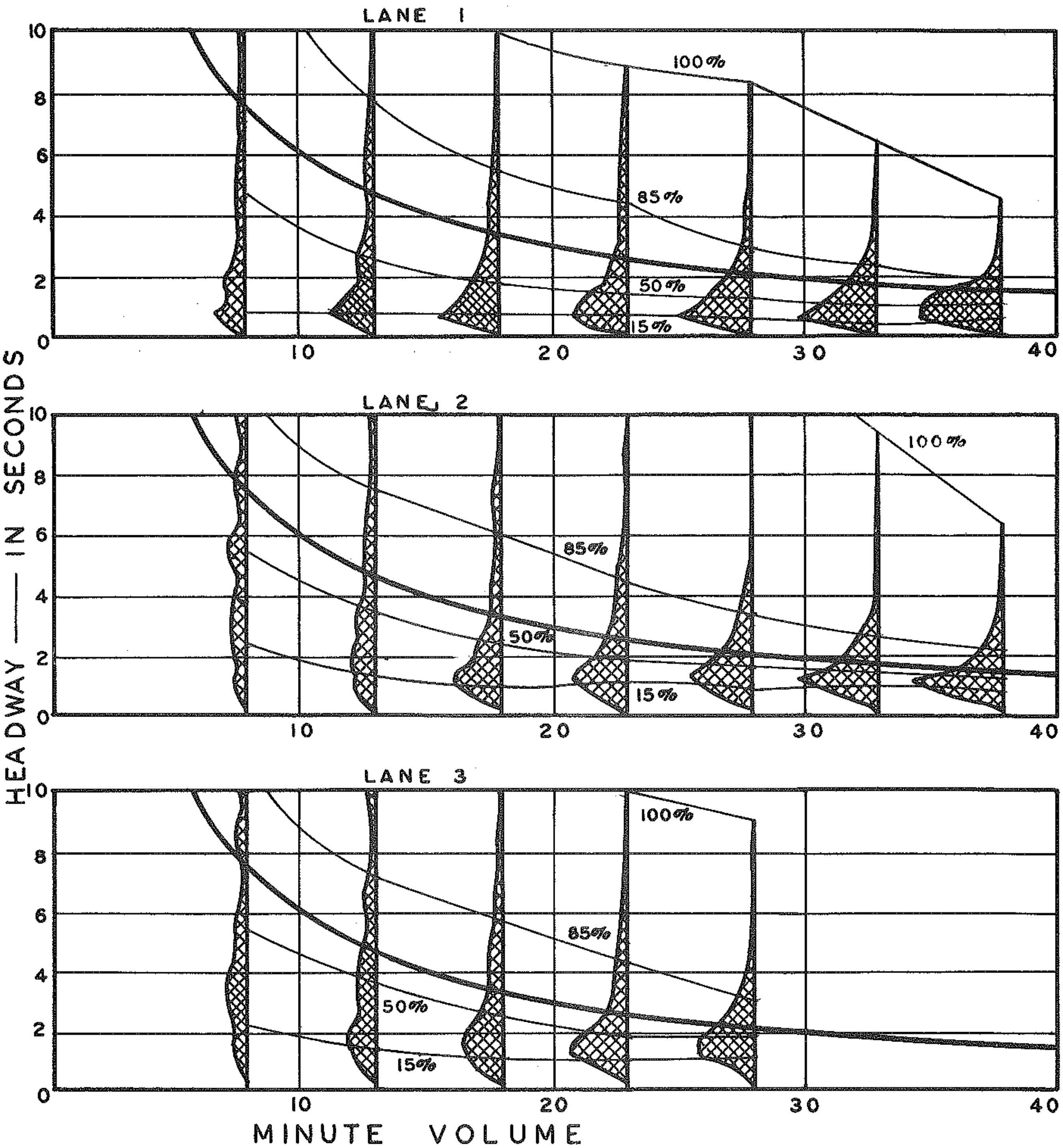
(c) 85 per cent of the vehicles are traveling at headways equal to or less than 3.0 seconds.

(d) 100 per cent of the vehicles are traveling at headways equal to or less than 9.0 seconds.

FIGURE 1

HEADWAY DISTRIBUTIONS RELATED TO TRAFFIC VOLUME

CELL 1 FORD EXPRESSWAY



Note from the graphs that the mode is always less than the median (50 percentile), and the median is always less than the average headway.

The headway distribution for each volume group and each lane for the Davison Expressway (cell 2) is presented in Figure 2. The volume group up to 30 vehicles per minute is presented for lanes 1 and 2, while the highest minute volume for lane 3 was approximately 15 vehicles per minute. Similar to the results obtained from the Ford Expressway, the headway distributions are well dispersed at the lower volume levels while as the minute volumes increase, the dispersion is less and the mode becomes more pronounced. The mode for lane 1 and 2 remains almost always in the 1.1 to 1.5 headway interval while for lane 3 the mode is between 1.5 and 2.0 seconds. The 15, 50, 85, and 100 percentile curves are shown in the three graphs and are generally parallel to the average headway curve. Again, like the results of the Ford Expressway, the mode is less than the median, and the median is less than the average headway.

The headway distribution for each volume group and each lane of Schaefer Road (cell 3) is presented in Figure 3. Lane 1 has volume groups up to 15 vehicles per minute, lane 2 has volume group up to 30 vehicles per minute, and lane 3 has volume groups up to 20 vehicles per minute. The shape of the distribution curves are similar to the distribution curves of the previously discussed facilities. The mode, although not as constant as previously discussed, is still between 1 and 2 seconds. Again the modes are less than the median, and the median is less than the average headway. The 15, 50, 85, 100 percentile curves are generally parallel to the average headway curve.

The headway distribution for each volume group and each lane of Michigan Avenue in East Lansing (cell 4) is shown in Figure 4. Since this route is less traveled than the previous ones mentioned, the volume groups included are the 6-10 vehicles for lanes 1, 2, and 3 and the 11-15 vehicles for lane 2. The headway distributions are well dispersed and in fact the 85 per cent is greater than 10 seconds for all three lanes for the lowest volume group. The mode is less pronounced but is still less than the median, which in turn is less than the average headway.

The headway distribution for each volume group and each lane of Michigan Avenue in Dearborn (cell 5) is given in Figure 5. The volume groups include up to 25 vehicles per minute for lanes 1 and 2, and up to 20 vehicles per mile for lane 3. The mode is almost in every volume group between 1 and 2 seconds, and in all cases is less than the median headway which in turn is less than the average headway. The 15, 50, 85, 100 percentile curves are

