Study of Operational Characteristics of Left-Hand Entrance and Exit Ramps on Urban Freeways

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The paper is essentially a companion to an earlier report dealing with left-hand exit ramps for freeways and is divided into three main sections: (a) a study of the general operating characteristics of left- and right-hand entrance ramps on urban freeways; (b) an analysis of traffic behavior along a 2-mi section of urban freeway containing two internal diamond interchanges; and (c) a comparative study of the reported accident rates at a sample of right- and left-hand entrance and exit ramps on urban freeways in the Chicago area.

Brief descriptions are given of study locations and study techniques, together with a discussion of major results. Conclusions are drawn concerning the operational efficiency, relative safety and general suitability of left-hand entrance and exit ramps for urban freeways under the type of site conditions existing in the Chicago area.

•THIS PAPER is essentially a companion to an earlier report by Berry, Ross and [illegible] ramps on urban freeways. The present paper develops some of those earlier analyses somewhat further, discusses a complementary study of left-hand entrance ramps and presents the results of a study of reported accident rates at a sample of left- and right-hand entrance and exit ramps in the Chicago area.

OPERATIONAL STUDIES—LEFT- AND RIGHT-HAND ENTRANCE RAMPS

The operational problems posed by a left-hand entrance ramp on a high-volume urban freeway differ considerably from those posed by a left-hand exit ramp. In the case of a left-hand exit, the major operational problems are generally associated with increases in the incidence of weaving and hazardous maneuvers immediately upstream of the ramp nose (1). In the case of a left-hand entrance, however, the major problems arise from the fact that ramp vehicles are forced to merge with through traffic traveling in the high-speed, high-volume left lane of the freeway, rather than in the lower speed, lower volume right-hand lane. The studies described in this first section of the paper assess some of the operational problems which are likely to occur at left-hand entrance ramps by comparing the operation of a series of left-hand ramps located in the Chicago area with an equivalent sample of "typical" right-hand entrance ramps.

Field studies were conducted at four left-hand and two right-hand entrance ramps on the Eisenhower and Kennedy Expressways in Chicago (Table 1). The studies encompassed a total of 24 hr of observations, during typical morning and afternoon weekday traffic conditions. They included a period of over 2 hr in the early morning, during which severe congestion backed up into the vicinity of one of the left-hand ramps

Paper sponsored by Committee on Freeway Operations.

TABLE 1

CHARACTERISTICS OF ENTRANCE RAMP STUDY LOCATIONS

Location of Entrance Ramp	Freeway Characteristics		Ramp Characteristics			Volume Characteristics (AWDT)	
	No. Lanes	Alignment	Accel. Lane Length (ft)	Width (ft)	Grade (%)	Freeway Vol. Upstream of Nose	Ramp Vol. At Nose
Left-hand entrance ramps Harlem Ave. EB, Eisenhower Expwy.	3	Depressed fwy., tangent and level.	1,075 (parallel)	16	-3	53,300	10,700
Harlem Ave. WB, Eisenhower Expwy.	3	Depressed fwy., tangent and level.	800 (dir. taper)	16	-3	53,300	7,600
Austin Blvd. WB, Eisenhower Expwy.	3	Depressed fwy., tangent and level.	1,100 (parallel)	16	-3	59,500	4,500
Diversey Ave. SB, Kennedy Expwy.	4	Embanked fwy., slight curve left, level.	900 (parallel)	16	+3	72,000	3,500
Right-hand entrance ramps First Ave. WB, Eisenhower Expwy.	3	Depressed fwy., tangent and level.	350 (dir. taper)	16	-2	52,500	4,500
Sayre Ave. SB, Kennedy Expwy.	3	Depressed fwy., tangent and level.	800 (parallel)	16	-2	52,700	1,300

studied (Harlem Ave. eastbound (EB) entrance ramp, Eisenhower Expressway) from a point more than 2 mi downstream. Field data were collected at all locations by means of time-lapse movie photography, supplemented by "direct observation" measurements.

