Application of Computer Simulation Techniques To Interchange Design Problems

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A study of the operating characteristics of the driver-vehicle combination has yielded a general digital simulation model. This simulation model, which can duplicate traffic flow on a 17,000-ft section of a freeway including two on-ramps and two off-ramps, can be used to economically evaluate alternate design criteria.

The basis for this simulation model is the statistical analysis of actual traffic data collected at a number of freeway locations by the Bureau of Public Roads and The Texas Transportation Institute. Significant information on the complex problem of gap acceptance by a merging vehicle was developed through the analysis of the collected data. Study of the collected data resulted in the development of the relationship between (a) average velocity and total traffic volume, (b) vehicle distribution to lanes and total traffic, and (c) exiting vehicle distribution to lanes and distance from the off-ramp. Furthermore, information was developed on velocity distributions in each lane at various total traffic volumes. The detailed information which describes actual traffic flow and driver behavior on a section of a freeway is reported in the section on "Freeway Operating Characteristics."

The simulated vehicle in the model, following decision rules based on the actual collected traffic data, is allowed to maneuver through the section of freeway under study. The effects of changes in traffic volume, velocity, freeway configuration, etc., can then be evaluated by noting changes in the computer output of traverse time, waiting time on ramp, volume-velocity relationship, weaving complexity, etc.

The computer simulation thus creates a duplication of the real situation at a small fraction of the cost of studying the real system. Furthermore, the simulation allows: (1) the evaluation of various freeway configurations without the expense of their construction, and (2) the performance of controlled experiments impossible to perform with the actual traffic.

Controlled experiments with a section of freeway 3,400 ft long and containing one on- and off-ramp sequence were performed. The experiments were conducted with the on- and off-ramps located at two different positions on the freeway section. The results of the experiment showed no significant difference between the traffic flow under the two different configurations for the traffic volumes used. It is possible that at on-ramp volumes higher than those simulated, one configuration may prove more satisfactory than the others. Detailed reports on the measures of effectiveness measured are presented in the section on "Experimental Results."

●IN 1959 Midwest Research Institute developed a digital simulation model which could be used to duplicate a 1,700-ft section of a freeway. Based on the success of this model in duplicating actual freeway conditions, a study was undertaken to expand the simulation model so that a complete interchange could be duplicated. The new simulation model was to be used in developing efficient design criteria for highways. Work on this project was undertaken in three phases.

Phase 1

One phase of the project was devoted to the study and analysis of traffic data gathered at locations in Detroit and Houston. The purpose of this portion of the study was to develop input data, describing the freeway operating characteristics of the driver-vehicle combination, which could be used with the simulation model. The results of this portion of the study are reported in the section on "Freeway Operating Characteristics."

Phase 2

A second phase of the project consisted of developing the logic and program for the digital simulation model. Emphasis was placed on making the model as simple as possible without sacrificing any reality. This phase of the project, which was carried out concurrently with Phase 1, is discussed in the section on "Simulation Model."

Phase 3

The third phase of the project consisted of testing the simulation model developed during the previous phases. Two controlled experiments were carried out, comparing the effects on traffic flow of two different freeway configurations. The two experiments are outlined in the section on "Design of Experiments." The section on "Experimental Results" is devoted to a comparison of the traffic characteristics of the two configurations. The section on "Conclusions and Recommendations" is devoted to some conclusions and recommendations based on the experimental results.

FREEWAY OPERATING CHARACTERISTICS

Data were gathered at two intersections in Detroit by the Bureau of Public Roads, and at intersections in Houston by the Texas Transportation Institute.

Detroit

The Detroit data on 25,000 punched cards were obtained from the Bureau of Public Roads. Each card represented a vehicle crossing one of the recording mechanisms at each site (Fig. 1). Each card contained information on the velocity, lateral placement, type and maneuver of the vehicle. The time of day to the nearest 0.0001 of an hour that the vehicle passed the recorder was also available. The format of these data made it suitable for obtaining information on (a) velocity distributions, (b) volume-velocity relations, and (c) vehicle distribution to lanes.

Velocity Distributions.—The distributions of through vehicle velocities at Sites 7 and 8 are shown in Figure 2. The distributions are slightly skewed in appearance. Some parameters of the distributions are given in Table 1. Analyses were also made of the velocity distribution at various traffic volumes. Figure 3 shows the velocity distributions at 6-min volumes of 91, 128, and 150 vehicles. These distributions are for Lane 1 at Site 8. Figure 4 shows additional velocity distribution for Lanes 1 and 2.

Volume-Velocity Relations.—Regression analyses were made for each lane of the two Detroit locations in order to determine the effect on average velocity of an increase in traffic volume. The input data consisted of the 6-min average velocity and the 6-min vehicle volumes. Graphs of velocity versus volume in Lane 2 for Sites 7 and 8 are shown in Figure 5.

A linear relationship between velocity and volume of the type shown in Equation 1 was assumed.

$$Y = a + b X \tag{1}$$

in which

Y = 6-min average velocity,

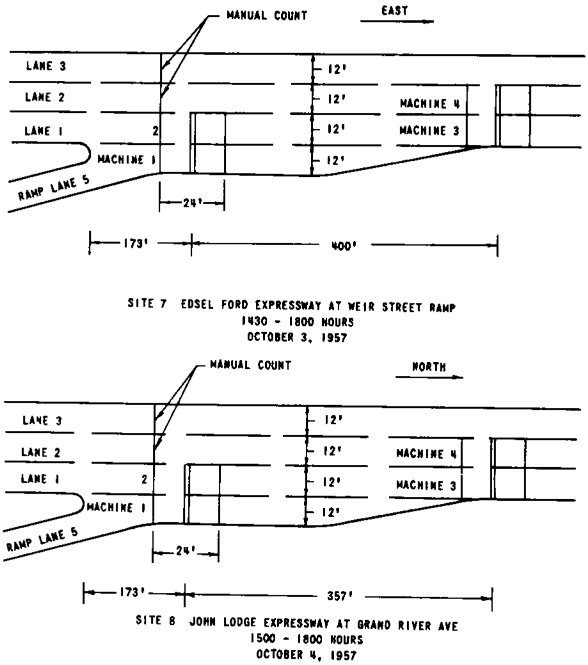


Figure 1. Detroit Study Sites, October 1957.

X = 6-min volume,
a, b = constants

The results of the analyses are shown in Table 2.

Vehicle Distribution to Lanes. —The distribution of vehicles to the three lanes was obtained at Sites 7 and 8 (four recording locations in all). The relationship between the distribution and the total freeway volume was determined. A plot of the data (Fig. 6) indicated that a linear relationship existed. The relationships were described by equations of the following type:

$$P_i = a + b\alpha \tag{2}$$

in which

P_i = percent of total volume in i^{th} lane
α = total freeway volume per 6-min increments

The results of the linear regression at all locations are given in Table 3. As expected the entering vehicles prevent significant correlation between through volumes and Lane 1 utilization in the proximity of the on-ramp.

Houston

The Houston data were obtained by the analysis of motion pictures taken at on- and off-ramp sites. These data were suitable for obtaining information about: (1) gap acceptance of merging vehicles, (2) path of exiting vehicles, and (3) distribution to lanes of exiting vehicles.

Gap Acceptance of Merging Vehicles. — It is difficult to determine the size of a gap accepted by a merging vehicle for the following reasons:

1. It is impossible to determine what the size of the gap was at the moment the merging driver made his decision.
2. It is impossible to determine how the merging driver's choice was affected by the size of other gaps being presented to him either in advance or following the gap accepted.