FIGURE 2

HEADWAY DISTRIBUTIONS RELATED TO TRAFFIC VOLUME

CELL 2 DAVISON EXPRESSWAY

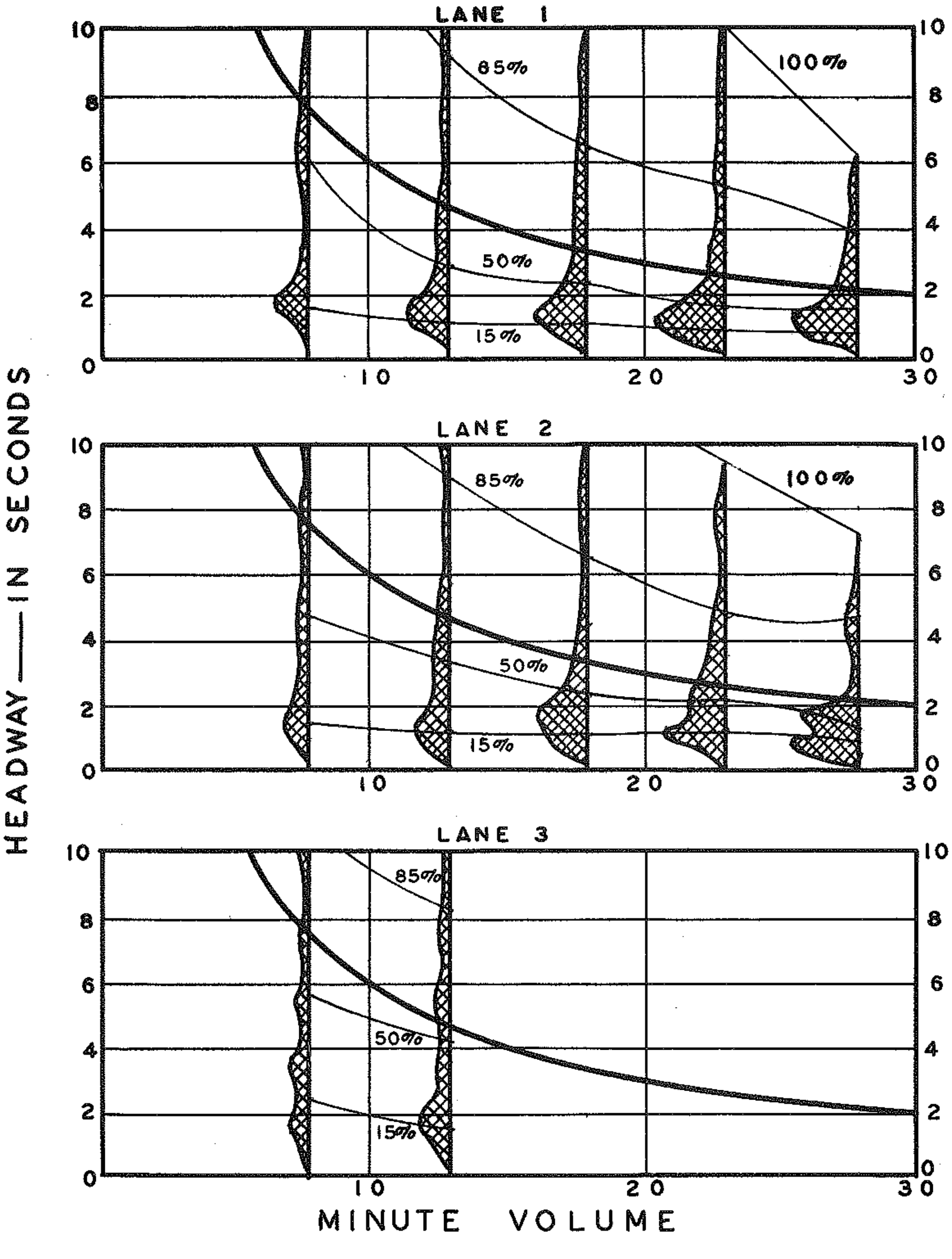


FIGURE 3

HEADWAY DISTRIBUTIONS RELATED TO TRAFFIC VOLUME

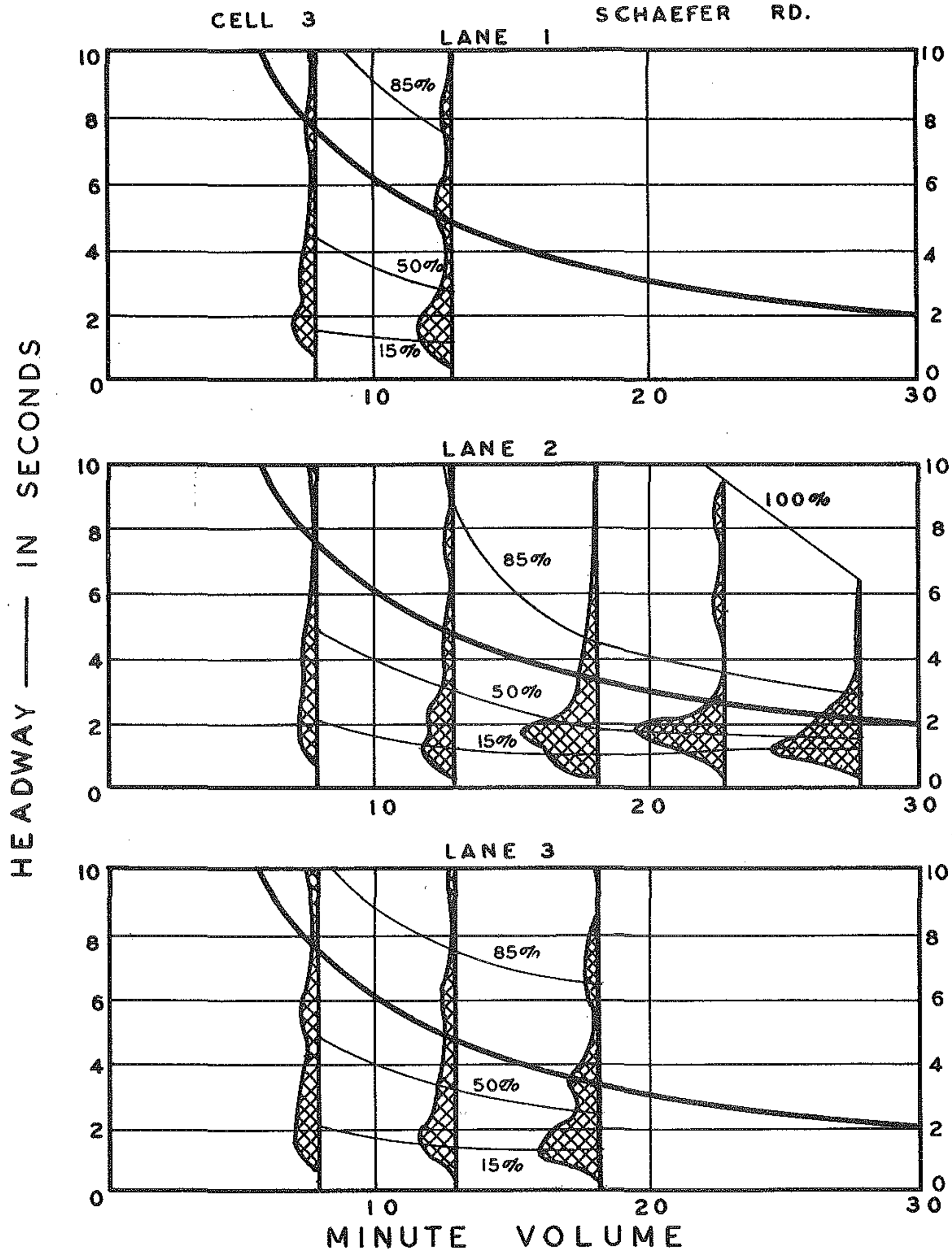


FIGURE 4

HEADWAY DISTRIBUTIONS RELATED TO TRAFFIC VOLUME

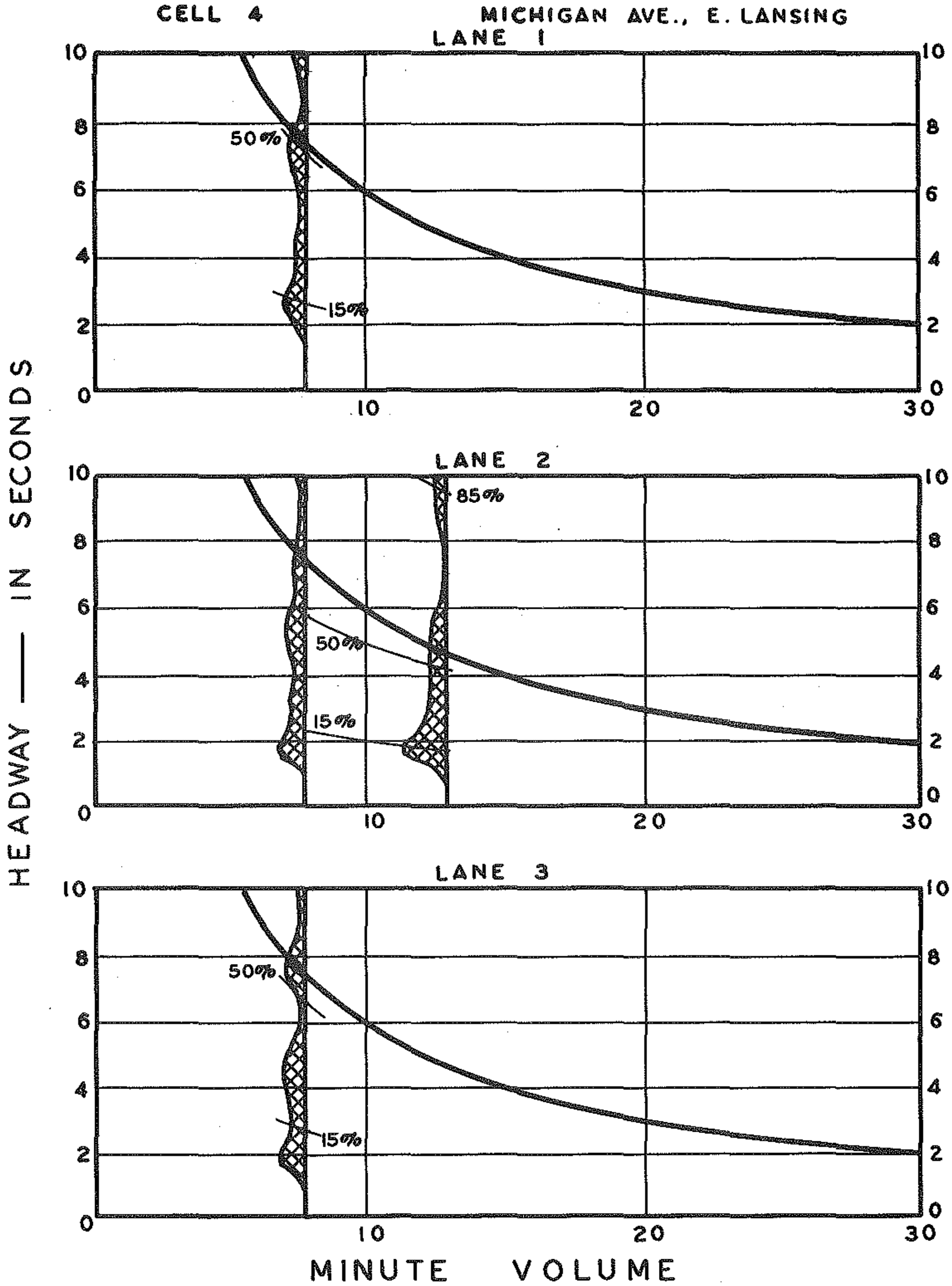
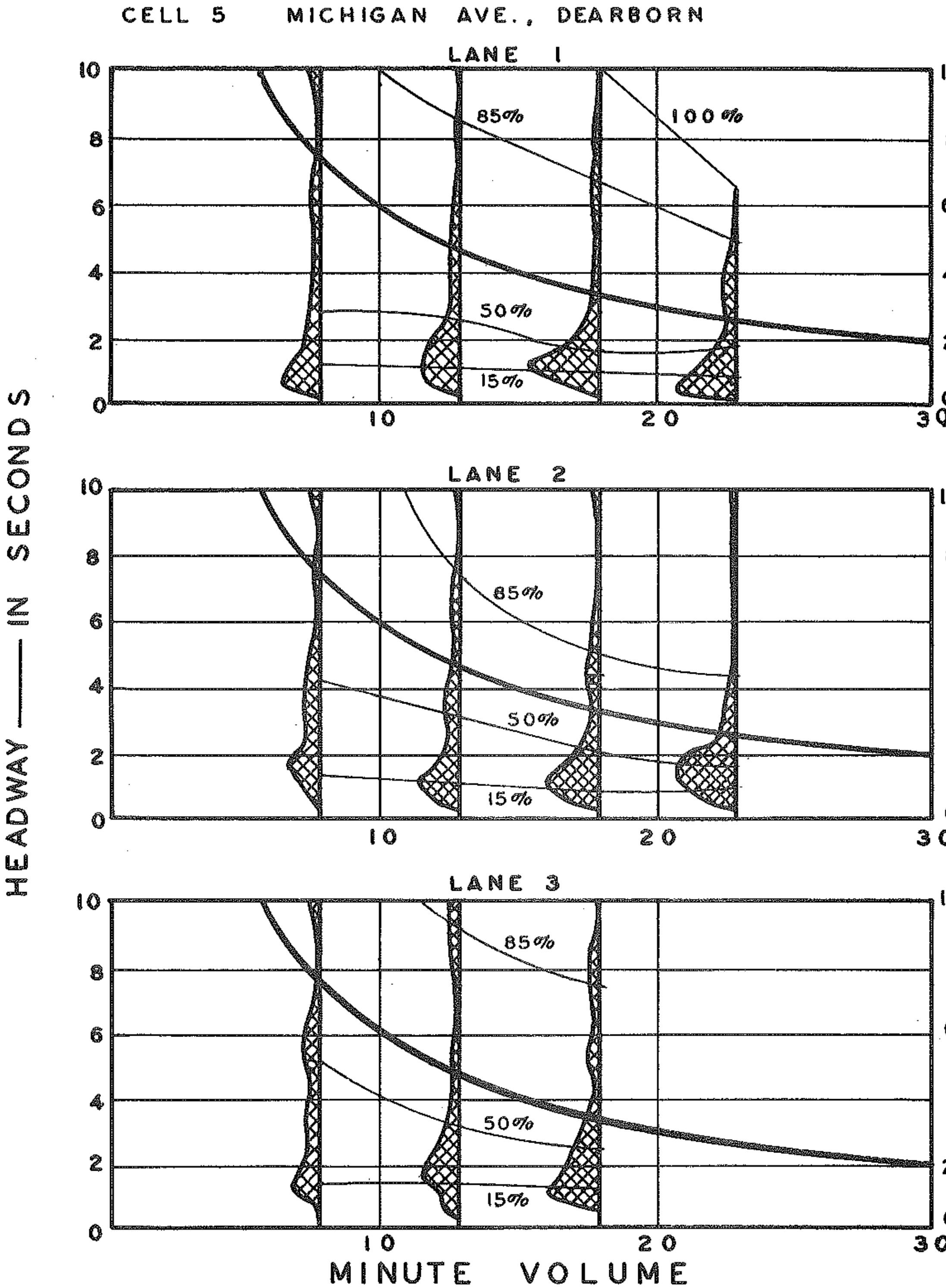


FIGURE 5

HEADWAY DISTRIBUTIONS RELATED TO TRAFFIC VOLUME



essentially parallel to the average headway curve, except for lane 1 at low minute volumes on the 50 percentile curve.

The headway distribution for each volume group and each lane of Grand River Avenue in East Lansing (cell 6) is presented in Figure 6. Grand River Avenue consists of only two lanes in each direction. Lane 2 in this case is the curb lane, while lane 1 is the median lane. The modes of the headway distributions are more "peaked". Again the mode usually occurs between 1 and 2 seconds, and is less than the median which in turn is less than the average headway. The 15, 50, 85, and 100 percentile curves are roughly parallel to the average headway curve.

The headway distribution for each volume group and each lane of James Couzens Highway (cell 7) is depicted in Figure 7. Lane 1 includes volume groups up to 30 vehicles per minute, lane 2 includes volume groups up to 25 vehicles per minute, and lane 3 includes volume groups up to 20 vehicles per minute. The modes are generally between 1 and 2 seconds. The 15, 50, and 85 percentile curves are roughly parallel to the average headway curve except for the 85 percentile curve of lane 2. The various percentile curves are positioned much lower than for the other six facilities. This is partly due to a traffic signal which is located approximately 1000 feet upstream from the study location. The traffic signal would cause a relatively higher number of vehicles to have smaller headways and consequently would lower the percentile curves.

B. Comparison and Summary of Headway Distributions

The headway characteristics presented in the previous section of this report will now be compared and summarized on a facility, lane, and volume group basis. The following sub-sections will include discussions of central tendencies, cumulative frequency percentiles, per cent of vehicles related to average headways, and frequency distributions.

1. Central Tendencies

The mode, median, and mean were determined for each volume group of each lane of each facility studied and are summarized in Figure 8. At the top of each vertical column the average headway is indicated, and the numbers not in parentheses are the medians, while the numbers in the parentheses are the mid-point of the headway intervals which are the modes. The average is greater than the median for each facility, lane, and minute volume group combination. The median is greater than the mode for each facility, lane, and minute volume group combination except for the James Couzens Highway, lane 1 with a volume group of 26-30 vehicles per minute.