With one exception (Diversey Ave. southbound (SB) left-hand entrance ramp, Kennedy Expressway), all of the locations studied were situated on three-lane level sections of six-lane depressed freeway. The Austin Blvd. and Harlem Ave. left-hand entrance ramps were elements of two internal diamond interchanges, located $1\frac{3}{4}$ mi apart on the Eisenhower Expressway in west suburban Chicago. The First Ave. and Sayre Ave. right-hand entrance ramps were both elements of conventional external diamond interchanges, also situated in suburban areas on the Eisenhower and Kennedy Expressways, respectively. The Diversey Ave. left-hand entrance ramp entered into a four-lane elevated section of the Kennedy Expressway at a point some 6 mi north of the city center. It was the only ramp studied whose approach to the freeway lay on an upgrade and which did not form part of a diamond interchange.

Figure 1 shows the location of each of the ramps studied within the Chicago area expressway system. Figures 2 and 3 are aerial views of the Harlem Ave. and First Ave. interchanges and Figures 4 through 9 are ground-level photographs of the six entrance ramps studied.

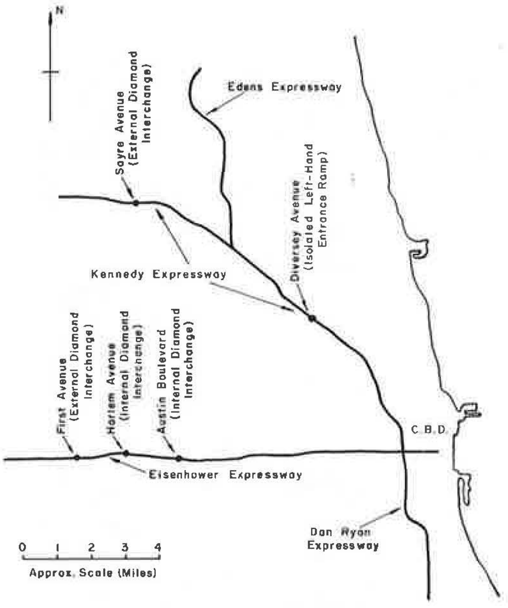


Figure 1. Operational studies—location of interchanges studied in first section of report.

Volume Studies

Figures 10, 11 and 12 illustrate the volume distributions by lane in the vicinity of the Harlem Ave. EB left-hand entrance