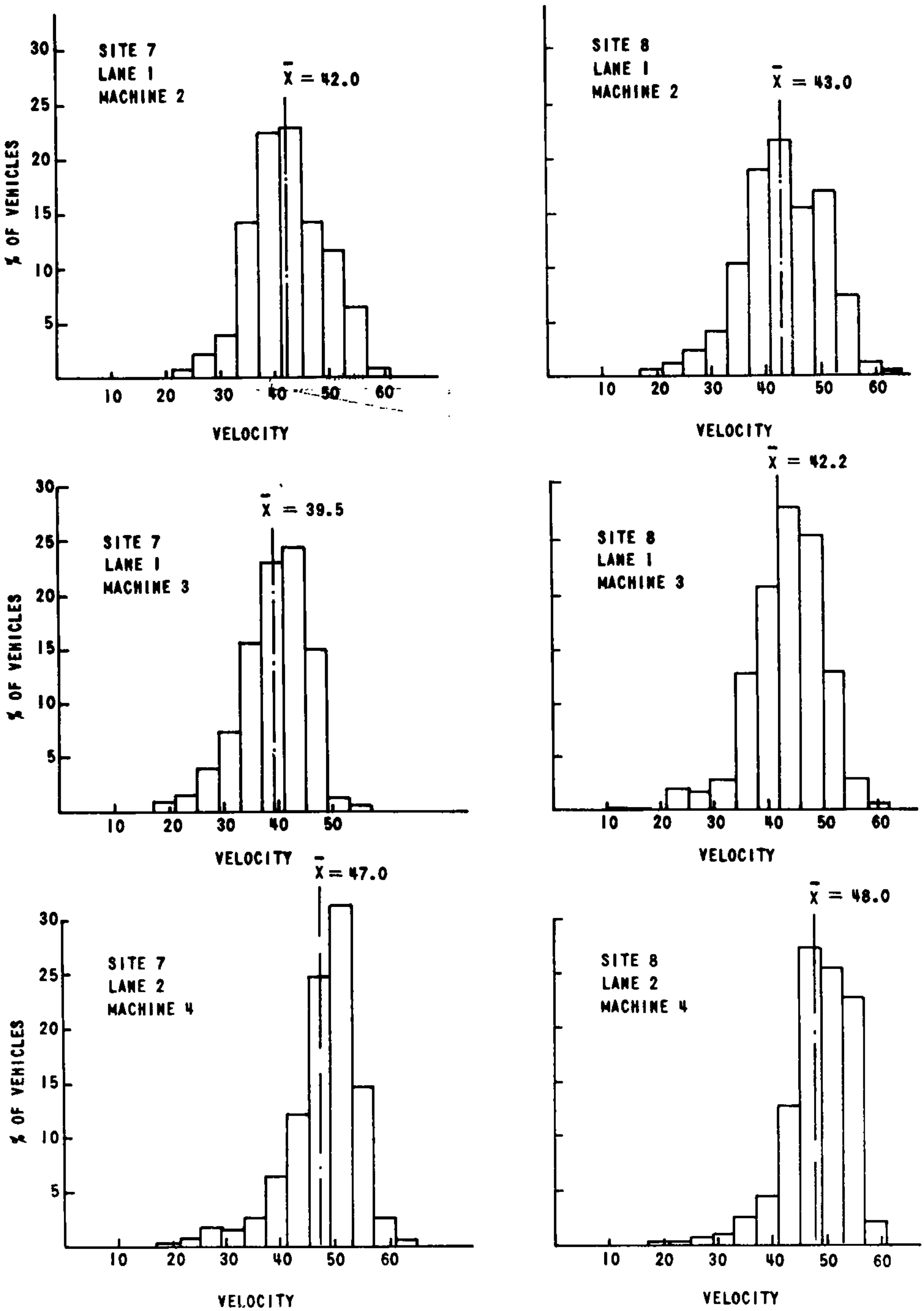


Figure 2. Through vehicle velocity distributions at Sites 7 and 8 in Detroit.

TABLE 1

THE MEAN, STANDARD DEVIATION, AND COEFFICIENT OF VARIATION OF THE VELOCITY DISTRIBUTIONS

Site	Lane	Machine	Mean Velocity ($\bar{x}$)	Standard Deviation of Velocity (s)	Coefficient of Variation ($s/\bar{x}$)
7	1	2	42.05	6.85	0.16
	1	3	39.54	6.83	0.18
	2	4	46.98	6.76	0.14
8	1	2	42.99	7.83	0.18
	1	3	42.16	6.90	0.16
	2	4	47.94	6.52	0.14

3. It is difficult to determine the rate at which the gap size is changing as it approaches the merging vehicle.

However, for the purpose of obtaining some meaningful data on gap acceptance, the following procedure for analyzing the film was adopted:

1. The film was projected and the merging, lead, and trailing vehicles were observed.
2. The film was projected back and the time the lead vehicle (No. 1) passed a given point 0 (Fig. 7) was observed.
3. The film was projected forward and the time that the trailing vehicle (No. 3) passed point 0 was observed (Fig. 7).
4. The time difference between Steps 2 and 3 was calculated. This value was used as a measure of the gap accepted.

A similar procedure was used to determine the size of gaps rejected. Gap acceptance data on passenger vehicles only were obtained. Multiple vehicle entries were not considered. The data were subdivided into merging behavior of stopped vehicles and merging behavior of moving vehicles.

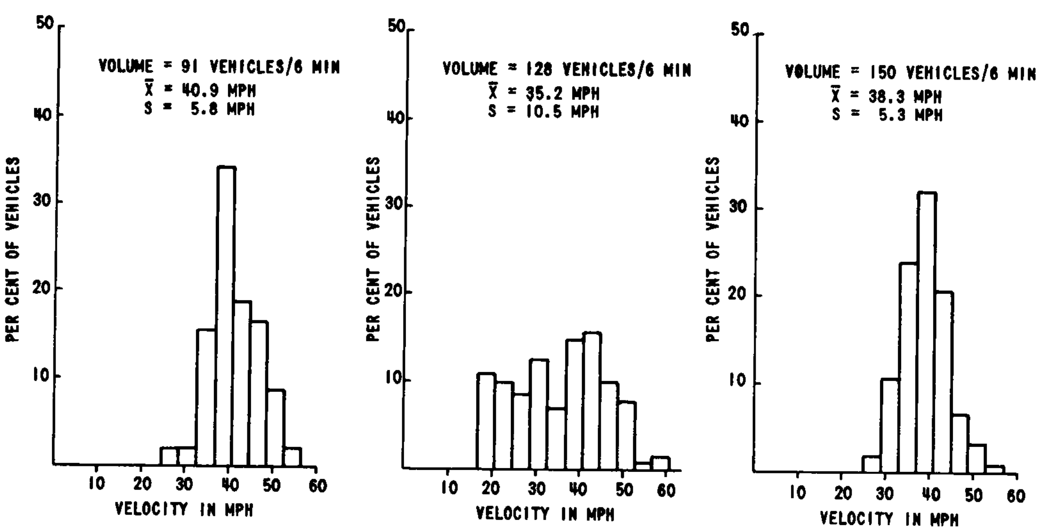


Figure 3. Velocity distributions for Lane 1, Site 8, at given vehicle volumes.

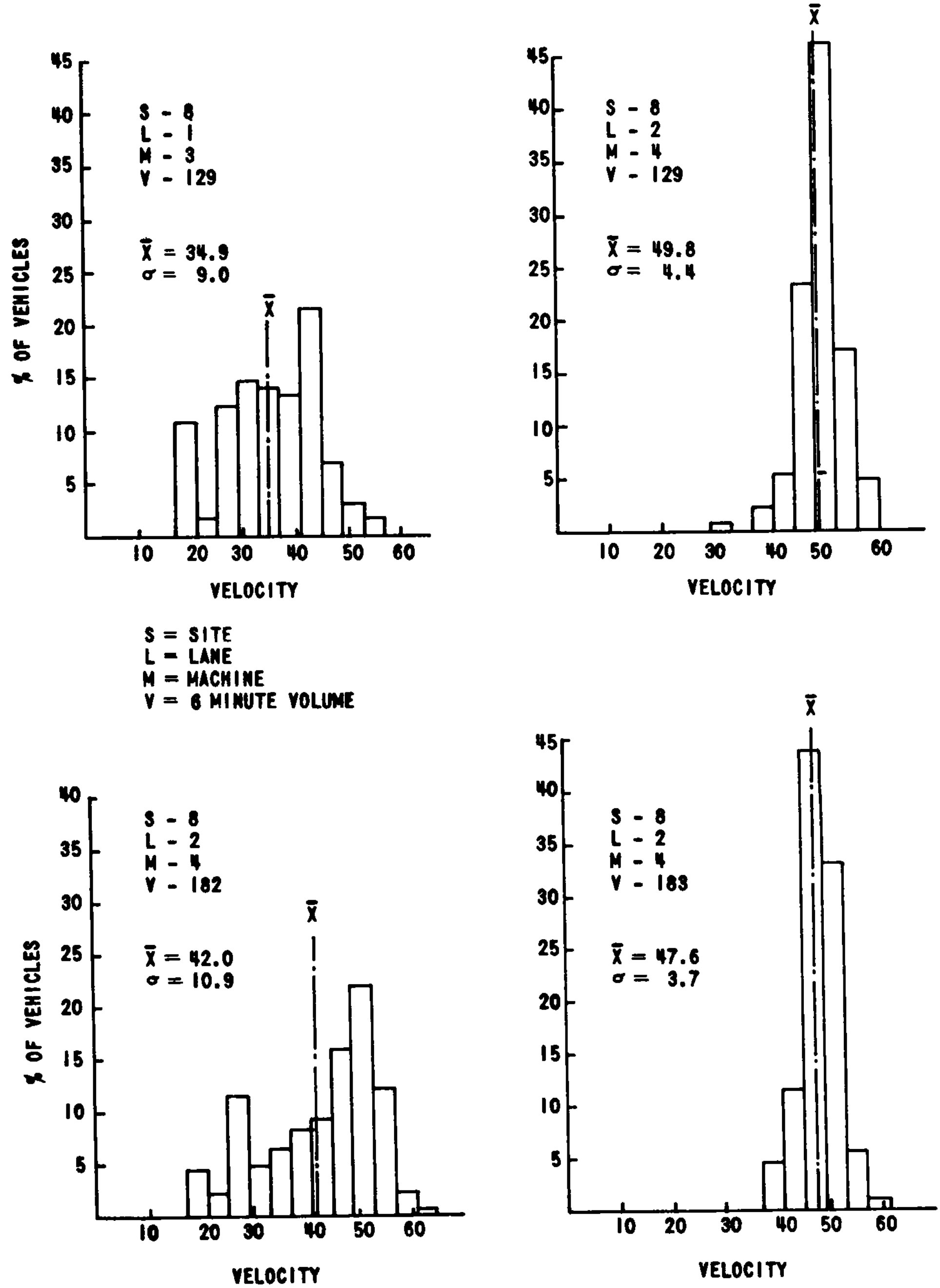


Figure 4. Velocity distributions for Lanes 1 and 2 at Site 8 for given vehicle volumes.