FIGURE 6

HEADWAY DISTRIBUTIONS RELATED TO TRAFFIC VOLUME

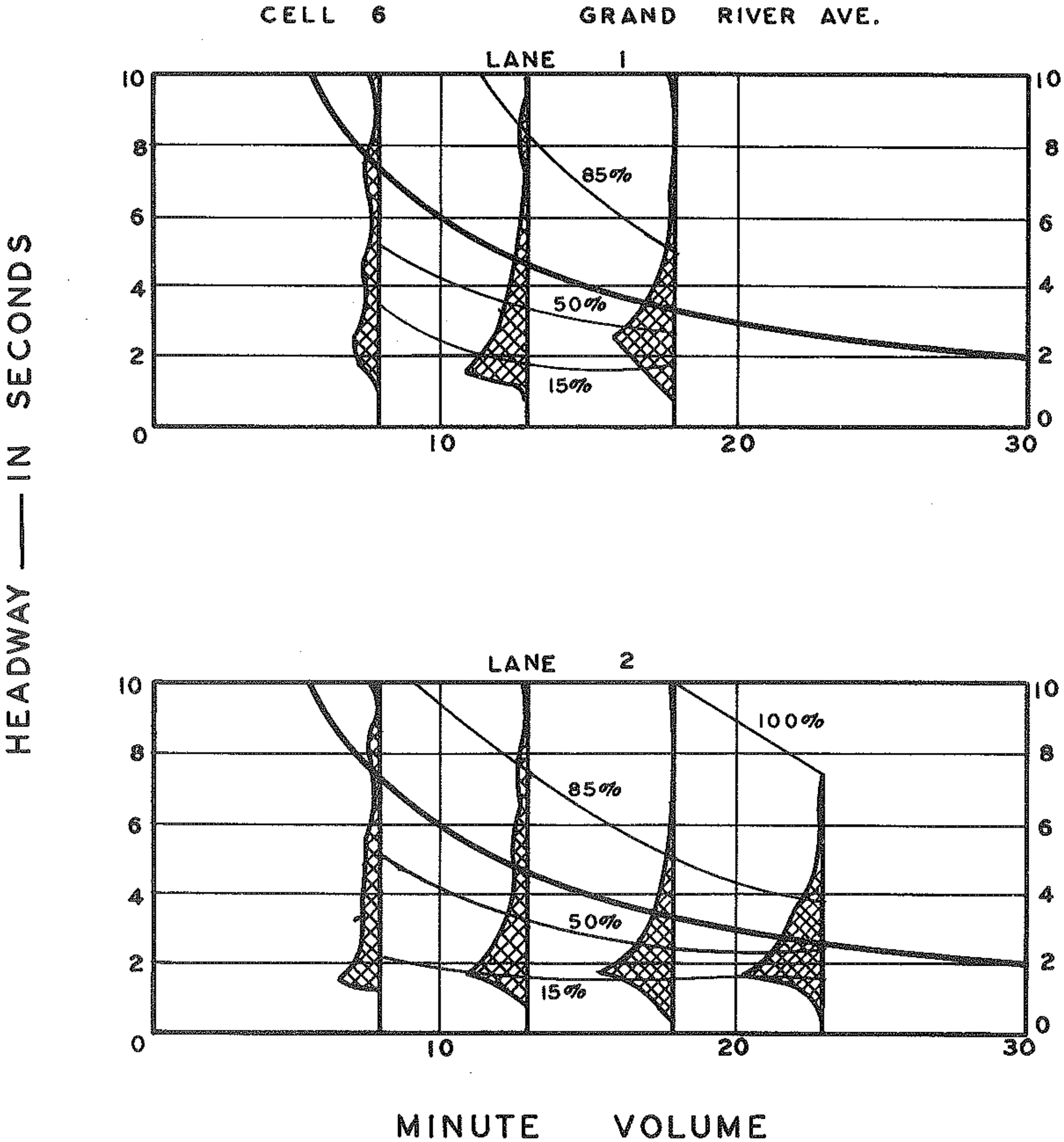


FIGURE 7

HEADWAY DISTRIBUTIONS RELATED TO TRAFFIC VOLUME

CELL 7 JAMES COUZENS HWY.

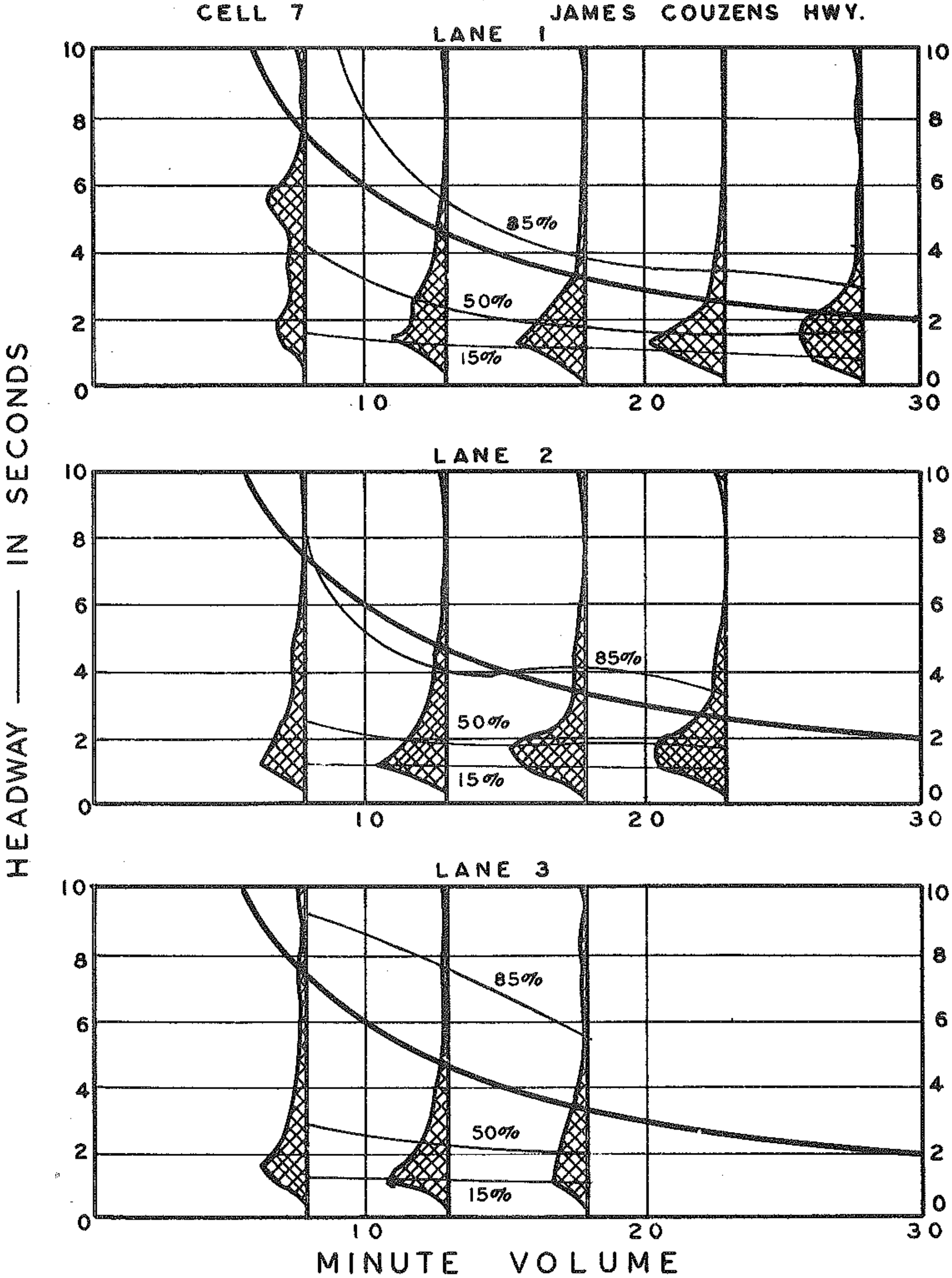


FIGURE 8
CENTRAL TENDENCIES OF HEADWAY DISTRIBUTIONS

Cell Number	Lane Number	Minute Volume Group and Average Headway				
		6-10 Veh.	11-15 Veh.	16-20 Veh.	21-25 Veh.	26-30 Veh.
		$\bar{H}$=7.5	$\bar{H}$=4.6	$\bar{H}$=3.3	$\bar{H}$=2.6	$\bar{H}$=2.1
1	1	4.7 (0.8)	2.6 (0.8)	1.8 (0.8)	1.5 (0.8)	1.3 (0.8)
2	1	6.0 (1.8)	3.0 (1.2)	2.4 (1.2)	1.6 (1.2)	1.6 (1.2)
3	1	4.4 (1.8)	2.8 (1.8)	-----	-----	-----
4	1	7.4 (2.5)	-----	-----	-----	-----
5	1	2.9 (0.8)	2.6 (1.2)	1.8 (1.2)	1.9 (0.8)	-----
6	1	5.1 (2.5)	3.3 (1.8)	2.7 (2.5)	-----	-----
7	1	4.2 (1.8)	2.3 (1.2)	1.8 (1.2)	1.6 (1.2)	1.6 (1.8)
Average	1	5.0 (1.6)	2.8 (1.3)	2.1 (1.4)	1.6 (1.0)	1.5 (1.3)
1	2	5.6 (3.5)	3.5 (2.5)	2.6 (1.2)	2.0 (1.2)	1.7 (1.2)
2	2	4.8 (1.2)	3.4 (1.2)	2.3 (1.8)	2.2 (1.2)	1.6 (0.8)
3	2	5.0 (1.8)	2.9 (1.2)	1.9 (1.8)	1.8 (1.8)	1.7 (1.2)
4	2	5.8 (1.8)	4.2 (1.8)	-----	-----	-----
5	2	4.1 (1.8)	3.2 (1.2)	2.1 (1.2)	1.9 (1.2)	-----
6	2	-----	-----	-----	-----	-----
7	2	2.5 (1.2)	1.9 (1.2)	1.8 (1.8)	1.7 (1.2)	-----
Average	2	4.6 (1.9)	3.2 (1.5)	2.2 (1.6)	1.9 (1.3)	1.7 (1.1)
1	3	5.5 (3.5)	3.8 (1.8)	2.6 (1.8)	1.9 (1.2)	2.0 (1.2)
2	3	5.8 (3.5)	4.2 (1.8)	-----	-----	-----
3	3	4.9 (1.8)	3.3 (1.8)	2.5 (1.2)	-----	-----
4	3	6.8 (1.8)	-----	-----	-----	-----
5	3	5.3 (1.2)	3.4 (1.8)	2.7 (1.2)	-----	-----
6	3	5.1 (1.8)	3.2 (1.8)	2.4 (1.8)	2.4 (1.8)	-----
7	3	2.9 (1.8)	2.3 (1.2)	2.0 (1.2)	-----	-----
Average	3	5.2 (2.2)	3.4 (1.7)	2.4 (1.4)	2.2 (1.5)	2.0 (1.2)
Overall Average		4.9 (1.9)	3.1 (1.5)	2.2 (1.5)	1.9 (1.3)	1.7 (1.2)

All numbers in table are in seconds. The numbers not in parentheses are medians, and the numbers in parentheses are the mid-point of the modes.

As the minute volume increases, the average, median, and mode headway decreases. Generally for corresponding minute volumes, lane 3 has higher medians and modes than lanes 1 and 2. The ratio of the overall average median to the average headway for each of the five volume groups is relatively constant at about 70%. In other words, if the minute volume is 10 vehicles, the average headway is 60 divided by 10 or 6 seconds, and it would be estimated that 50 per cent of the vehicles are traveling at headways less than 70 per cent of 6 seconds or less than 4.2 seconds.

2. Cumulative Frequency Percentiles

The 15 and 85 percentile levels were determined for each volume group of each lane of each facility studied and are summarized in Figure 9. At the top of each vertical column the average headway is indicated, and the numbers not in parentheses are the 15 percentiles, while the numbers in parentheses are the 85 percentiles. As would be expected, as the minute volume increases the 15 and 85 percentiles decrease. There is considerable similarity between facilities and between lanes. The difference between the 15 and 85 percentiles (seventy per cent of the vehicles) have headway values between these two percentiles, and as minute volume increases the difference between percentiles decreases. Headways greater than 10 seconds were not classified and are simply indicated by the symbol ">10".

The ratio of the 15 percentile values to their corresponding 85 percentile values, and the ratio of either percentile to their corresponding average headway gradually increases with minute volumes. Roughly the 85 percentile is 60% greater than its corresponding average headway, while the 15 percentile is one-third of the average headway.

3. Per Cent of Vehicles Related to Average Headways

The per cent of vehicles with headways less than one-half of the average headway and the per cent of vehicles with headways less than the average headway are presented in Figure 10. At the top of each vertical column the minute volume group and the average headway are indicated. The numbers not in parentheses represent the per cent of vehicles with headways less than one-half the average headway, while the numbers in parentheses represent the per cent of vehicles with headways less than the average headway.