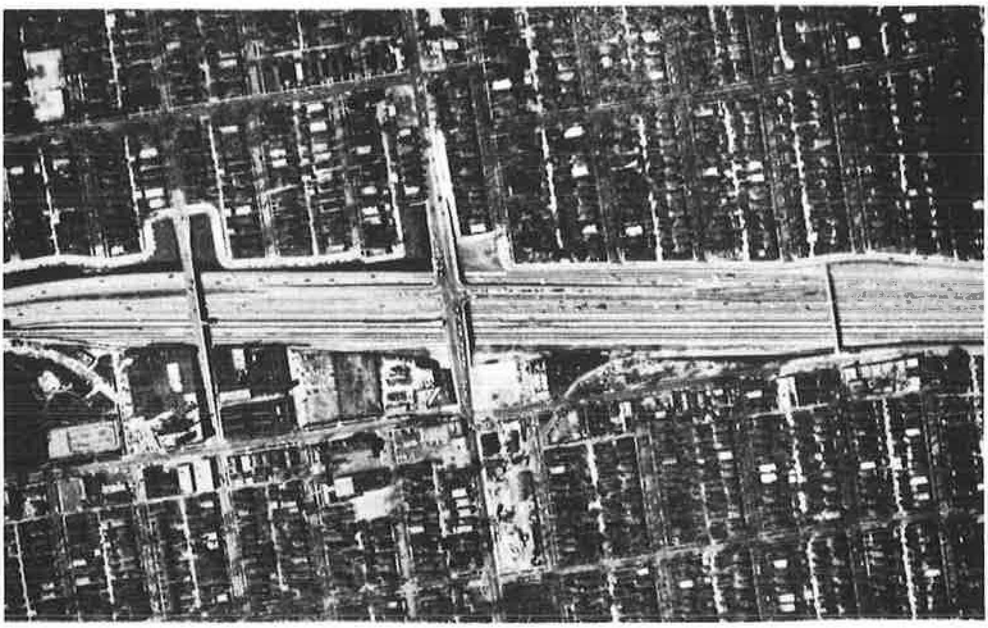


Figure 2. Aerial view of Harlem Ave. internal diamond interchange, Eisenhower Expressway, Chicago.

Figure 3. Aerial view of First Ave. external diamond interchange, Eisenhower Expressway, Chicago.

Figure 4. Harlem Ave. EB left-hand entrance ramp, Eisenhower Expressway, Chicago.

Figure 5. First Ave. WB right-hand entrance ramp, Eisenhower Expressway, Chicago.

Figure 6. Austin Blvd. WB left-hand entrance ramp, Eisenhower Expressway, Chicago.

Figure 7. Harlem Ave. WB left-hand entrance ramp, Eisenhower Expressway, Chicago.

Figure 8. Sayre Ave. SB right-hand entrance ramp, Kennedy Expressway, Chicago.

Figure 9. Diversey Ave. SB isolated left-hand entrance ramp, Kennedy Expressway, Chicago.

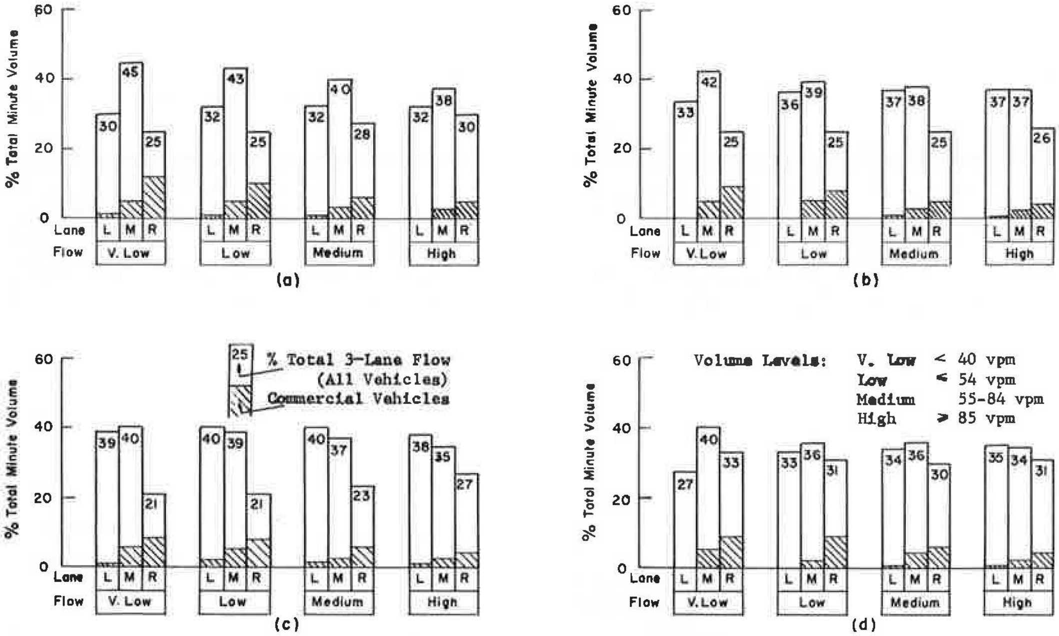


Figure 10. Volume distributions by lane: (a) Harlem Ave. left-hand entrance ramp, at nose; (b) First Ave. right-hand entrance ramp, at nose; (c) Harlem Ave. left-hand entrance ramp, at end of acceleration lane; and (d) First Ave. right-hand entrance ramp, at end of acceleration lane.