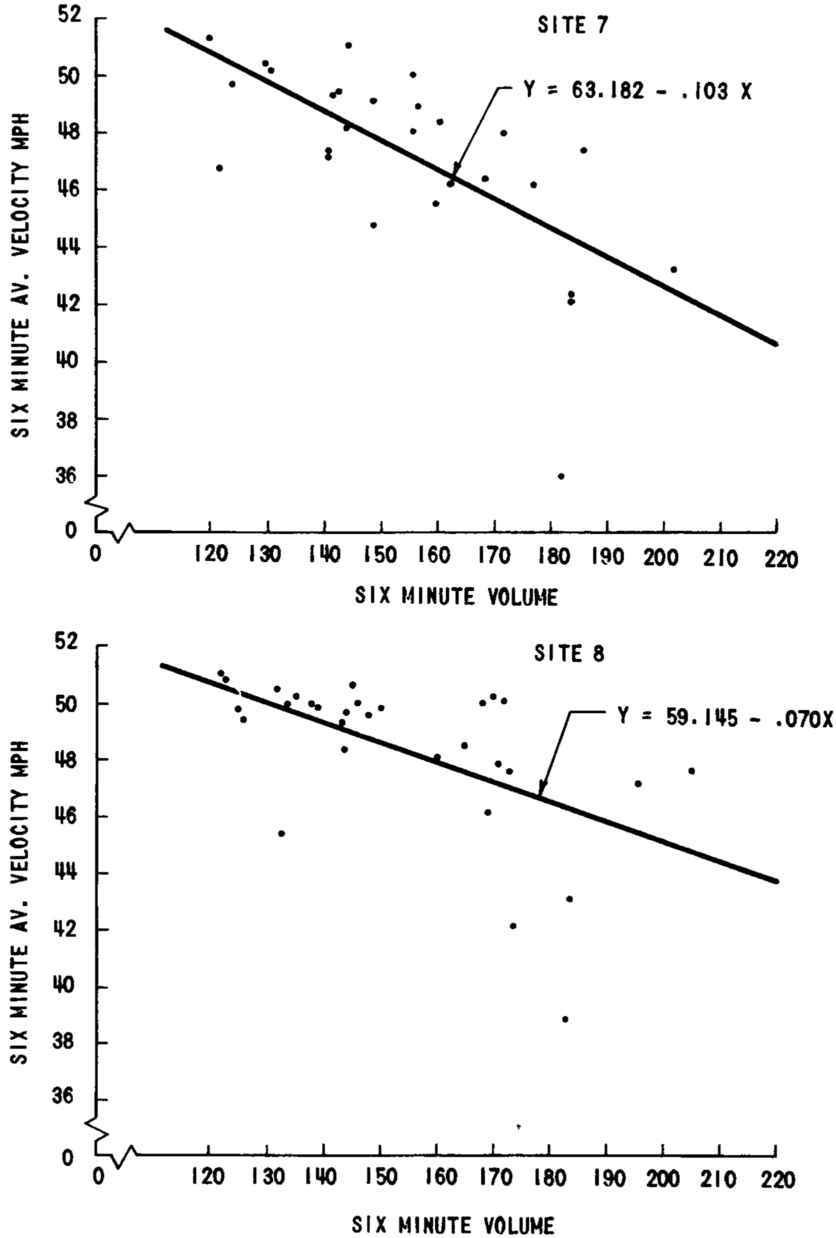


Figure 5. Relationship between average velocity and volume in Lane 2.

An analysis was made of film taken during the peak morning and afternoon traffic periods. The results (Table 4) show that vehicles merging after they have stopped require a longer time gap than those which merge without stopping.

Path of Exiting Vehicle. —The deceleration lane at the Cullens Interchange on the Gulf Freeway in Houston was studied to determine the path of the exiting vehicles. The lane was divided into four sectors (Fig. 8) and the number of cars moving into the deceleration lane in each sector was recorded (Table 5). Observations were carried out for 1 hr and 20 min during the peak morning volume and for 50 min during the peak evening hours.

TABLE 2

LINEAR EQUATIONS FOR VELOCITY-VOLUME RELATIONSHIP

Site	Lane	Machine	Equation	Correlation Coefficient (r)	Test of Significance at 0.05 Level
7	1	2	Y = 47.630 - 0.015X	-0.758	Significant
7	1	3	Y = 50.548 - 0.097X	-0.622	Significant
7	2	4	Y = 63.182 - 0.103X	-0.683	Significant
8	1	2	Y = 51.062 - 0.085X	-0.580	Significant
8	1	3	Y = 53.703 - 0.077X	-0.738	Significant
8	2	4	Y = 59.145 - 0.070X	-0.585	Significant

Distribution to Lanes of Exiting Vehicles. —To determine the effect of the flow pattern of vehicles in an interchange area on the efficiency of a freeway, the Cullens Interchange on the Gulf Freeway in Houston was analyzed. During the period of analysis, the total volume of through traffic varied from 2,100 to 3,900 vehicles per hour. The exiting vehicles made up, on the average, 6.6 percent of the through traffic. Analysis showed that for the range of volumes under investigation, there was no relationship between the total volume and the distribution to lanes of exiting vehicles. On the average, vehicles were distributed as shown in Figure 9.

SIMULATION MODEL

The purpose of the simulation model is to duplicate in a digital computer the real life vehicle-driver combination passing through a section of a freeway in order to permit controlled experiments. The purpose of these experiments is to obtain knowledge of the relationships among the various factors that control the smooth and efficient flow of traffic. On the basis of this knowledge of traffic behavior improved highway design criteria can be developed. Digital simulation is an effective tool in highway traffic study as it permits the performance of experiments which cannot be performed, or which are too costly to perform, on a real freeway.

Input Factors for Simulation Model

In order to obtain a true duplication of actual traffic behavior on the freeway the simulation model should contain all factors which influence traffic behavior. In this model the following factors are considered:

1. The volume of entering and exiting vehicles.
2. The distribution of vehicles to lanes.
3. The velocity distributions of vehicles.
4. The gap acceptance distribution of merging and weaving vehicles.
5. The acceleration of entering vehicles.
6. The deceleration of exiting vehicles.
7. The distribution to lanes of exiting vehicles.

In addition, all vehicles are allowed to shift lanes in order to pass slower moving vehicles in front of them.

The Study Area

The study area is set up in a 4 x N matrix, ($N \leq 999$), (Fig. 10). The four rows represent: (1) the three through Lanes 1, 2, and 3, and (2) the ramp, acceleration and deceleration Lane 5. Each of the N blocks represents a 17-ft section of freeway, the approximate length of an automobile. For the simulation runs on the computer any

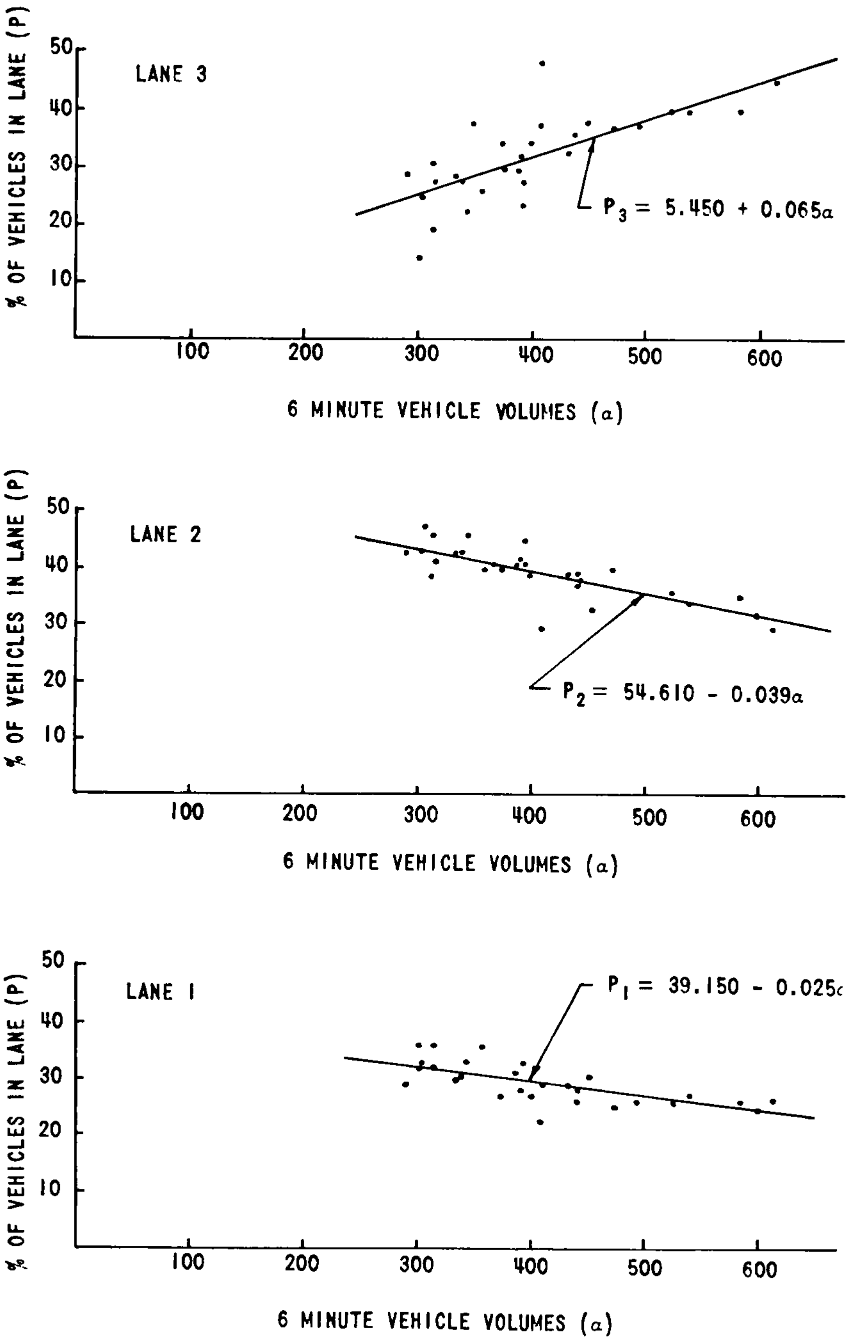


Figure 6. Distribution of traffic volumes to the three lanes.