The per cent of vehicles with headways less than one-half the average headway varies considerably between facilities while the comparison between lanes is similar. This percentage decreases with an increase in minute volumes. At low volumes 40 per cent

FIGURE 9

CUMULATIVE FREQUENCY PERCENTILES

Cell Number	Lane Number	Minute Volume Group and Average Headway				
		6-10 Veh. $\bar{H}$ = 7.5	11-15 Veh. $\bar{H}$ = 4.6	16-20 Veh. $\bar{H}$ = 3.3	21-25 Veh. $\bar{H}$ = 2.6	26-30 Veh. $\bar{H}$ = 2.1
1	1	0.9 (>10)	0.8 (7.8)	0.8 (5.6)	0.7 (4.5)	0.5 (3.0)
2	1	1.8 (>10)	1.2 (9.1)	1.1 (6.4)	0.8 (5.2)	0.8 (3.8)
3	1	1.7 (>10)	1.2 (7.5)	-----	-----	-----
4	1	2.8 (>10)	-----	-----	-----	-----
5	1	1.0 (>10)	1.1 (8.6)	1.0 (6.7)	0.9 (4.7)	-----
6	1	2.4 (>10)	1.8 (8.1)	1.8 (4.8)	-----	-----
7	1	1.7 (>10)	1.0 (5.5)	1.1 (3.9)	1.0 (3.6)	0.8 (2.8)
Average	1	1.8 (>10)	1.2 (7.8)	1.2 (6.1)	0.8 (4.5)	0.7 (3.2)
1	2	2.3 (>10)	1.4 (7.5)	1.0 (6.0)	1.0 (4.3)	0.9 (3.5)
2	2	1.5 (>10)	1.2 (9.0)	1.1 (6.5)	1.1 (4.7)	0.9 (4.7)
3	2	2.1 (>10)	1.3 (8.7)	1.1 (4.2)	1.2 (5.5)	1.1 (3.0)
4	2	2.4 (>10)	1.8 (9.8)	-----	-----	-----
5	2	1.6 (>10)	1.1 (7.6)	1.0 (7.0)	1.0 (4.5)	-----
6	2	-----	-----	-----	-----	-----
7	2	1.2 (8.0)	1.1 (4.0)	1.1 (4.1)	1.1 (3.4)	-----
Average	2	1.9 (>10)	1.3 (7.8)	1.0 (5.6)	1.1 (4.5)	1.0 (3.7)
1	3	2.2 (>10)	1.6 (7.3)	1.2 (5.8)	1.1 (4.3)	1.1 (2.6)
2	3	2.5 (>10)	1.7 (8.3)	-----	-----	-----
3	3	2.0 (>10)	1.5 (7.6)	1.3 (6.6)	-----	-----
4	3	2.7 (>10)	-----	-----	-----	-----
5	3	1.7 (>10)	1.6 (9.4)	1.4 (7.6)	-----	-----
6	3	2.1 (>10)	1.7 (7.6)	1.6 (5.0)	1.6 (3.8)	-----
7	3	1.4 (9.3)	1.2 (6.6)	1.2 (5.5)	-----	-----
Average	3	1.8 (>10)	1.6 (7.8)	1.3 (6.1)	1.4 (4.1)	1.1 (2.6)
Overall Average		1.8 (>10)	1.4 (7.8)	1.2 (5.9)	1.1 (4.4)	0.9 (3.2)

All numbers in table are in seconds. The numbers not in parentheses are 15 percentiles and the numbers in parentheses are 85 percentiles.

FIGURE 10

PERCENT OF VEHICLES RELATED TO AVERAGE HEADWAYS

Cell Number	Lane Number	Minute Volume Group and Average Headway				
		6-10 Veh.	11-15 Veh.	16-20 Veh.	21-25 Veh.	26-30 Veh.
		$\bar{H}$ = 7.5	$\bar{H}$ = 4.6	$\bar{H}$ = 3.3	$\bar{H}$ = 2.6	$\bar{H}$ = 2.1
1	1	45 (64)	45 (67)	47 (70)	44 (70)	43 (74)
2	1	38 (67)	42 (69)	35 (64)	33 (67)	24 (63)
3	1	43 (64)	42 (64)	-----	-----	-----
4	1	26 (58)	-----	-----	-----	-----
5	1	55 (74)	46 (66)	44 (70)	32 (63)	-----
6	1	36 (70)	30 (66)	13 (70)	-----	-----
7	1	44 (76)	49 (80)	44 (82)	34 (74)	25 (75)
Average	1	41 (68)	42 (69)	37 (71)	36 (68)	31 (71)
1	2	31 (65)	47 (63)	37 (67)	28 (65)	22 (65)
2	2	41 (68)	38 (73)	30 (65)	24 (59)	32 (68)
3	2	34 (62)	37 (64)	32 (74)	26 (78)	13 (66)
4	2	31 (62)	29 (65)	-----	-----	-----
5	2	45 (68)	38 (66)	40 (65)	29 (66)	-----
6	2	-----	-----	-----	-----	-----
7	2	62 (84)	54 (84)	40 (77)	28 (76)	-----
Average	2	41 (68)	41 (69)	36 (70)	27 (69)	23 (66)
1	3	34 (59)	43 (61)	27 (62)	22 (64)	14 (62)
2	3	32 (60)	27 (54)	-----	-----	-----
3	3	40 (69)	36 (66)	40 (70)	-----	-----
4	3	25 (57)	-----	-----	-----	-----
5	3	37 (67)	38 (60)	31 (66)	-----	-----
6	3	35 (65)	32 (64)	20 (69)	8 (63)	-----
7	3	62 (81)	51 (79)	33 (74)	-----	-----
Average	3	38 (65)	38 (64)	30 (68)	15 (64)	14 (62)
Overall Average		40 (67)	40 (67)	34 (70)	26 (67)	22 (66)

All numbers in table are per cents. The numbers not in parentheses represent the per cent of vehicles with headways less than one-half the average headway and the numbers in parentheses represent the per cent of vehicles with headways less than the average headway.

or two-fifths of the vehicles have headways less than one-half the average headway while at high volumes the corresponding value is 22 per cent or about one-fifth. The overall average for all lanes of all facilities and at all volume groups is 32 per cent or about one-third.

The per cent of vehicles with headways less than the average headway is relatively constant. An increase in minute volume does not seem to affect this percentage and the difference between lanes is slight.

Cell 7 (James Couzens Highway) has higher percentages than other facilities but the proximity of a traffic signal could explain the larger percentages. The overall average for all lanes of all facilities and at all volume levels is 67 per cent or approximately two-thirds. Considering the overall set of data, one could roughly say that one-third of the vehicles are traveling at headways less than one-half the average headway; one-third of the vehicles are traveling at headways between one-half of the average headway and the average headway; and one-third of the vehicles are traveling at headways greater than the average headway.

4. Frequency Distributions

The headway frequency distributions were determined for each volume group and are summarized in Figure 11. These percentages are the average of all seven facilities and all lanes. The numbers not in parentheses indicate the per cent of vehicles in a particular headway interval. The numbers in parentheses indicate the actual number of vehicles traveling at the particular headway interval at volumes of 8, 13, 18, 23 and 28 vehicles per minute. Note that the first four headway intervals are one-half second intervals, the next eight headway intervals are one second intervals, and the last headway interval is for those vehicles having headways greater than ten seconds.

Care should be exercised in using the data from this Figure since the numbers represent the average for the seven facilities and for all lanes. It is included in the report for use as a guide and to indicate that a pattern does appear to exist between headway distributions and traffic volumes. This type of data should be most useful in the simulation of traffic flow on computers.

The numbers in parentheses give some indication of the number of vehicles traveling at the various headway intervals at the various volume levels. The mid-point minute volume (8, 13, 18, 23, and 28 vehicles per minute) were selected as examples for each of the volume groups.

FIGURE 11

HEADWAY FREQUENCY DISTRIBUTIONS AT VARIOUS MINUTE VOLUMES

COMPOSITE - ALL LANES - ALL FACILITIES

Headway Interval (Seconds)	Minute Volume Group and Average Headway				
	6-10 Veh.	11-15 Veh.	16-20 Veh.	21-25 Veh.	26-30 Veh.
	$\bar{H}$ = 7.5	$\bar{H}$ = 4.6	$\bar{H}$ = 3.3	$\bar{H}$ = 2.6	$\bar{H}$ = 2.1
0 - 0.5	1%	1%	1%	2%	3% (1)
0.5 - 1.0	3	7 (1)	8 (2)	12 (3)	16 (5)
1.0 - 1.5	7 (1)	12 (2)	17 (3)	20 (5)	24 (7)
1.5 - 2.0	9 (1)	14 (2)	17 (3)	20 (5)	20 (6)
2.0 - 3.0	12 (1)	17 (2)	20 (4)	18 (4)	17 (5)
3.0 - 4.0	11 (1)	11 (2)	11 (2)	10 (3)	8 (2)
4.0 - 5.0	8 (1)	8 (1)	7 (1)	7 (2)	5 (1)
5.0 - 6.0	8 (1)	7 (1)	5 (1)	4 (1)	3 (1)
6.0 - 7.0	5	4 (1)	4 (1)	2	1
7.0 - 8.0	5	4	2	1	1
8.0 - 9.0	4	3	2	1	1
9.0 - 10.0	4	3	2	1	0
> 10	23 (2)	9 (1)	4 (1)	2	1
All Headways	100% (8)	100% (13)	100% (18)	100% (23)	100% (28)

The numbers not in parentheses indicate the per cent of vehicles in a particular headway interval. The numbers in parentheses indicate the actual number of vehicles traveling at the particular headway interval at volumes of 8, 13, 18, 23, and 28 vehicles per minute.

II. INTER-RELATIONSHIPS OF FUNDAMENTAL CHARACTERISTICS

The fundamental characteristics of traffic flow have been discussed as separate phenomena in the early portion of this report. This chapter will attempt to illustrate how these characteristics--volume, speed, and headway--are inter-related. A fourth characteristic, traffic density, will be introduced in this discussion. Traffic density, as the name implies, is a measure of the density of traffic and can be expressed as the number of vehicles occupying a one mile section of highway. In this discussion all traffic characteristics will be presented on a per lane per minute basis. Density can be determined by photographic techniques or by input-output volume counts. Another method, used in this study, is to compute density mathematically by dividing the traffic volume by average speed.

Mathematical equations needed in order to develop the inter-relationships are (a) density (vehicles per mile) as a function of average speed (miles per hour) and volume (vehicles per lane per minute); (b) distance highway (feet per vehicle) as a reciprocal function of density (vehicles per mile); (c) time headway (seconds per vehicle) as a reciprocal function of volume (vehicles per lane per minute); (d) travel time (minutes per mile) as a reciprocal function of average speed (miles per hour); and (e) time loss (minutes per mile) as the difference between actual travel time per mile and an assumed standard travel time per mile.

$$\text{(a)} \quad D = \frac{60\,Q}{S}$$

$$\text{(b)} \quad H_d = \frac{5280}{D}$$

$$\text{(c)} \quad H_t = \frac{60}{Q}$$

$$\text{(d)} \quad T = \frac{60}{S}$$

$$\text{(e)} \quad T_L = T - 1.0 = \frac{60}{S} - 1.0$$

The construction of the Figures to be presented for each of the seven locations will now be discussed. One figure for each facility was prepared and there are two graphs on each figure.

The top graph on each of the seven figures illustrates the speed-volume relationship for each lane. The vertical scale is minute average lane speed in miles per hour and the horizontal scale is minute lane volume. The lower diagram on each of the seven figures illustrates a graphical presentation of the inter-relationships of volume, speed, density, average distance headway, and average time headway. The left vertical scale is minute lane volume while the right vertical scale is average time headway (seconds). The lower horizontal scale is lane density (vehicles per mile) while the upper horizontal scale is average distance headway (feet). The sloping straight lines, extending from the lower left hand corner of the graph, represent average speed (miles per hour). The steeper the slopes the higher the speeds.

The inter-relationships of fundamental characteristics for each of the seven locations will now be presented and later these inter-relationships will be compared and summarized.

A. Presentation of Inter-Relationships of Fundamental Characteristics

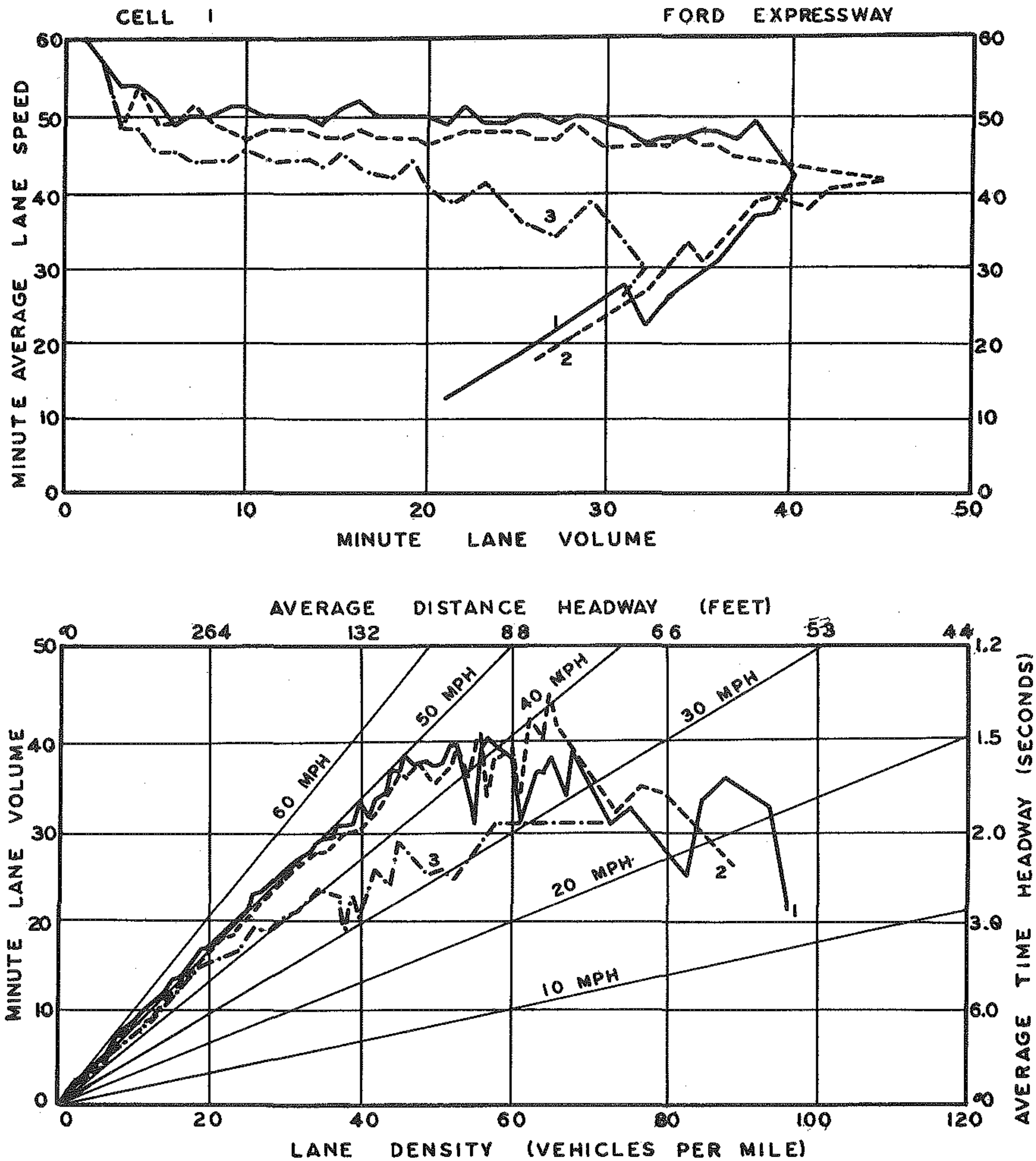
The speed-volume relationships and the density related to other fundamental characteristics for each lane of the Ford Expressway (cell 1) is presented in Figure 12. The solid line represents lane 1 (median lane), the dashed line represents lane 2 (middle lane), and the dot-dashed line represents lane 3 (curb lane).