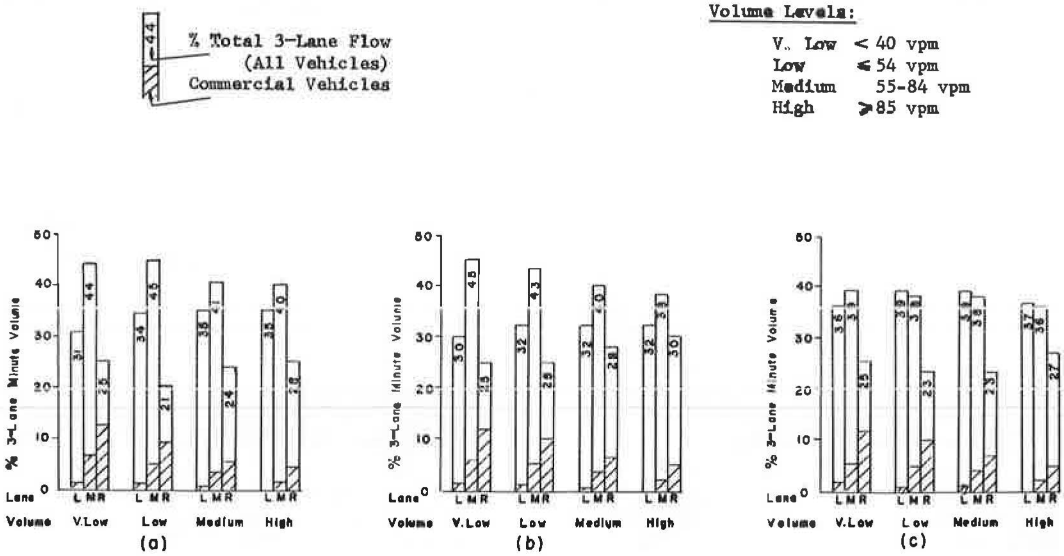


Figure 11. Volume distributions by lane in vicinity of Harlem Ave. EB left-hand entrance ramp, Eisenhower Expressway, Chicago: (a) at nose of left-hand exit ramp, 1,700 ft upstream; (b) at nose; and (c) at point 3,300 ft downstream.

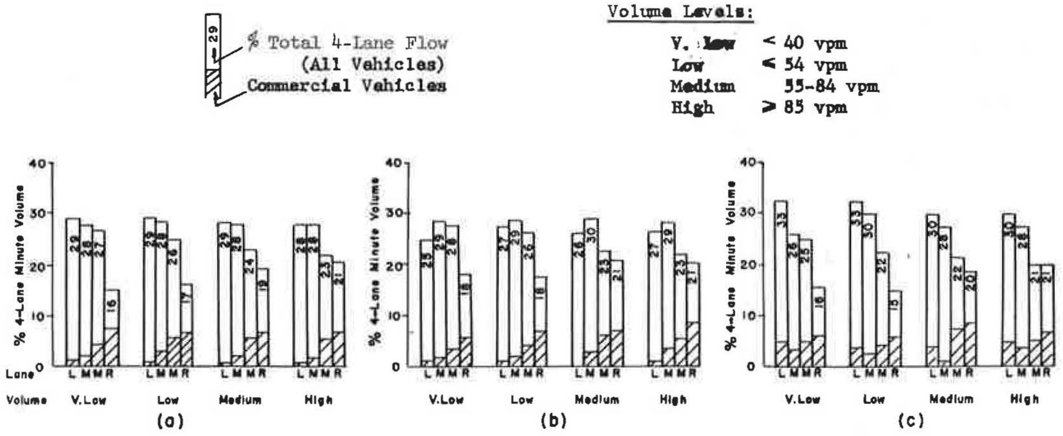


Figure 12. Volume distribution by lane in vicinity of Diversey Ave. SB isolated left-hand entrance ramp, Kennedy Expressway, Chicago: (a) "average" lane distribution on eight-lane freeway; (b) at nose; and (c) at end of acceleration lane.

ramp, the Diversey Ave. SB left-hand entrance ramp and the First Ave. westbound (WB) right-hand entrance ramp.