TABLE 3

LINEAR EQUATIONS FOR DISTRIBUTION TO LANES—VOLUME RELATIONSHIPS

Site	Distance From Nose of Ramp (ft)	Lane	Equation	Correlation Coefficient (r)	Test of Significance at 0.05 Level
7	179	1	$P_1 = 27.78 - 0.010\ a$	-0.337	Not significant
		2	$P_2 = 53.48 - 0.031\ a$	-0.615	Significant
		3	$P_3 = 19.16 + 0.041\ a$	+0.670	Significant
	579	1	$P_1 = 39.15 - 0.025\ a$	-0.619	Significant
		2	$P_2 = 54.61 - 0.039\ a$	-0.734	Significant
		3	$P_3 = 5.45 + 0.065\ a$	+0.735	Significant
8	179	1	$P_1 = 26.12 - 0.006\ a$	-0.202	Not significant
		2	$P_2 = 47.01 - 0.014\ a$	-0.350	Significant
		3	$P_3 = 24.61 + 0.025\ a$	+0.519	Significant
	536	1	$P_1 = 39.25 - 0.015\ a$	-0.532	Significant
		2	$P_2 = 45.16 - 0.026\ a$	-0.751	Significant
		3	$P_3 = 15.59 + 0.041\ a$	+0.745	Significant

TABLE 4

GAP ACCEPTANCE OF MERGING VEHICLES

	Moving Merging Vehicles			Stopped Merging Vehicles		
Size of Gap Presented (sec)	No. of Veh Accepting Gap	No. of Veh Rejecting Gap	% of Total No. of Veh Accepting Gap	No. of Veh Accepting Gap	No. of Veh Rejecting Gap	% of Total No. of Veh Accepting Gap
0 -1.00	1	1	12.5	0	31	0.00
1.01-2.00	58	44	56.8	8	270	2.8
2.01-3.00	111	33	77.0	21	100	17.4
3.01-4.00	120	6	95.1	32	57	36.0
4.01-5.00	102	3	97.0	24	13	64.9
5.01-6.00	101	2	98.0	19	1	95.0
6.01-7.00	70	0	100.0	16	0	100.0
7.01-8.00	46	0	100.0	5	1	-
8.01-9.00	36	1	98.0	-	-	-
9.01-10.00	40	0	100.0	-	-	-

value of N (≤ 999) can be utilized. Locations of interchanges are designated as follows:

A = ramp input location
B = nose of on-ramp
C = end of acceleration lane
D = beginning of deceleration lane
E = nose of off-ramp
F = off-ramp output location

The program is very flexible and permits the on- and off-ramps to be located at any point on the section of freeway under investigation.

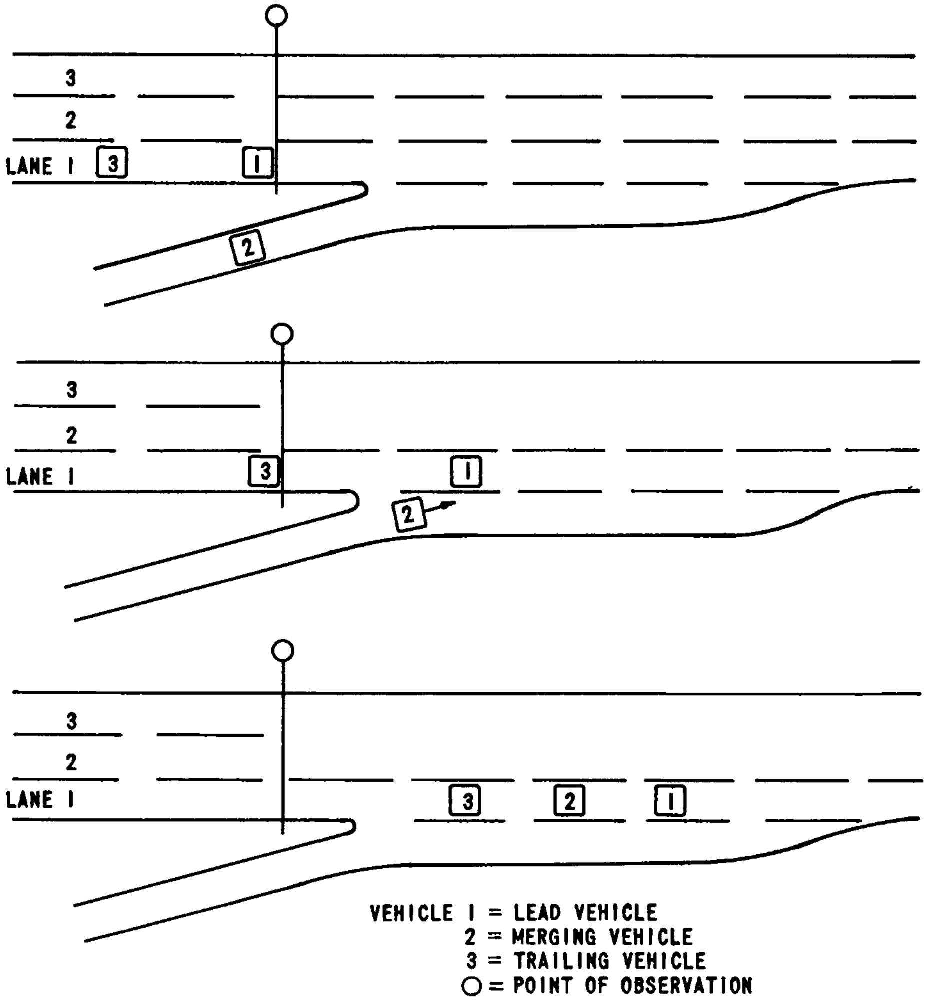


Figure 7. Observation point for the collection of gap acceptance data.

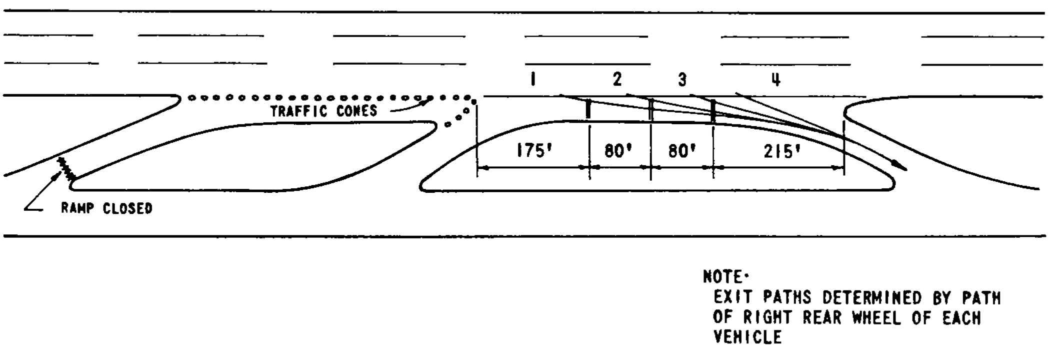


Figure 8. Site for the collection of data on the path of an exiting vehicle.

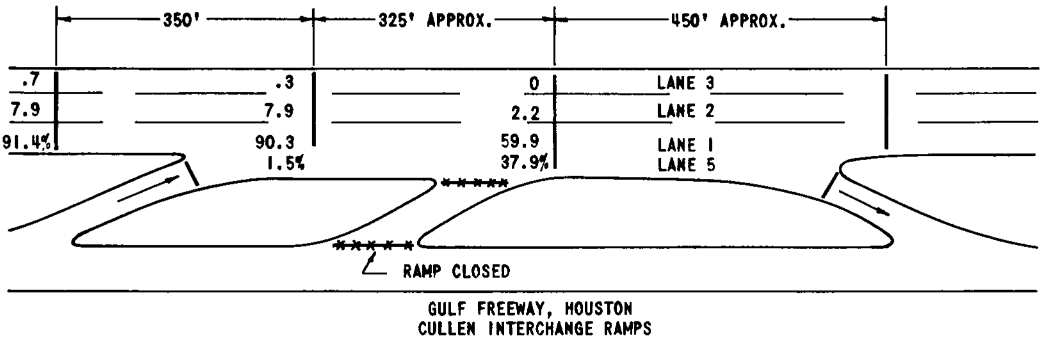


Figure 9. The distribution of exiting vehicles to lanes at various distances from the off-ramp.

TABLE 5

PATH OF EXITING VEHICLES

	Morning Peak Hours		Evening Peak Hours	
Exit Sector	No. of Veh	% of Total Exiting in Sector	No. of Veh	% of Total Exiting in Sector
1	112	32.6	44	22.2
2	148	43.0	86	43.4
3	74	21.5	66	33.3
4	10	2.9	2	1.1

Simulation Procedure

Basically, the procedure consists of simulating the arrivals of cars into the section of highway under consideration and then controlling the action of the vehicle by a set of decision processes. During each second of real time each vehicle in the matrix is examined. The vehicle is allowed to advance, weave, merge, accelerate, decelerate, or exit according to logical rules describing the behavior of actual vehicle-driver

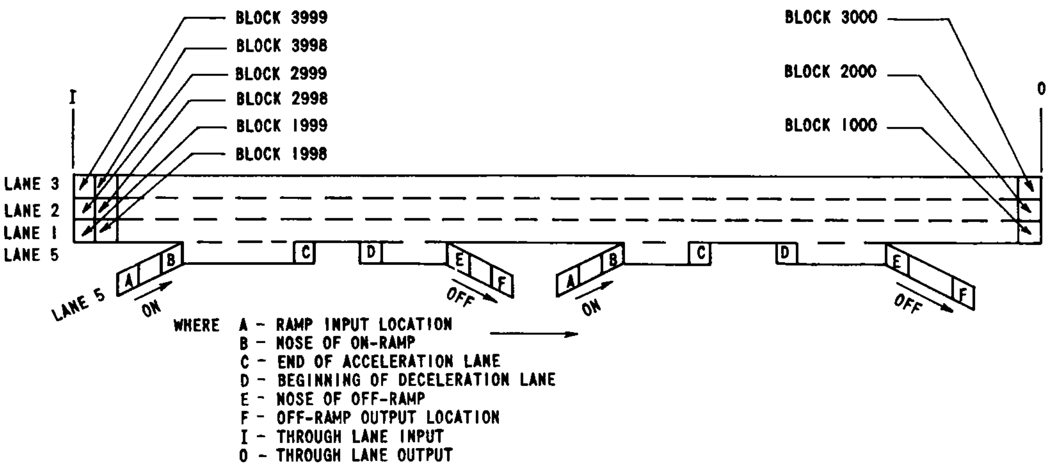


Figure 10. Study area matrix for computer simulation of an interchange area.

combinations. Just prior to examining all vehicles at each second, each of the input locations is evaluated. Inspection starts at vehicles closest to the end of the section of highway under examination and proceeds to vehicles in the input location.