The speed-volume relationships for each of the three lanes is presented in the upper graph. Starting at the high speed-low volume portion of the curve and moving to the right, there is a slight downward to the right slope for lanes 1 and 2 while the slope for lane 3 is steeper. For lanes 1 and 2 this slope continues up to a volume load of 40 vehicles per minute where the speed is 42-43 miles per hour. For lane 3 this slope continues up to a volume load of 32 vehicles per minute where the speed is 30 miles per hour. At this maximum volume point there is a rapid reduction with no increase in traffic volume. This is followed by a downward to the left sloped curve indicating a reduction in both volume and speed. Extremely low volume-low speed combinations were not encountered in the field, however it is obvious that all three curves theoretically will have to pass through the lower left hand origin where speed and volume are zero.

This graph illustrates the point that traffic volume data alone does not provide a true indication of whether an expressway is operating in a satisfactory or unsatisfactory condition. For example, if a traffic volume recorder was placed on lane 1, and volume information was being transmitted to a central office, a

FIGURE 12

INTER-RELATIONSHIPS OF FUNDAMENTAL CHARACTERISTICS



volume of 30 vehicles per minute would only indicate that the average speed was between 26 and 49 miles per hour. This graph also illustrates that average speed data alone is not too adequate as a measure of satisfactory operation. The reason for this is that there is little change in speed (58 to 48 miles per hour) for a large increase in volume (0 to 35 vehicles per minute) while an increase of volume from only 35 vehicles to 40 vehicles per minute reduces speed from 48 to 40 miles per hour. In other words, the rate of change in speed at low volumes (upper curve) is small until the critical point is almost reached and then the speed decreases very rapidly over a small range of volume (and time).

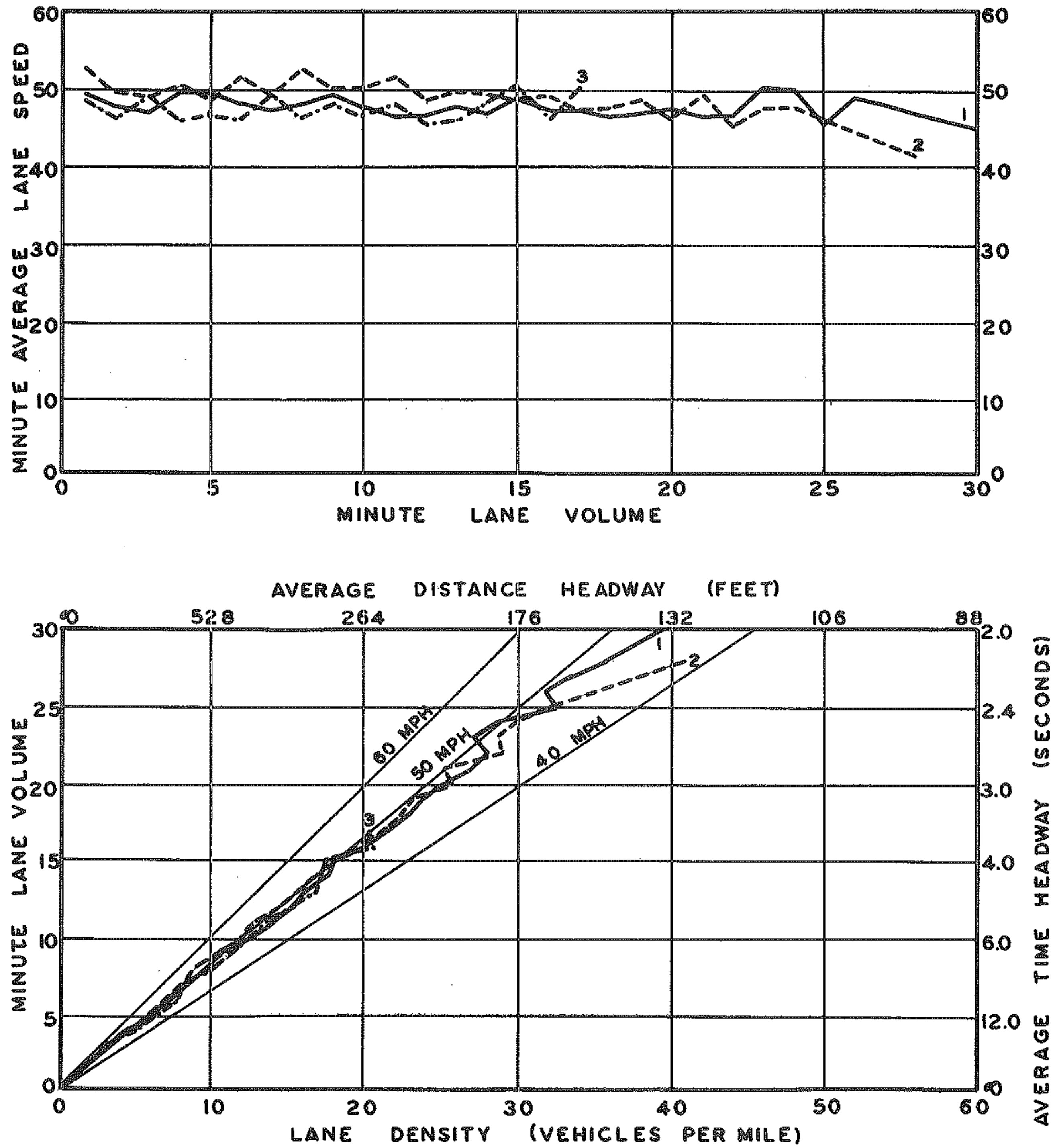
Density related to the other fundamental characteristics for each lane of the Ford Expressway (cell 1) is presented in the lower graph of Figure 12. As in the case of the speed-volume relationships, all characteristics were computed on a per minute basis and each minute of the selected twenty-four hour period is included. The three curves representing the three lanes are similar in the 0 to 15 density range to the sloping straight line representing 50 miles per hour. In the density range from 15 to 60 the curves for lane 1 and 2 continue to be extended up and to the right but with a continuing decrease in the slope of the curve. At about a density of 60 the maximum volume is reached and the slope of the curve is zero. The curve for lane 3 began to flatten out at a lower volume, and reaches its maximum volume (31 vehicles per minute) at a density of 60 to 70. The maximum rate of flow is reached for lanes 1, 2, and 3 at speeds of 42, 39 and 27 miles per hour. The curve for lane 3 did not have a negative slope or any observations at densities greater than the density when the volume is maximum. The curves for lane 1 and 2 did have negative slopes from densities of 60 up to densities of 100. Average densities greater than 100 did not exist for a full minute at the field location. However, manual checks were made of density for shorter intervals of time during complete stoppage (zero speed and zero instantaneous volume) and found to be 200 to 225 vehicles per lane per mile. In other words, in theory at least, the maximum density is 200 to 225 and would occur at zero speed and zero volume. An important conclusion to be drawn is that when the curves have negative slopes we are not only inconveniencing each motorist but the ability to carry traffic volume has been reduced.

The speed-volume relationships and density related to other fundamental characteristics for each lane of the Davison Expressway (cell 2) is presented in Figure 13. The number shown next to each curve is the lane number. There is a slight downward slope to the right on the speed-volume graph (upper graph) with speeds at the lower volume levels being approximately 46 to 50 miles per hour while the speeds at 25 to 30 vehicles per minute were 42 to 48 miles per hour. The traffic demand did not reach a high enough

FIGURE 13

INTER-RELATIONSHIPS OF FUNDAMENTAL CHARACTERISTICS

CELL 2 DAVISON EXPRESSWAY



level to cause a drastic reduction in speed. The positions of the three curves are quite similar. In the lower graph, density related to other fundamental characteristics is depicted. Again, as would be expected from the upper graph, all three curves have almost the same position. The three curves are almost linear up to a density of 30 vehicles per mile and lie on the 50 mile per hour sloping line. At a density of 30, the curves for lanes 1 and 2 begin to flatten out but only extend up to a density of 41 vehicles per mile.

The speed-volume relationships and density related to other fundamental characteristics for each lane of Schaefer Road (cell 3) is presented in Figure 14. In the speed-volume relationship (upper graph) there appears to be a slight downward to the right slope for the curves representing lanes 2 and 3, but it is difficult to interpret the travel for lane 1. The curve for lane 3 lies approximately five miles per hour lower than lane 2. The traffic demand was never great enough to cause a drastic reduction in speed. The lower graph indicates that the lanes are essentially linear up to a density of 15 and appear similar to the 40 mile per hour curve. As density increases beyond 15, the curves for lanes 2 and 3 begin to flatten out.

The speed-volume relationships and density related to other fundamental characteristics for each lane of Michigan Avenue in East Lansing (cell 4) is given in Figure 15. The range in traffic volume at this location was limited and a trend is not apparent from the graph. The curves for lanes 1 and 2 are somewhat similar while the curve for lane 3 is approximately 5 miles per hour lower. The conclusions that can be drawn from the lower graph are also limited due to the relatively small range in lane density. There appears to be little effect of traffic density on average speed.

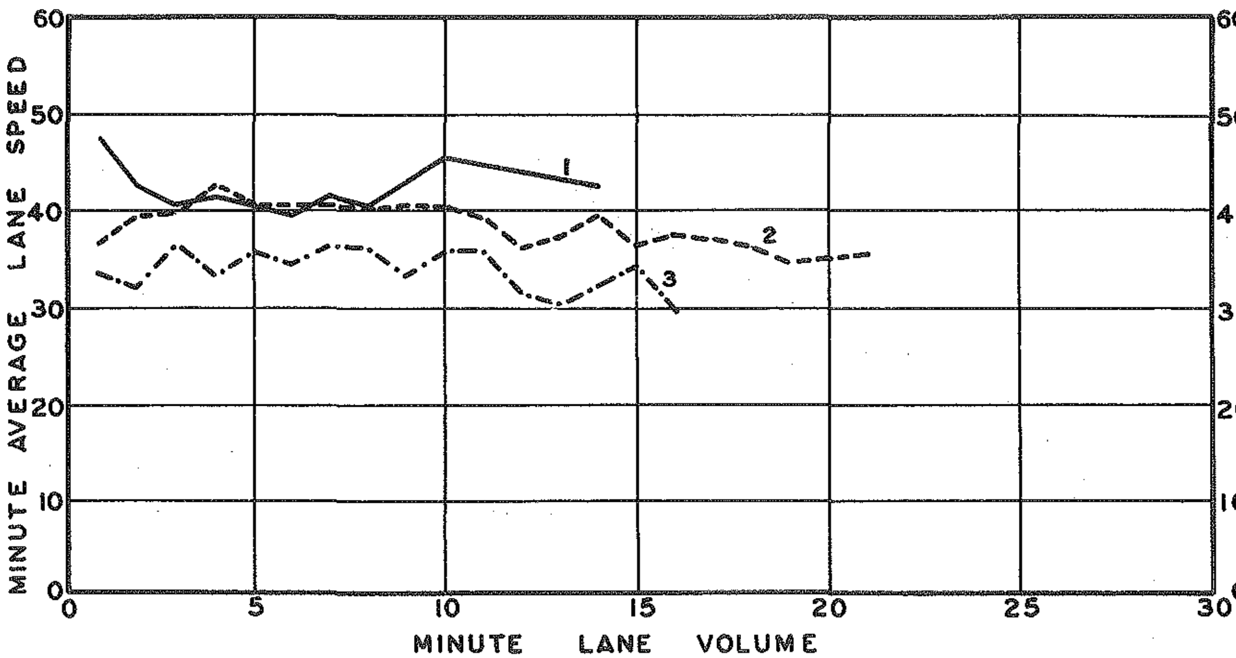
The speed-volume relationships and density related to other fundamental characteristics of traffic flow for each lane of Michigan Avenue in Dearborn (cell 5) is depicted in Figure 16. Although the volume range is relatively great, there appears to be little effect of volume on average speed. The curves for lanes 1 and 2 are similar while lane 3 is 5 to 8 miles per hour lower. The lower graph indicates that up to a density of at least 35, average speed is essentially not affected by increased density.