Figure 10 compares the lane distributions at the nose and at the end of the acceleration lane of the Harlem Ave. EB left-hand ramp and First Ave. WB right-hand ramp for four different levels of mainstream freeway volume. These volume levels (i. e., v. low < 40 vpm, low ≤ 54 vpm, medium 55 to 84 vpm, and high ≥ 85 vpm), measured at a point immediately upstream of the ramp nose, correspond to the levels used in the exit-ramp study referred to earlier (1). From this figure it may be concluded that:

1. The left-lane volumes at the nose of the Harlem Ave. left-hand entrance ramp were consistently lower and the center- and right-lane volumes consistently higher than the comparable volumes at the nose of the First Ave. right-hand on-ramp. The proportion of traffic traveling in the extreme left lane on the approach to the Harlem Ave. left-hand entrance ramp was considerably lower at all volume levels than that using the adjacent center lane, but still higher than the proportion traveling in the right lane.
2. Immediately downstream from the left-hand entrance, the left lane carried from 1 to 3 percent more traffic than the center lane, and 11 to 19 percent more than the right lane. Downstream from the right-hand entrance, the distribution of traffic was much more uniform; the maximum difference between individual lane proportions in this case was only 6 percent (as opposed to 19 percent downstream of the left-hand on-ramp). There was a tendency in both cases for the lane distributions to even out at higher volume levels.
3. At both locations, the distribution of trucks in the freeway lanes opposite the ramp nose was roughly 60 percent in the right lane, 36 percent in the center lane and only 4 percent in the left lane, reflecting the presence of "Trucks Use Two Right Lanes" signs along the expressway. Immediately downstream of the left-hand ramp, however, the left lane carried over 35 percent of the total commercial traffic, due to the large number of trucks and buses entering from the left-hand on-ramp.

In interpreting the data of Figure 10, it is important to note that the Harlem Ave. left-hand entrance ramp was located only some 1, 700 ft downstream of a left-hand exit ramp which carried an ADT of 7, 600 veh. The pronounced effect of this off-ramp on the volume distribution in the vicinity of the on-ramp is illustrated in Figure 11. Clearly, the 6 to 9 percent difference between the left- and center-lane volumes observed at the nose of the left-hand entrance ramp may be largely attributed to the effect of the left-hand exit ramp immediately upstream. There was apparently no tendency for the left lane to "fill up" over the 1,700 ft between the left-hand exit and entrance ramps. This point is discussed in more detail later. Figure 11c illustrates the distribution of main line traffic at a point 3,300 ft downstream of the Harlem Ave. left-hand entrance. At this point, approximately halfway between the Harlem Ave. and Austin Blvd. interchanges, the volume distribution appears to have stabilized, with the left and center lanes carrying approximately the same proportions of traffic at all flow levels.

As might be expected, a single isolated low-volume left-hand entrance ramp had considerably less effect than an internal diamond interchange on the mainline volume distribution. In the case of such an isolated ramp, the volume distributions in the vicinity of the entrance ramp differed very little from the distributions determined on an "average" four-lane section of freeway (average distributions computed from data collected on the Eisenhower Expressway in Chicago), though there was again a tendency for the left-hand lane to carry a slightly lower volume than "normal" on the approach to the on-ramp and a higher volume at the end of the acceleration lane (Fig. 12).