An over-all description of the logic involved in processing a vehicle through the system is given in the flow diagram (Fig. 11). Detailed descriptions can be obtained in MRI Report No. 2349P.

Simulation Output

The present model was programed so that the following information can be obtained about each simulation run.

1. The volume of vehicles traversing the system in each lane.
2. The volume of vehicles entering the freeway through each on-ramp.
3. The volume of vehicles exiting the system at each off-ramp.
4. The number of vehicles which stop on the acceleration lane.
5. The length of the queue on the acceleration lane.
6. The number of vehicles that desire to exit but cannot.
7. The distribution of through-vehicle traverse times.
8. The distribution of ramp-vehicle traverse times.
9. The average vehicle velocity in each lane.
10. The number of weaves from:
    (a) Lane 1 to 2;
    (b) Lane 2 to 1;
    (c) Lane 2 to 3; and
    (d) Lane 3 to 2.

DESIGN OF EXPERIMENTS

Various types of controlled experiments can be carried out using the simulation model described in the section on "Simulation Model." For example, experiments on the effects on traffic flow of (a) various on-ramp vehicle volumes; (b) various accera-

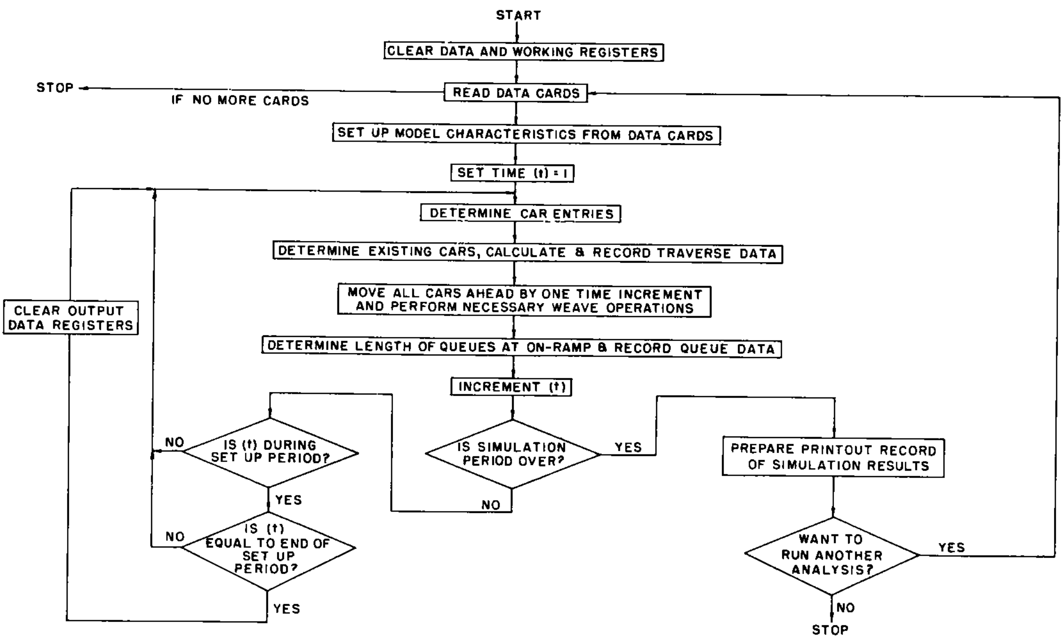


Figure 11. Flow diagram of over-all computer logic.

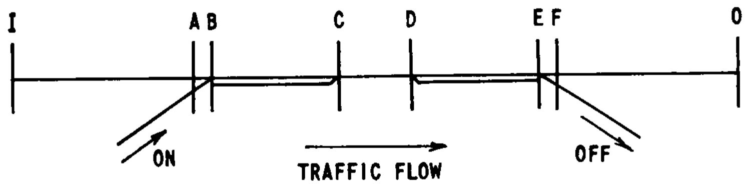
tion lane lengths; (c) various velocity distributions; (d) combinations of the above; and (e) various geometric configurations, etc., can be carried out with this model.

With the limited machine time available, it was decided to carry out experiments on the effect on traffic flow of spacing between an on-ramp and an off-ramp, under varying traffic volumes. The geometric configurations which were utilized, and the simulation input data, are described in this section.

Interchange Configurations

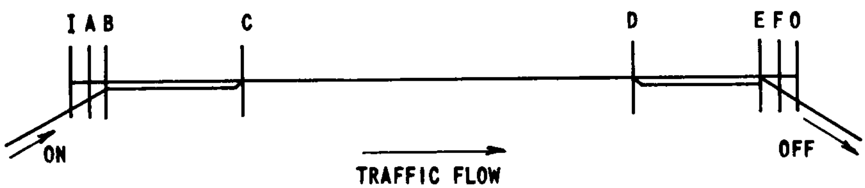
Two interchange configurations (Fig. 12) were examined. Each configuration was 200 blocks or 3,400 ft long and contained one on- and off-ramp combination. Each acceleration and deceleration lane was 595 ft long. In Configuration I exiting vehicles have 2,465 ft to travel to the nose of the off-ramp while in Configuration II the distance is 3,230 ft. In Configuration I the distance between the acceleration and deceleration lane is 340 ft and 1,870 ft in Configuration II. All exiting vehicles were designated at block number 199 (that is, as they enter the system).

CONFIGURATION I



	BLOCK	DISTANCE
I =	200	3400 FT
A =	150	2550 FT
B =	145	2465 FT
C =	110	1870 FT
D =	90	1530 FT
E =	55	935 FT
F =	50	850 FT
O =	00	000 FT

CONFIGURATION II



	BLOCK	DISTANCE
I =	200	3400 FT
A =	195	3315 FT
B =	190	3230 FT
C =	155	2635 FT
D =	45	765 FT
E =	10	170 FT
F =	5	85 FT
O =	00	00 FT

Figure 12. The configuration of the two sections of freeway being examined.

Input Data

Volume of Traffic. —For both configurations the input to the simulation was for 750 ramp vehicles per hour. For Configuration I experiments with through-lane volumes of 2,000, 3,000, 4,000, 5,000 and 6,000 vehicles per hour were conducted. For Configuration II experiments with through-lane volumes of 1,000, 2,000, 3,000, 4,000, 5,000 and 6,000 were conducted. Two tests were conducted at each volume.

Distribution of Volume to Lanes. —In all experiments carried out, the traffic volumes were assigned to the three lanes according to the following relationships:

$$P_1 = 0.43693 - 0.22183\alpha + 0.05730\alpha^2 - 0.00046\alpha^3 \quad (3)$$

$$P_2 = 0.48820 - 0.03136\alpha + 0.00006\alpha^2 + 0.00024\alpha^3 \quad (4)$$

$$P_3 = 0.07487 + 0.25319\alpha - 0.05736\alpha^2 + 0.00382\alpha^3 \quad (5)$$

in which

p_i = proportion of total volume in the i^{th} lane; and

α = total freeway volume in thousands of vehicles per hour.

These relationships are based on data observed in Chicago (1), and were utilized, as the digital program for them was available from the previous study.

Velocity Distributions. —The velocity distributions used with both highway configurations are based on the analysis of the Detroit data. Three different velocity distributions were used in the simulations. One velocity distribution was used for the on-ramp vehicles, a second for the vehicles in Lane 1 and a third for vehicles in Lanes 2 and 3 (Table 6).

Gap Acceptance Distributions. —Three different gap acceptance distributions were used in the simulation tests. The distributions for merging vehicles (both stopped and moving) are given in Table 7. The gap acceptance data for vehicles weaving between lanes are given in Table 7 (1).

TABLE 6

INPUT VELOCITY DISTRIBUTIONS

Vehicle Velocity (blocks/sec)	Cumulative Percent		
	Ramp Lane	Lane 1	Lanes 2 and 3
1.50	0.026	0.001	0.003
2.00	0.061	0.010	0.015
2.38	0.116	0.040	0.034
2.81	0.314	0.180	0.064
3.25	0.683	0.435	0.138
3.69	0.888	0.737	0.322
4.13	0.979	0.899	0.759
4.56	0.994	0.989	0.970
5.00	0.998	0.999	0.998
5.44	1.000	1.000	1.000

Exiting Vehicles. —For both freeway configurations 10 percent of the through vehicles were designated as exiting vehicles. These exiting vehicles were further allocated to the three lanes according to the following schedule:

1. Ninety percent of exiting vehicles in Lane 1 at Block No. 199;
2. Nine percent of exiting vehicles in Lane 2 at Block No. 199; and
3. One percent of exiting vehicles in Lane 3 at Block No. 199.

TABLE 7

GAP ACCEPTANCE DISTRIBUTION FOR WEAVING VEHICLES

Length of Gap (w) (sec)	Cumulative Probability of Acceptance
0.00-0.25	0.00
0.26-0.50	0.00
0.51-0.75	0.00
0.76-1.00	0.00
1.01-1.25	0.10
1.26-1.50	0.30
1.51-1.75	0.60
1.76-2.00	1.00

EXPERIMENTAL RESULTS

The controlled experiments described in the section on "Design of Experiments," were carried out on a 704 digital computer. The ratio of computer time to real time varied from 1 to 5 for low traffic volumes, to almost 1 to 1 for the higher volumes.