The speed-volume relationships and density related to other fundamental characteristics of traffic flow for each of the two lanes of Grand River Avenue in East Lansing (cell 6) is presented in Figure 17. The speed-volume curves appear to have the steepest negative slopes of any of the previous curves presented. From

FIGURE 14

INTER-RELATIONSHIPS OF FUNDAMENTAL CHARACTERISTICS

CELL 3 SCHAEFER ROAD



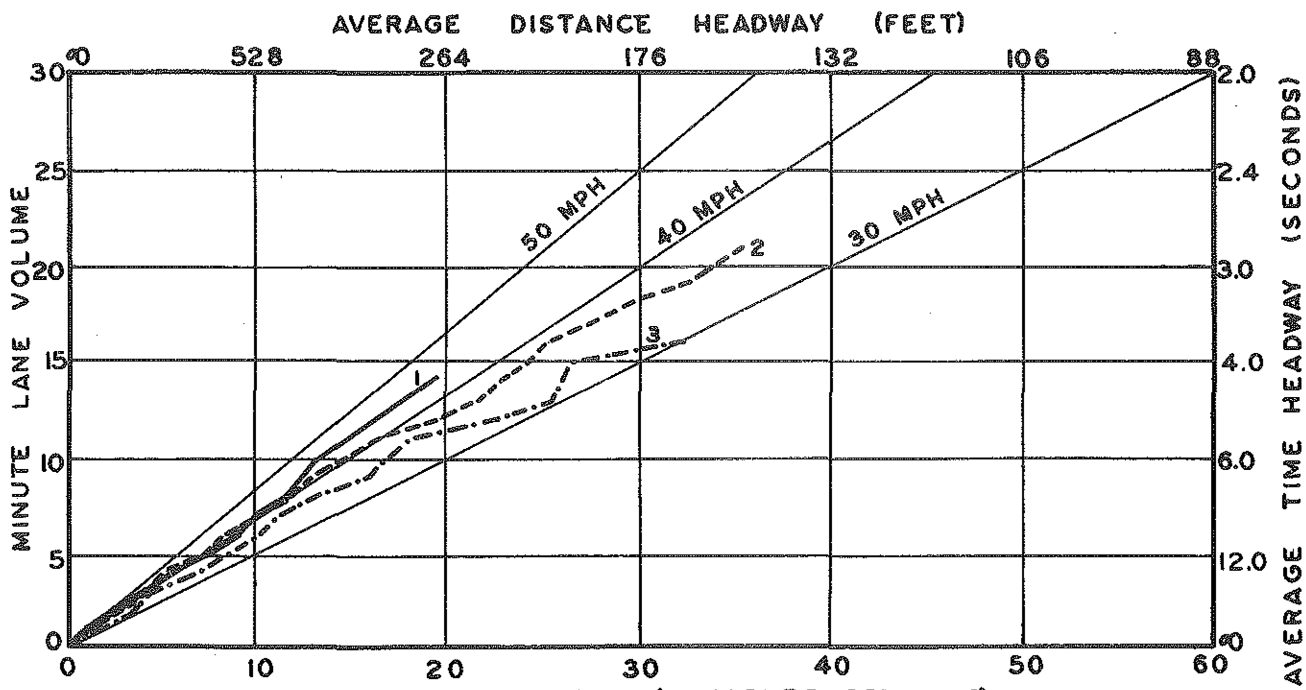
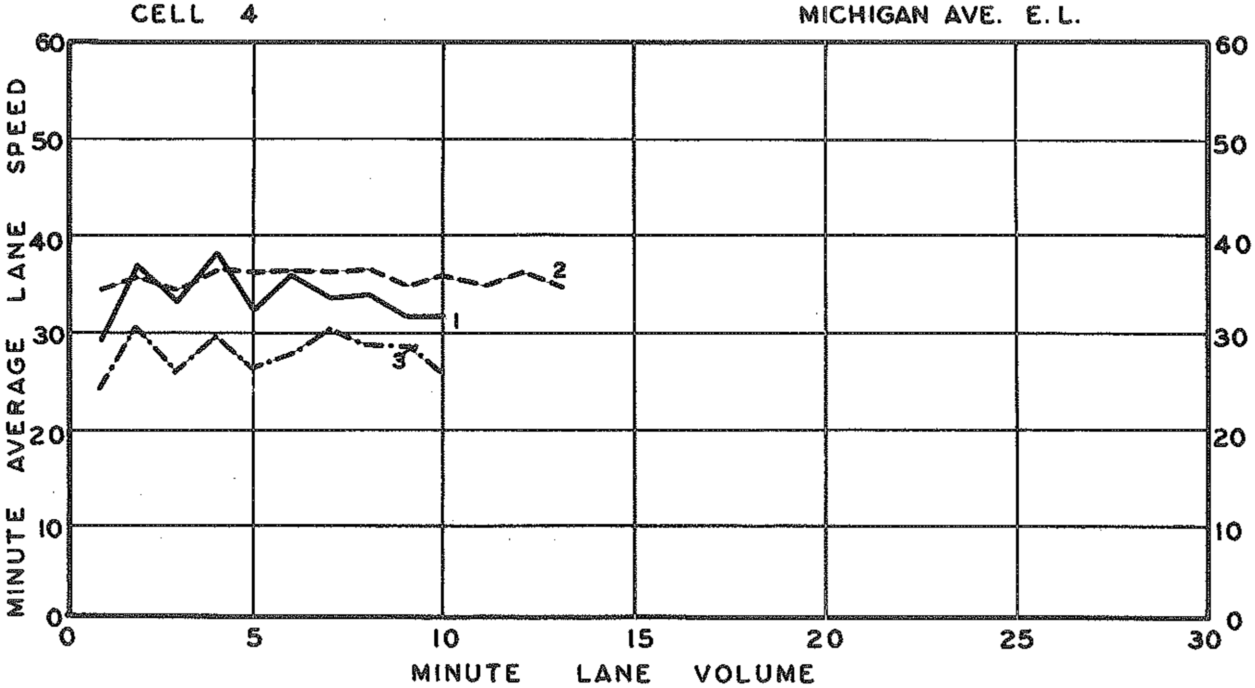


FIGURE 15

INTER-RELATIONSHIPS OF FUNDAMENTAL CHARACTERISTICS



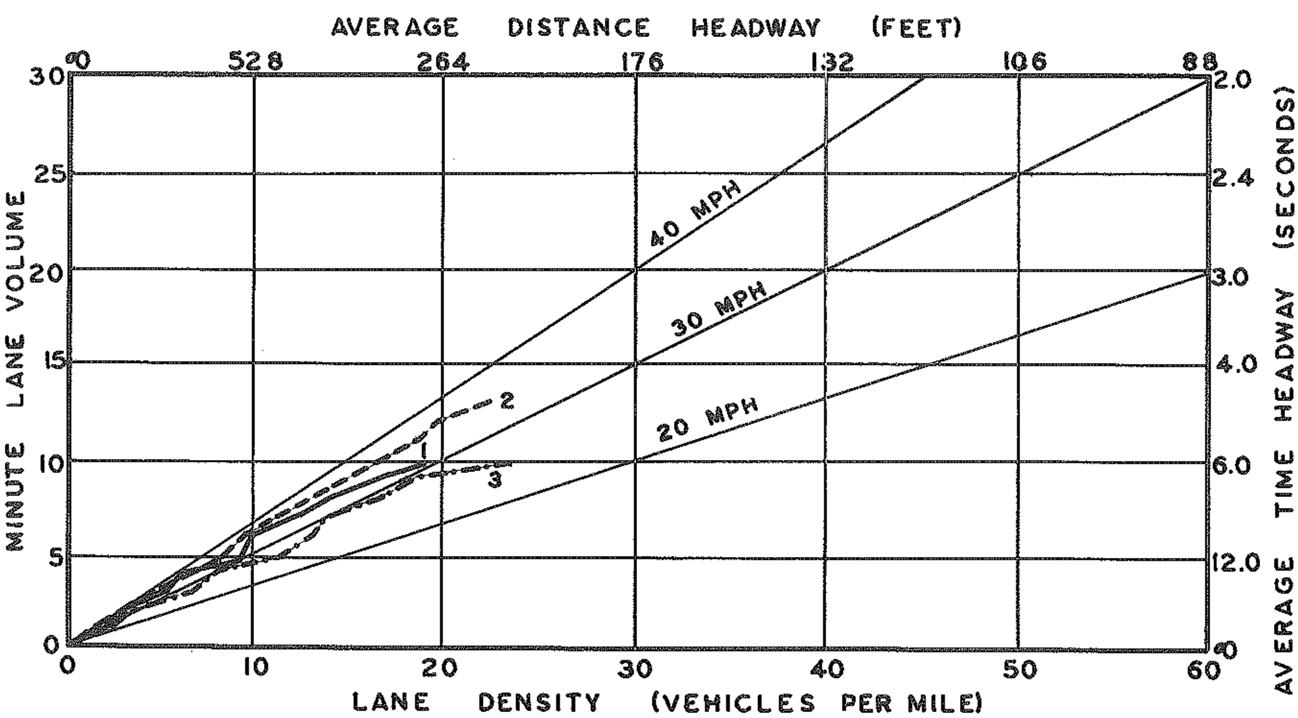
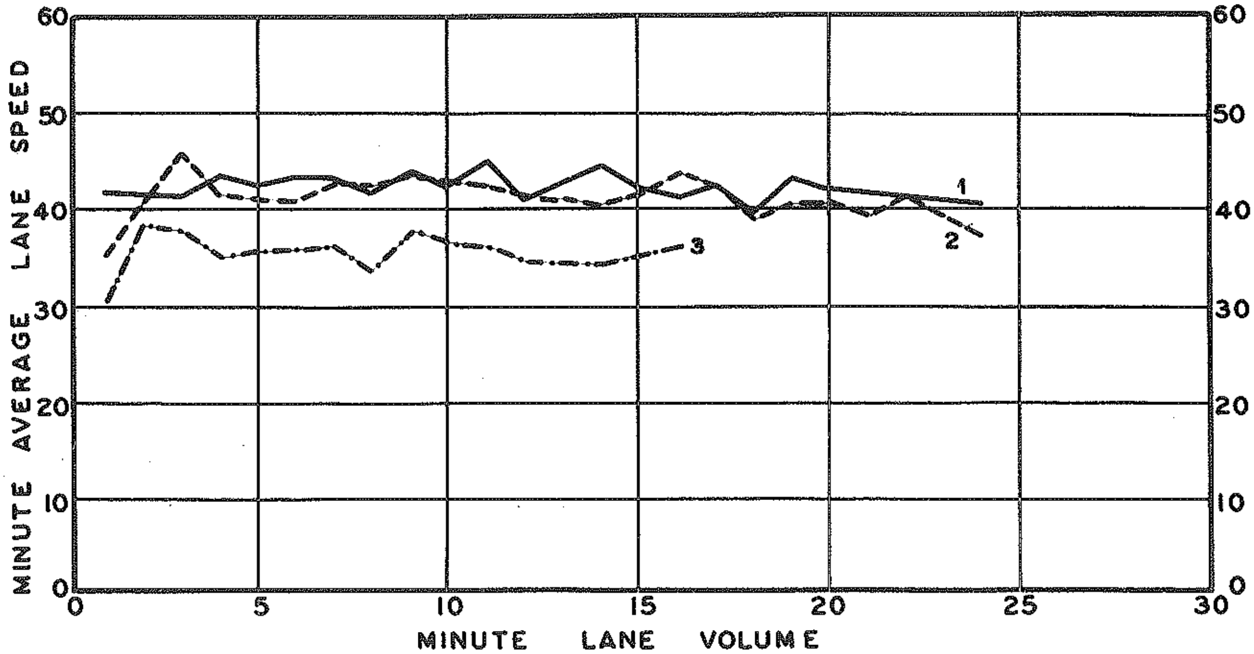