Speed Studies

Observations of average-minute-lane-speeds (average of the individual speeds of a series of vehicles passing a given point in a given lane of a freeway within 1 min) adjacent to the Harlem Ave. left-hand and First Ave. right-hand entrance ramps were classified according to the following general conditions of flow:

1. Off-peak—three-lane density < 35 vpm/lane (free flow);
2. Peak uncongested—three-lane density between 35 and 60 vpm/lane (no complete stoppages); and
3. Peak congested—three-lane density > 60 vpm/lane (regular stoppages in all lanes).

For each of these flow conditions, cumulative distributions of average-minute-lane-

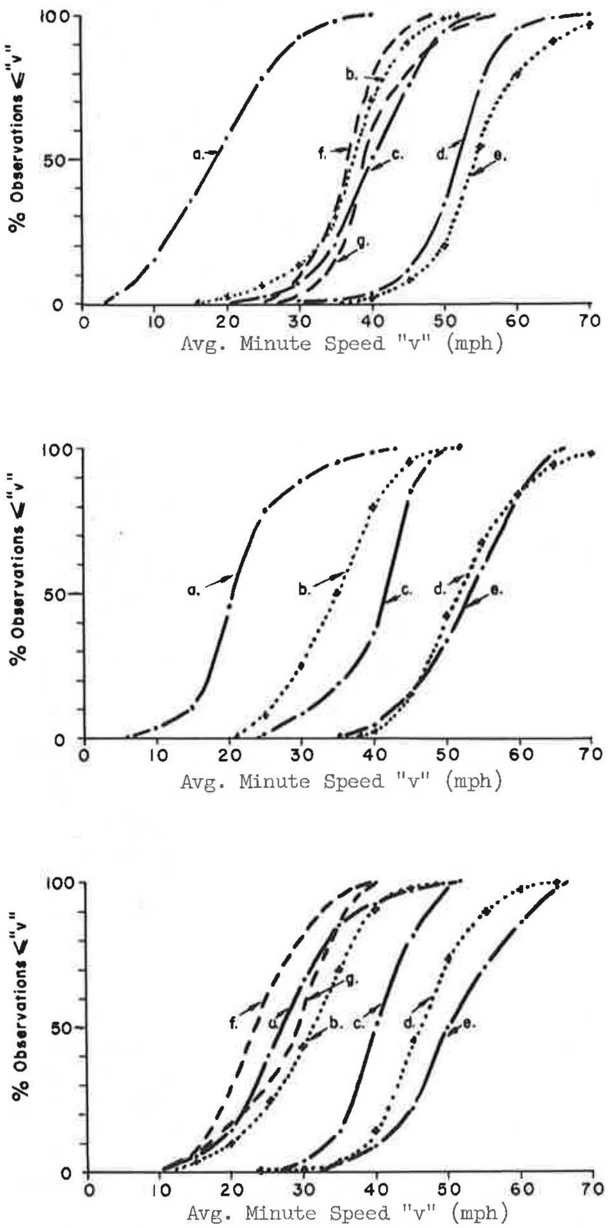
determined for the speeds of entering vehicles, measured in this case over a 300-ft trap length located on the ramp proper immediately upstream of the ramp nose.

These ramp speeds are also plotted on Figure 13. The distributions of peak-congested and peak-uncongested ramp speeds were not significantly different at the Harlem Ave. left-hand entrance ramp, and no peak congested flow condition was observed at the First Ave. right-hand entrance ramp; consequently, no curves are plotted in Figure 13 for the Harlem Ave. ramp peak congested or the First Ave. peak congested conditions.

Off-Peak Speeds.—During off-peak periods, the distribution of average-minute-speeds in the left lane adjacent to the left-hand on-ramp was significantly lower (at the 5 percent level of significance) and that of right-lane speeds was significantly higher (at the 5 percent level of significance) than in the comparable lanes adjacent to the right-hand entrance. There was no significant difference, however, in the distributions of the center-lane speeds.