The over-all results of the experiments indicated that there were no significant effects on the traffic flow patterns of the freeway as a result of this change in geometric configuration.

The remainder of this section is devoted to the examination of a number of the simulation outputs in order to obtain a quantitative view of the traffic performance. The following outputs will be examined:

1. The distribution of through-vehicle traverse times;
2. The average velocity-volume relationships;
3. The vehicle distribution to lanes;
4. The number of vehicles stopping on the acceleration lane;
5. The number of exiting vehicles that cannot exit; and
6. The number of weaving movements on the freeway.

The Distribution of Through-Vehicle Traverse Times

Distributions of the through-vehicle traverse times were obtained for each through-volume simulated for both configurations. In each case the distributions were skewed to the right. There did not appear to be any difference in traverse time between the

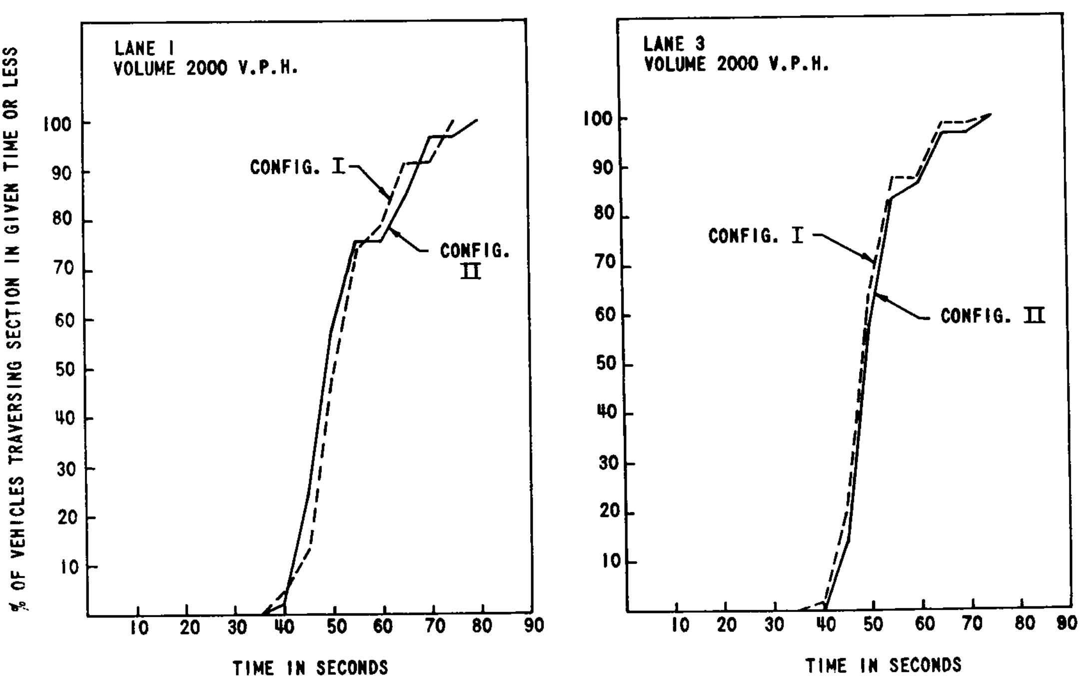


Figure 13. Cumulative distribution of through vehicle traverse times at a freeway volume of 2,000 vph.

two freeway geometric configurations. Cumulative distributions for Lanes 1 and 3 for each configuration at traffic volumes of 2,000 and 6,000 vehicles per hour are shown in Figures 13 and 14. For example (Fig. 14), in Lane 1 with a total freeway through-volume of 6,000 vehicles, 88.6 percent of the vehicles had a traverse time of 75 sec or less in Configuration II, while in Configuration I, 84.1 percent of the vehicles had a traverse time of 75 sec. From these cumulative distributions it is apparent that the difference in configuration does not affect the traverse time to any great extent. The total through-volume, however, does have an influence on the traverse time. An increase in through-volume causes an increase in average traverse time.

Average Velocity-Volume Relationships

The relationship between the average velocity and the volume of traffic in the lane was examined for each of the two configurations. The purpose of this examination was to evaluate the effect that distance between adjacent on- and off-ramps had on the average velocity. There was no apparent average velocity difference for the two freeway configurations under investigation. Linear relationships between average velocity and vehicle volumes of the form in Equation 6 were determined.

$$Y = a + bX \tag{6}$$

in which

Y = average velocity;

X = volume of traffic in lane (veh/hr); and

a, b = constants.

The relationship holding in each configuration in Lane 1 are shown in Figure 15. Ninety-five percent confidence limits were established around each regression line. These confidence limits indicate the area within which the true values indicated by the regression line will lie 95 percent of the time. Because of the large overlap of areas between the two configurations, one cannot assume any significant difference between the average velocity-volume relationship of the two configurations. A complete tabulation of the average velocity-volume relationship for each lane is given in Table 8. In each case correlation coefficients $r > 0.80$ were found.

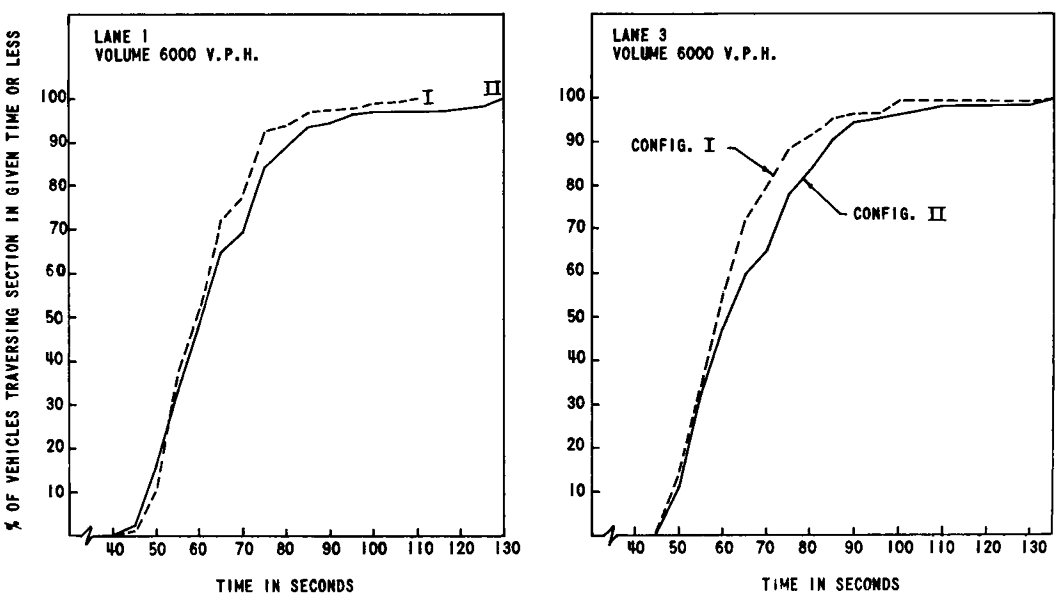


Figure 14. Cumulative distribution of through vehicle traverse times at a freeway volume of 6,000 vph.

Vehicle Distribution to Lanes

The distributions of the vehicles to the three lanes were examined for each configuration. The output was considerably different from the input. For example, the input relationship between the percent of traffic in Lane 1 and the total volume of traffic was given by Equation 7.

$$P_1 = 0.43693 - 0.22183\alpha + 0.05730\alpha^2 - 0.00046\alpha^3 \quad (7)$$

Chi square tests were used to compare the output and the input, and for each configuration one had to reject the hypothesis that the output had the same form as the input distribution. This change of distribution may be caused by the great number of weaving movements which occur in an interchange area.

Plots of the distribution of traffic to lanes at the various volumes are shown in Figure 16. Regression analysis was used to relate the distribution to lanes and total volume of traffic. The results, along with the correlation coefficients, are given in Table 9. These results may indicate that in Configuration II, where the output is measured at a greater distance from the on-ramp than in Configuration I, the traffic has had an opportunity to reach a steady-state condition. In Configuration I, a number of ramp vehicles may still be weaving between lanes in order to reach a lane in which the traffic moves at the vehicle's desired rate.

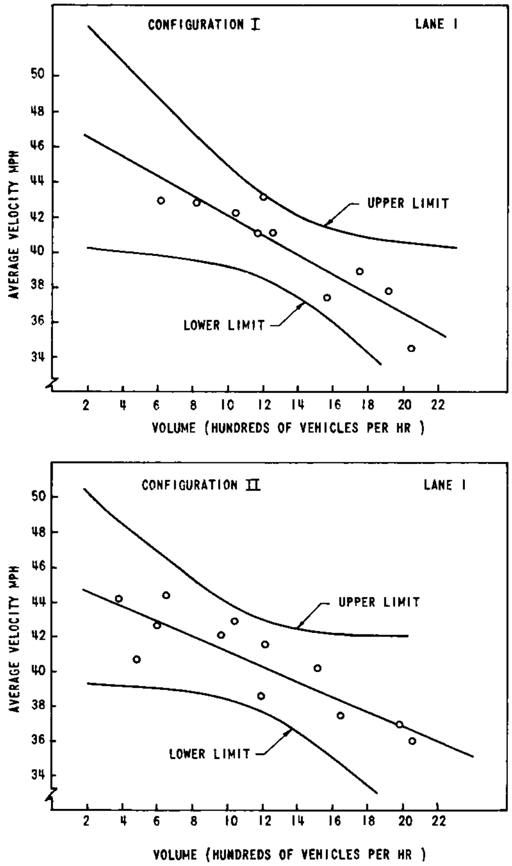


Figure 15. Relationship between average velocity and the number of vehicles in the lane.