FIGURE 16

INTER-RELATIONSHIPS OF FUNDAMENTAL CHARACTERISTICS

CELL 5 MICHIGAN AVE. DEARBORN



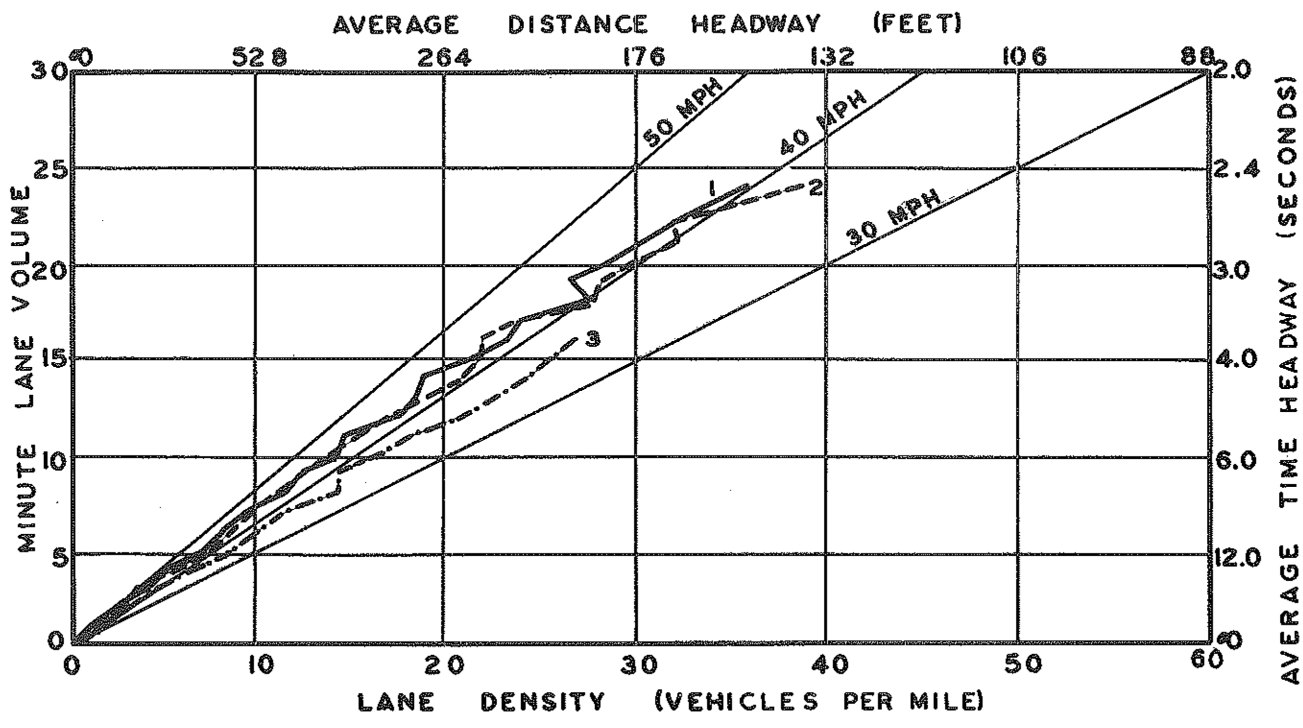
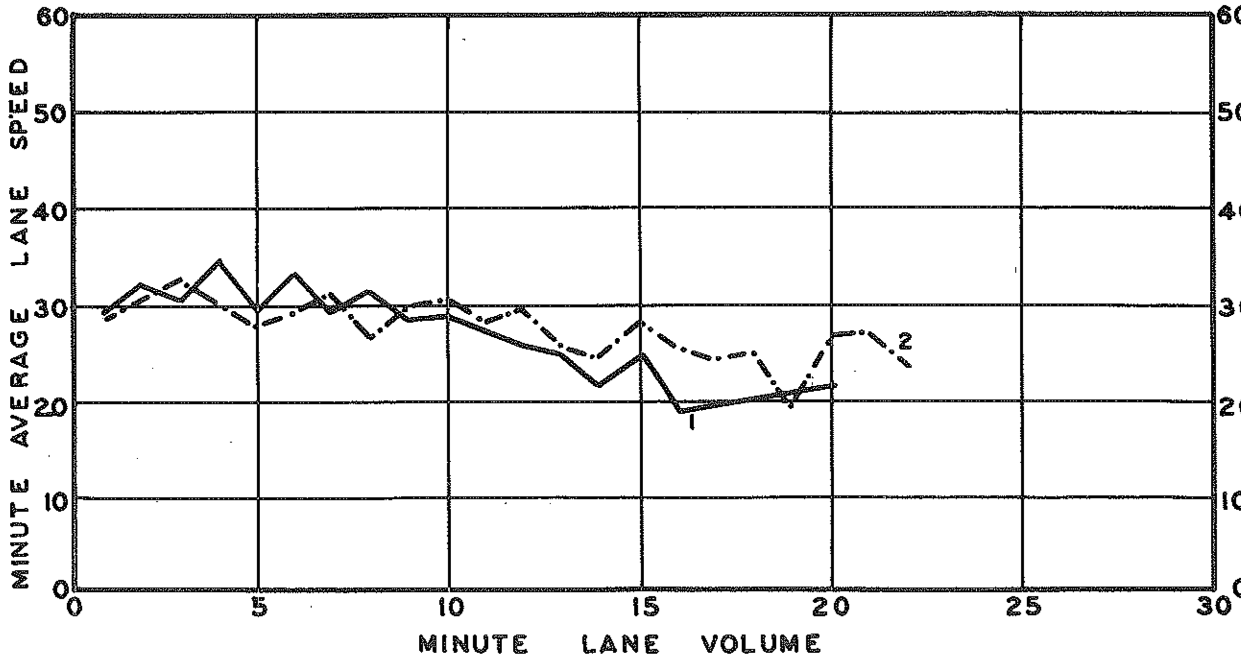
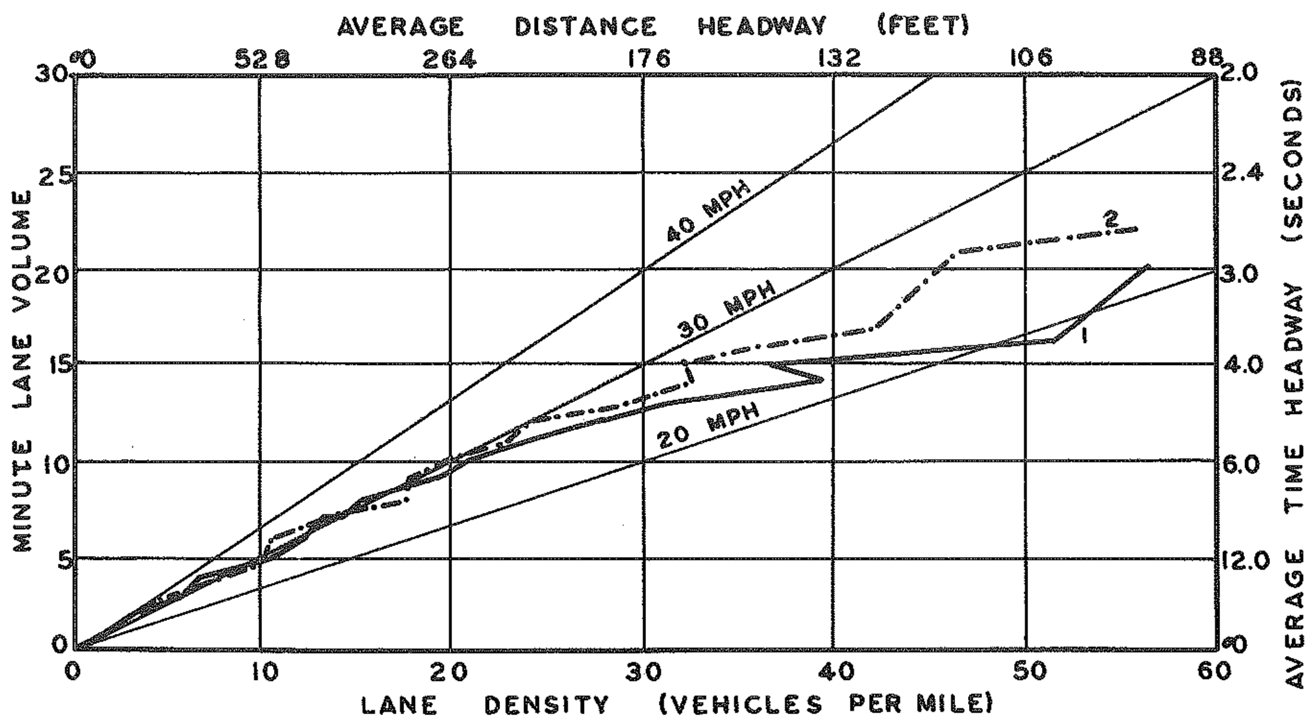


FIGURE 17

INTER-RELATIONSHIPS OF FUNDAMENTAL CHARACTERISTICS





very low volumes up to volumes of 20 vehicles per minute per lane, the average speed decreases from 30 to 34 miles per hour down to 19 to 25 miles per hour. This might be a significant result in that two lane (in each direction) facilities are more affected by increased lane volume than three lane (in each direction) facilities. The lower graph also indicates that speed has been significantly reduced by increase in traffic demand. Except for the Ford Expressway, this facility had the greatest traffic density of the seven locations studied. This large density range may be the reason for the drastic reduction in speed. In fact, a study of the lower graph reveals that as density exceeds 25 vehicles per mile there is a steady decrease in the slope of the lane curves, and by extending the curves slightly above the maximum density recorded, the curves approach a slope of zero at about a density of 60, a speed of 22 and a lane volume of 22.

These graphs give some indication that maximum volume occurs at a lane density of about 60 vehicles per mile. Additional research on this specific point would be most desirable.

The speed-volume relationships and density related to other fundamental characteristics of traffic flow for each of the four lanes of James Couzens Highway (cell 7) is given in Figure 18. The upper graph presenting the speed-volume relationship indicates a very slight negative slope over a relatively large volume range. The curves for lanes 1, 2, and 3 are quite similar while the curve for lane 4 is approximately 5 to 7 miles per hour lower. The curves in the lower graph are slightly above the 30 mile per hour curve and then there appears to be a flattening out of the curves for lanes 2 and 3 in the 50 to 60 vehicles per mile density level.

B. Comparison and Summary of Inter-Relationships of Fundamental Characteristics

The comparison and summary of inter-relationships of fundamental characteristics of traffic flow will be presented in two parts. The first part will pertain to the speed-volume relationships, and the second part will be devoted to density related to other fundamental characteristics.