TABLE 8

LINEAR EQUATIONS FOR AVERAGE VELOCITY-VOLUME RELATIONSHIPS

Configuration No.	Lane No.	Equation	Coefficient Correlation (r)	Test of Significance at 0.05 Level
I	1	Y = 47.698 - 0.0056X	-0.912	Significant
	2	Y = 49.918 - 0.0049X	-0.847	Significant
	3	Y = 51.516 - 0.0062X	-0.865	Significant
II	1	Y = 45.515 - 0.0043X	-0.865	Significant
	2	Y = 48.940 - 0.0046X	-0.860	Significant
	3	Y = 49.253 - 0.0058X	-0.853	Significant
I and II data grouped	1	Y = 46.180 - 0.0047X	-0.876	Significant
	2	Y = 49.160 - 0.0046X	-0.850	Significant
	3	Y = 49.958 - 0.0054X	-0.848	Significant

Number of Vehicles Stopping on Acceleration Lane

For each traffic-volume input, information was obtained about the number of vehicles which were forced to stop on the acceleration lane because they could not find a suitable gap for merging. The relationship between the percent of ramp vehicles stopping and the total volume of through traffic for both configurations is shown in Figure 17. Ninety-five percent confidence limits about each regression line are shown. The overlap of the confidence regions indicates that there is no difference between the two configurations. This result is to be expected because this difference in interchange configuration should have no effect on the gap arrivals. The regression line for the grouped data is shown in Figure 18 with its confidence region. This output indicates that with traffic volumes as high as 6,000 vehicles per hour, there are still sufficient gaps in the traffic for merging operations. This finding agrees with the findings of Webb and Moskowitz in their study of California freeways (2).

Number of Exiting Vehicles that Cannot Exit

The simulation output includes a count of the number of vehicles that have been tagged as exiting vehicles which cannot weave to the off-ramp in the distance allotted. In Configuration I, exiting vehicles have 2,465 ft in which to move to the nose of the off-ramp. In Configuration II, the distance available is 3,230 ft. A

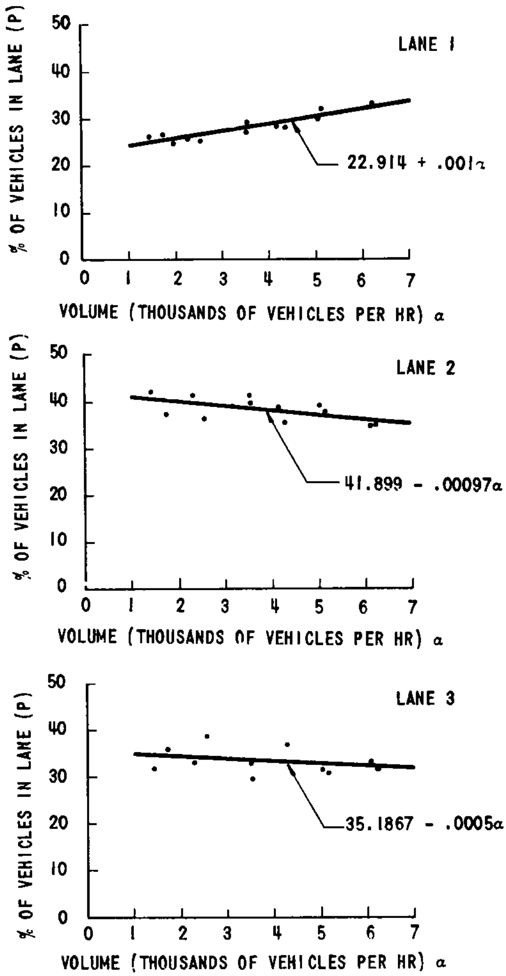


Figure 16. Distribution of traffic to the three lanes on configuration II.

TABLE 9

LINEAR EQUATIONS FOR THE VOLUME AND LANE DISTRIBUTION RELATIONSHIP

Configuration No.	Lane No.	Equation	Coefficient Correlation (r)	Test of Significance at 0.05 Level
I	1	$P_1 = 25.8081 + 0.00083a$	+0.450	Not Significant
	2	$P_2 = 40.5669 - 0.00062a$	-0.308	Not Significant
	3	$P_3 = 33.4049 - 0.00004a$	-0.019	Not Significant
II	1	$P_1 = 22.9138 + 0.00149a$	+0.905	Significant
	2	$P_2 = 41.8995 - 0.00097a$	-0.623	Significant
	3	$P_3 = 35.1867 - 0.00052a$	-0.313	Not Significant

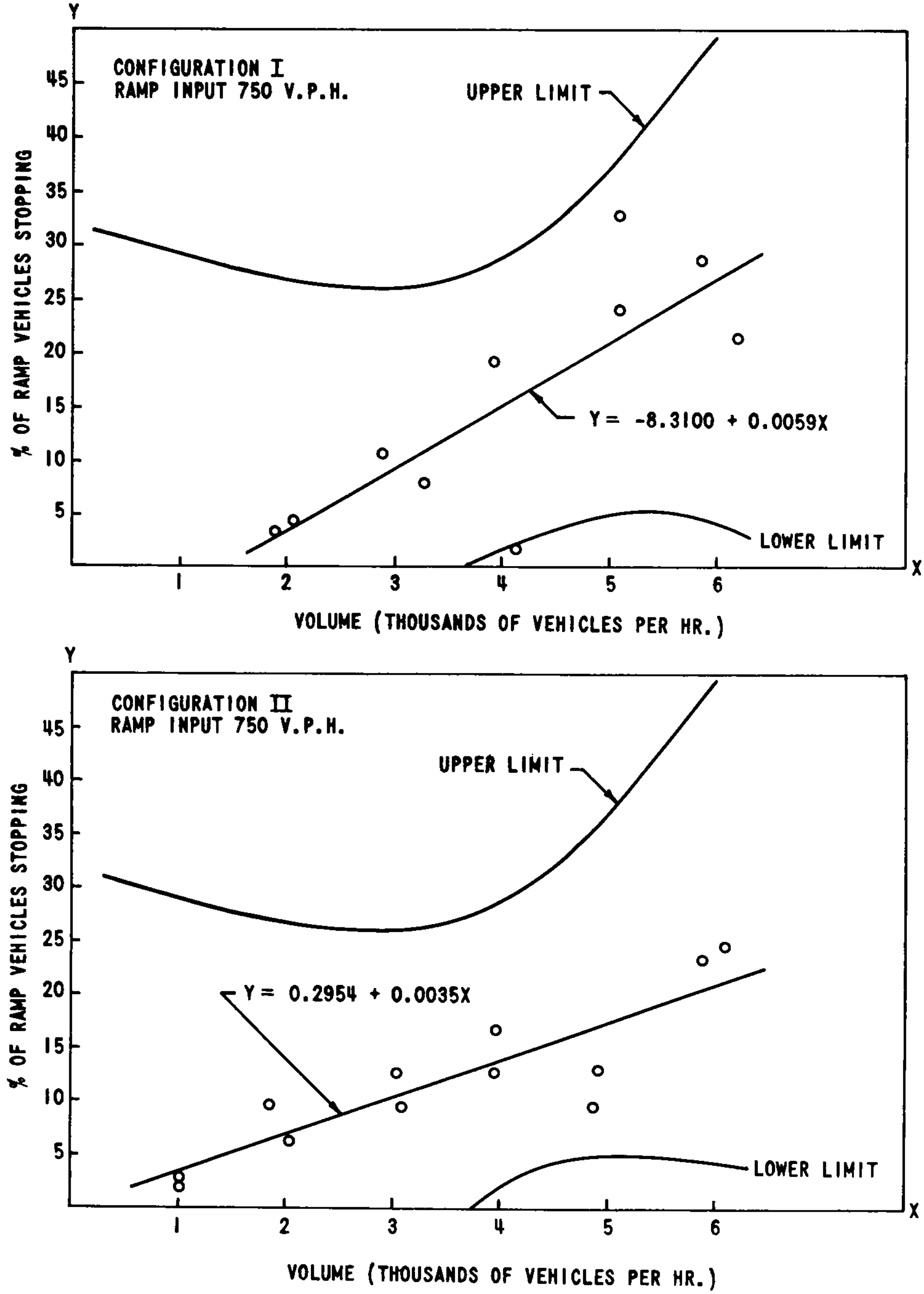


Figure 17. Relationship between the percent of vehicles stopping on acceleration lane (Y) and the total through volume (X).

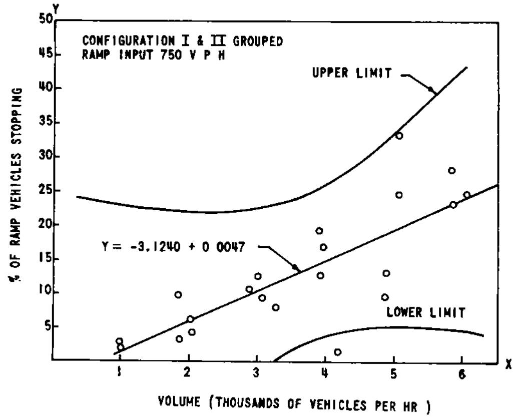


Figure 18. Percent of vehicles stopping on ramp vs the total through volume (grouped data).

scatter diagram of the number of vehicles which cannot exit at various traffic volumes is shown in Figure 19. The variation is such that it is not possible to determine whether one configuration is superior to the other.

With 10 percent exiting vehicles (90 percent of which are in Lane 1, 9 percent in Lane 2, and 1 percent in Lane 3), it is necessary to start the exiting behavior more than 3,230 ft before the nose of the off-ramp to insure that all vehicles can complete their maneuver. This information may be helpful in determining where to post exit signs.

To examine the effect of a lower percentage of exiting vehicles, simulations were carried out for a 6 percent value. A comparison of results for Configuration II with 6 and 10 percent exiting vehicles are given in Table 10.

Weaving Movements on Freeway

During a 5-min time interval the total number of weaves (Y) between the lanes occurring on the 3,400-ft section of freeway increased linearly with the volume of traffic (X). A comparison between the number of weaves from Lane 1 to 2 for the two highway

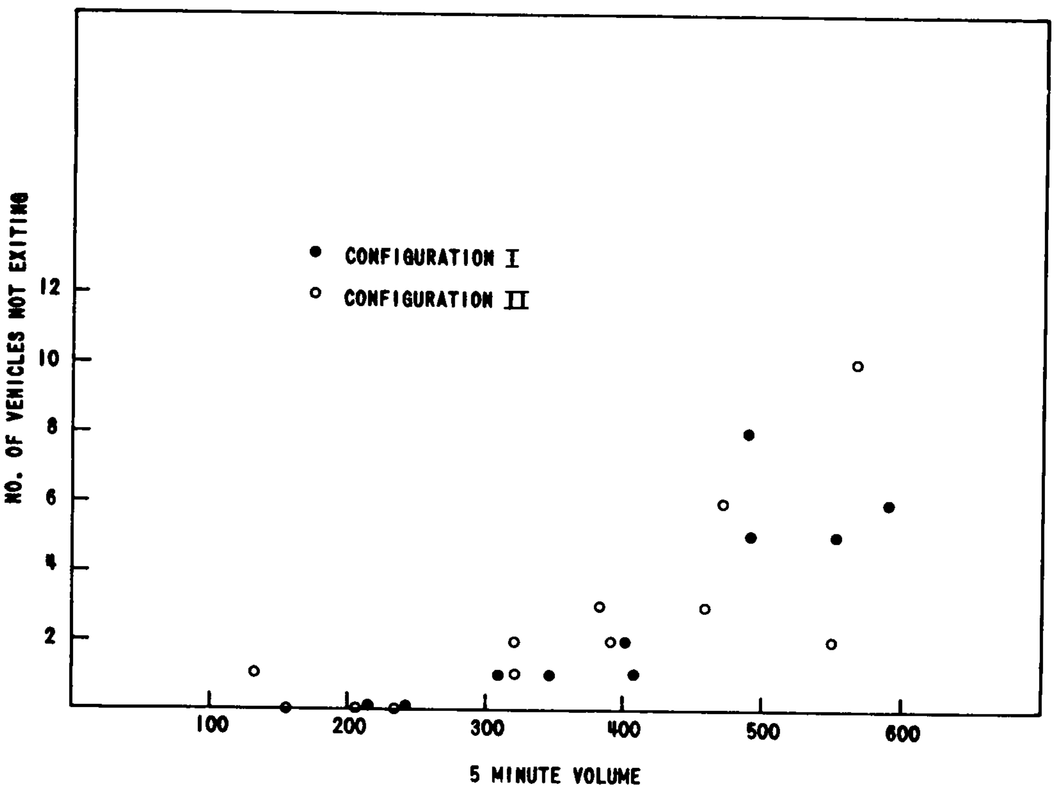


Figure 19. Scatter diagram of the number of exiting vehicles not able to reach the off-ramp.

TABLE 10

COMPARISON OF NUMBER OF VEHICLES NOT ABLE TO EXIT

Percent of All Vehicles Exiting	5-Min Volume of Traffic	Number of Vehicles (Not Able to Exit)
10	384	3
	391	2
6	382	1
	398	0

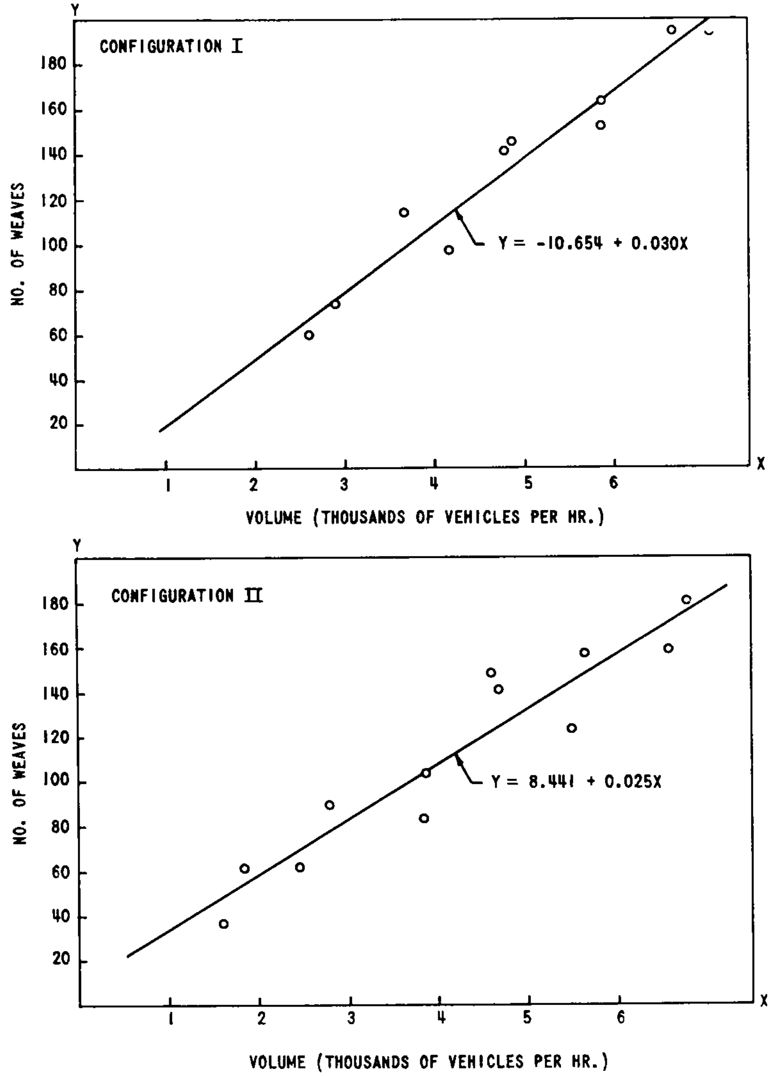


Figure 20. Number of weaves in 5 min on a 3,400-ft section of freeway as a function of total through volume.

configurations is shown in Figure 20. Table 11 gives the relationship between Y (the number of weaves) and X (the hourly volume of traffic). These results show that even at volumes as high as 6,000 vehicles per hour, sufficient gaps exist to permit weaving.

TABLE 11

RELATION BETWEEN THE NUMBER OF WEAVES (Y) AND THE VOLUME OF TRAFFIC (X)

Freeway Configuration	Lane Weaving Movement From	To	Linear Relation (Y = a + bX)	Correlation Coefficient (r)	Test of Significance At 0.05 Level
I	1	2	Y = -10.654 + 0.030X	0.975	Significant
	2	1	Y = -29.807 + 0.032X	0.936	Significant
	2	3	Y = 27.903 + 0.024X	0.824	Significant
	3	2	Y = 13.743 + 0.029X	0.799	Significant
II	1	2	Y = 8.441 + 0.025X	0.946	Significant
	2	1	Y = -1.337 + 0.029X	0.965	Significant
	2	3	Y = -29.350 + 0.037X	0.950	Significant
	3	2	Y = -35.052 + 0.033X	0.949	Significant

CONCLUSIONS AND RECOMMENDATIONS

This study has shown that digital simulation can be used to faithfully duplicate actual traffic flow in an on- and off-ramp area of a freeway. The output of the simulation furthermore, gives measures of effectiveness which can be used to evaluate alternate highway designs.

Experiments were performed for the two following on- and off-ramp configurations:

1. A distance of 1,530 ft between the on- and off-ramps (Configuration I); and
2. A distance of 3,060 ft between the on- and off-ramps (Configuration II).

The resulting traffic flow characteristics for both systems were similar over the volume range 1,000 to 6,000 vehicles per hour.

The computer outputs, however, do indicate that the area immediately following an interchange is an area of transient behavior. The distribution to lane versus volume relationship for vehicles leaving the interchange area has less variation, as indicated by the correlation coefficient, in Configuration II than in I. Output measurements in Configuration II were performed at a greater distance from the on-ramp than in Configuration I. Similar results were found to be true for the actual data collected by the Bureau of Public Roads in Detroit (Table 3). These results indicate the need to measure traffic flow variables at a distance from the on-ramp. It is, therefore, important for effective comparison of traffic data that the location of the sensing equipment should be standardized. Such standardization may well be prescribed through simulation studies.

A further result of the study is useful for planning the location of exit signs. For example, a simulation with 750 on-ramp vehicles per hour and with 400 or more exiting vehicles at an adjoining off-ramp was performed. Results indicated that fewer than 10 percent of the exiting vehicles could be in Lanes 2 and 3 if all exiting vehicles were to successfully perform their exiting movement. For the above volume conditions, exit signs should be located more than 3,000 ft in advance of the off-ramp if friction induced by exiting cars is to be minimized.

The simulation experiments performed indicate the need for research and experimentation in a wide variety of areas to answer questions such as the following:

1. What is the effect of various vehicle distributions to lanes on the traffic flow?
2. What is the effect on traffic flow of various distances between adjoining on-ramps?

3. What is the effect of various desired velocity distributions on traffic flow?
4. At what volume of traffic do weaving movements between lanes become hazardous?
5. What is the effect on traffic flow of various volumes of commercial vehicles?

The simulation model developed in this study can serve as an efficient tool to answer these and other problems in the continuous quest for means of moving traffic safely and efficiently.

REFERENCES

1. "Application of Digital Simulation Techniques to Freeway on Ramp Traffic Operations." Final Report, MRI Project No. 2234-P (Sept. 1, 1958-June 30, 1959).
2. Webb, G. M. and Moskowitz, K., "California Freeway Capacity Study—1956." Proc., 36th Ann. Meeting HRB, NAS-NRC Pub. 542.