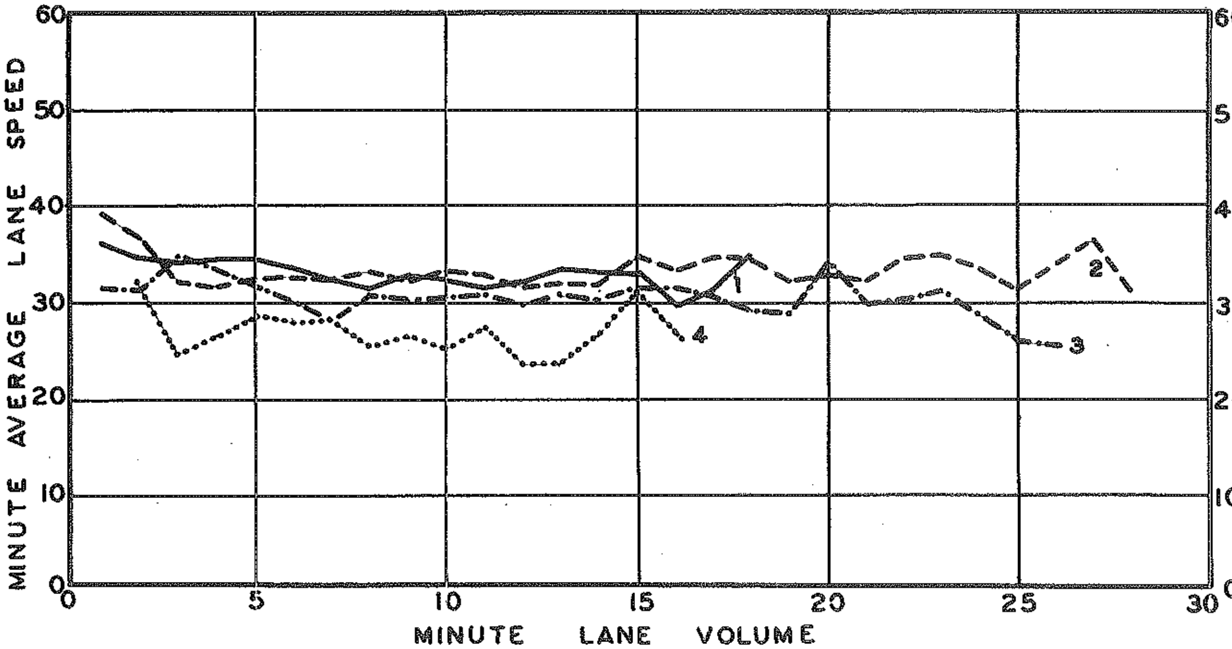
1. Speed-Volume Relationships

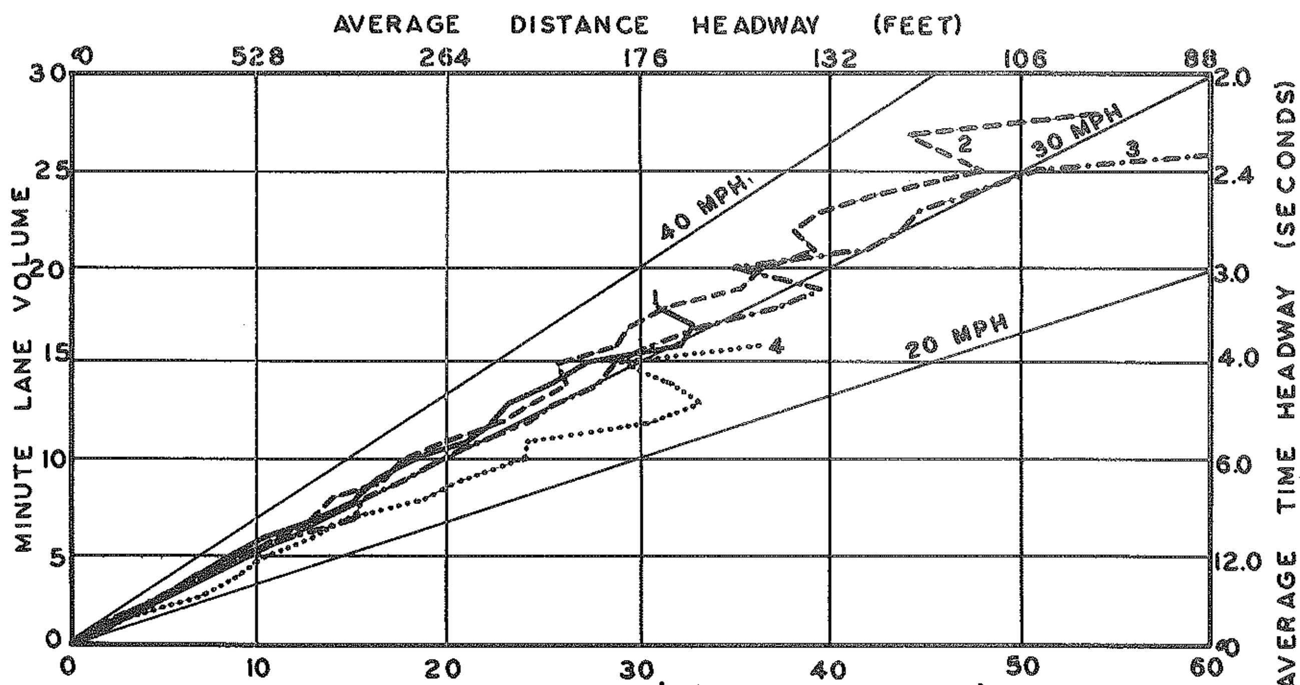
Linear regression analyses were made for each lane of each of the seven locations in order to determine if volume adversely affected speed for minute volumes up to 30 vehicles per minute. In addition, this type of analysis would permit the derivation of equations so that speed could be estimated when the minute lane volume data were available. It is assumed that the speed-volume

FIGURE 18

INTER-RELATIONSHIPS OF FUNDAMENTAL CHARACTERISTICS

CELL 7 JAMES COUZENS HWY.





relationship is linear for the volume range of 0 to 30 vehicles per minute. The summary of the linear speed-volume relationships for each lane of each facility is presented in Figure 19.

The symbol "S" represents average speed in miles per hour and "Q" represents minute lane volume. For example, if one wishes to estimate the average speed on lane 1 of the Ford Expressway (cell 1) at a volume of 20 vehicles per minute, then

$$
\begin{aligned}
S &= 54.5 - 0.215\,Q \\
\text{Since } Q &= 20 \\
S &= 54.5 - 0.215(20) \\
&= 54.5 - 4.3 \\
S &= 50.2 \text{ miles per hour}
\end{aligned}
$$

The constant "54.5" indicates the theoretical speed in miles per hour at a minute volume of zero, or in other words, under the lightest traffic volume. The algebraic sign on the right side of the equation indicates whether the line has a upward or downward slope to the right. A "plus" sign indicates a upward slope (increasing volume with a increasing speed) while a "negative" sign indicates a downward slope (increasing volume with a decreasing speed). The constant "0.215" preceding the Q indicates the steepness of the slope, and numerical means that there is a change of 0.215 miles per hour for each additional vehicle per minute.

The "a" values (average speed at zero volume) for the various lanes and facilities vary from 27.0 to 54.5 miles per hour. The "b" values (slope of linear relationship) vary from a positive slope of +.122 to a negative slope of .700. Three of the lines have positive slopes (increases in speed with increases in volume).

2. Density related to other Fundamental Characteristics

In the previous section a linear equation of the speed-volume relationship for each lane of each facility was developed. The form of the linear equation is

$$S = a \pm bQ$$

where,

S = speed in miles per hour
a = speed at zero volume
b = slope of the line
Q = volume in vehicles per minute

FIGURE 19

LINEAR EQUATIONS FOR SPEED-VOLUME RELATIONSHIPS

Cell Number	Lane Number	Equation
1	1	$S = 54.5 - .215\ Q$
	2	$S = 53.3 - .271\ Q$
	3	$S = 47.3 - .474\ Q$
2	1	$S = 48.4 - .044\ Q$
	2	$S = 52.0 - .229\ Q$
	3	$S = 48.2 + .065\ Q$
3	1	$S = 42.7 - .061\ Q$
	2	$S = 41.1 - .240\ Q$
	3	$S = 34.5 - .082\ Q$
4	1	$S = 34.1 - .111\ Q$
	2	$S = 35.1 + .044\ Q$
	3	$S = 27.0 + .122\ Q$
5	1	$S = 42.8 - .048\ Q$
	2	$S = 48.4 - .597\ Q$
	3	$S = 35.7 + .036\ Q$
6	1	$S = 34.1 - .700\ Q$
	2	$S = 31.5 - .339\ Q$
7	1	$S = 34.4 - .150\ Q$
	2	$S = 33.5 - .017\ Q$
	3	$S = 32.1 - .131\ Q$
	4	$S = 27.7 - .116\ Q$

since,

$$60Q = D \times S$$

$$S = \frac{60Q}{D}$$

substituting,

$$\frac{60Q}{D} = a \pm bQ$$

solving for Q,

$$Q = \frac{a}{\frac{60}{D} - (\pm b)}$$

Substituting the appropriate values for "a" and "b", the volume-density equation can be determined for each lane of each facility. The summary of these equations are presented in Figure 20.

These equations were developed for volume data up to 30 vehicles per minute. Consequently their use for minute volume conditions beyond 30 vehicles per minute are limited, and can only be used for approximations. It was decided to investigate a method of approximating maximum lane minute volume. On several of the high density lanes, notably the expressway lanes, it appeared that maximum volume occurred at densities of about 60 vehicles per mile. Using the equations given in Figure 20, and a density of 60, an estimate was made of maximum minute volume for each lane and are tabulated in Figure 20. It is obvious that additional research is needed in area of endeavor and the overloading of these facilities artificially might be one approach for solution.

The equations given previously,

$$S = a \pm bQ$$

$$\text{and} \quad 60Q = D \times S$$

can be rearranged in order to solve for speed (S) in terms of density (D).

$$\text{since} \quad Q = \frac{DS}{60}$$

$$\text{then} \quad S = a \pm b\left(\frac{DS}{60}\right)$$

FIGURE 20

EQUATIONS FOR VOLUME-DENSITY RELATIONSHIPS

Cell Number	Lane Number	Equation	Estimated maximum minute volumes
1	1	$Q = 54.5 / \frac{60}{D} + .215$	45
	2	$Q = 53.3 / \frac{60}{D} + .271$	42
	3	$Q = 47.3 / \frac{60}{D} + .474$	32
2	1	$Q = 48.4 / \frac{60}{D} + .044$	46
	2	$Q = 52.0 / \frac{60}{D} + .229$	42
	3	$Q = 48.2 / \frac{60}{D} - .065$	-*
3	1	$Q = 42.7 / \frac{60}{D} + .061$	40
	2	$Q = 41.1 / \frac{60}{D} + .240$	33
	3	$Q = 34.5 / \frac{60}{D} + .082$	32
4	1	$Q = 34.1 / \frac{60}{D} + .111$	31
	2	$Q = 35.1 / \frac{60}{D} - .044$	-*
	3	$Q = 27.0 / \frac{60}{D} - .122$	-*

*Not computed because of positive slopes

FIGURE 20 (Concluded)

Cell Number	Lane Number	Equation	Estimated maximum minute volumes
5	1	$Q = 42.8 / \frac{60}{D} + .048$	41
	2	$Q = 48.4 / \frac{60}{D} + .597$	30
	3	$Q = 35.7 / \frac{60}{D} - .036$	-*
6	1	$Q = 34.1 / \frac{60}{D} + .700$	20
	2	$Q = 31.5 / \frac{60}{D} + .339$	24
7	1	$Q = 34.4 / \frac{60}{D} + .150$	30
	2	$Q = 33.5 / \frac{60}{D} + .017$	33
	3	$Q = 32.1 / \frac{60}{D} + .131$	24
	4	$Q = 27.7 / \frac{60}{D} + .116$	25

*Not computed because of positive slopes

Rearranging

$$S = \frac{a}{1 - \left(\frac{\pm bd}{60}\right)}$$

or

$$S = \frac{60a}{60 - \left(\pm bd\right)}$$

when D = 60,

$$S = \frac{a}{1 - \left(\pm b\right)}$$

This permits the calculation of average speed for various values of density. It is developed specifically for volumes up to 30 vehicles per minute.

In summary, the volume-density relationships were curvilinear and the equations for the curves were determined. Maximum volume appeared to occur at a density of approximately 60 vehicles per mile, and the maximum volumes were computed.

III. SUMMARY

The more important findings pertaining to the headway characteristics and the inter-relationships of the fundamental characteristics of traffic flow of the seven locations on major urban arterials are summarized below.

1. The effect of traffic volume on headway distributions follows definite patterns, and these patterns are similar for the locations studied.

2. Statistical components of the various headway distributions are in close agreement. For example, modes are essentially unaffected by traffic volumes, and are less than the medians which are in turn less than the means.

3. Techniques of estimating headway characteristics are included. The techniques are particularly applicable in problems of simulating traffic flow on computors.

4. Speed-volume relationships and density related to other fundamental characteristics for each lane of each of the seven locations studied were developed, and are expressed by linear and curvilinear equations.

5. An increase in density above 60 vehicles per mile per lane on the Ford Expressway results in great inconveniences to each motorist and in the reduction in the ability of carrying traffic.

6. The measurement, traffic density, appears to be most appropriate for use in centralized control systems of freeways. Density determinations indicate the operational level of the facility.

PART FOUR

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Keese, Charles J.; Pinnell, Charles; McCasland, William R.; "A Study of Freeway Traffic Operation", Highway Research Board, January, 1959.

2. Webb, George M.; Moskowitz, Karl; "California Freeway Capacity Study", Highway Research Board, January, 1957.

3. Malo, A. F.; Mika, H. S.; Walbridge, V. P.; "Traffic Behavior on an Urban Expressway", Highway Research Board, January, 1959.

4. Edie, Leslie C.; Foote, Robert S.; "Traffic Flow in Tunnels", Highway Research Board, January, 1958.

5. McClintock, Miller; "Unfit for Modern Motor Traffic", Fortune Magazine, August, 1936.

6. Halsey, Maxwell; Traffic Accidents and Congestion, 1941.

7. Forbes, T. W.; Zagorski, H. J.; Holshouser, E. L; Deterline, W. A.; "Measurement of Driver Reactions to Tunnel Conditions", Highway Research Board, January, 1958.

8. Highway Capacity Manual, U. S. Department of Commerce, Bureau of Public Roads, 1950.

9. Langsner, George; "Design Features That Have Enhanced the Performance of the Hollywood Freeway", American Association of State Highway Officials, December, 1958.

10. Ricker, Edmund R.; "Monitoring Traffic Speed and Volume", Traffic Quarterly, January, 1959.

11. Legarra, John; "Progress In Freeway Capacity Studies", American Highways, v. 37, no. 3, July, 1958, pp. 11, 21-22.

12. Royster, Paul F.; "Traffic Operations On Freeways", Traffic Engineering, v. 29, no. 2, November, 1958, pp. 18-21.

13. Lighthill, M. J. and Whitman, G. B.; "Kinematic Waves - Part II. A Theory of Traffic Flow on Long Crowded Roads", Proceedings of the Royal Society of London, Series A, 1955, Vol. 229, pp. 317-345.