The average speeds of ramp vehicles approaching the nose of the left-hand entrance were about 4 to 6 mph higher than the equivalent speeds measured at the right-hand ramp. This difference was significant at the 10 percent level. The average speed of entering trucks was approximately 4 mph lower than that of entering automobiles at the left-hand ramp, and 3 mph lower at the right-hand ramp. These differences were not statistically significant.

Comparison of the average speed differentials between entering vehicles and vehicles traveling in the adjacent through lane at each ramp indicated that this differential varied from 8 to 15 mph at the left-hand ramp to 6 to 12 mph at the right-hand ramp. The distributions of average speed differentials at the two locations were not, however, significantly different at the 10 percent level. There was a tendency at both locations for entering speeds to be slightly lower during periods of very heavy flow.



a) RAMP & LEFT-LANE SPEEDS

a Harlem, L.Lane, Peak Cong.
b First, L.Lane, Peak Uncong.
c Harlem, L.Lane, Peak Uncong.
d Harlem, L.Lane, Off-Peak
e First, L.Lane, Off-Peak
f Harlem, Ramp, Peak Uncong.
g Harlem, Ramp, Off-Peak

b) CENTER-LANE SPEEDS

a Harlem, Peak Congested
b First, Peak Uncongested
c Harlem, Peak Uncongested
d First, Off-Peak
e Harlem, Off-Peak

c) RAMP & RIGHT-LANE SPEEDS

a Harlem, R.Lane, Peak Cong.
b First, R.Lane, Peak Uncong.
c Harlem, R.Lane, Peak Uncong.
d First, R.Lane, Off-Peak
e Harlem, R.Lane, Off-Peak
f First, Ramp, Peak Uncong.
g First, Ramp, Off-Peak

Figure 13. Distributions of average-minute-lane-speeds and average-minute-ramp-speeds at Harlem Ave. EB left-hand entrance ramp and First Ave. WB right-hand entrance ramp, Eisenhower Expressway, Chicago.

The average speeds in the vicinity of the Diversey Ave. left-hand entrance ramp (not illustrated in Figure 13) followed the same general pattern, with ramp vehicle speeds very slightly lower and truck speeds about 5 mph lower than automobile speeds in the main through lanes.

Peak Uncongested Speeds. —The average peak uncongested speeds in all three lanes adjacent to the left-hand entrance ramp were significantly higher (at the 5 percent level of significance) than the comparable speeds adjacent to the right-hand ramp over the whole volume range studied. Similarly, the average speeds of entering vehicles were significantly higher at all volume levels (again at the 5 percent level) at the left-hand than at the right-hand on-ramp. There was again no significant difference between the speeds of entering trucks and entering automobiles.

As the total volume increased adjacent to the left-hand entrance ramp, the average speed of through traffic in the left lane dropped below that for the center lane. The left-lane speed again remained consistently higher, however, than the right-lane speed.

Peak Congested Speeds. —During the peak congested period, there was a considerable backup of traffic from downstream of the Harlem Ave. interchange. This backup greatly reduced average speeds in all lanes near the left-hand entrance ramps. However, the mean speed in the left lane during that period was somewhat lower than that in the center lane. Congestion caused by high-density merging maneuvers at the left-hand entrance undoubtedly contributed to the lowering of left-lane speeds.

Headways and Gap Availability

Figure 14 summarizes the relative availability of time gaps in the adjacent lane at the nose of the Harlem Ave. EB left-hand entrance ramp and the First Ave. WB right-hand entrance ramp on the Eisenhower Expressway. The time-gap distributions are presented in terms of the percentage of time expended in gaps greater than or equal to a given value. They refer only to gaps in the lane adjacent to the acceleration lane at each ramp (i.e., in the extreme left lane at Harlem Ave. and in the extreme right lane at First Ave.). Distinction is again drawn between the distributions obtained at four different levels of mainstream volume (< 40, ≤ 54, 55-84, ≥ 85 vpm). A total of 2,067 and 1,810 gaps were observed at the left- and right-hand ramps, respectively.

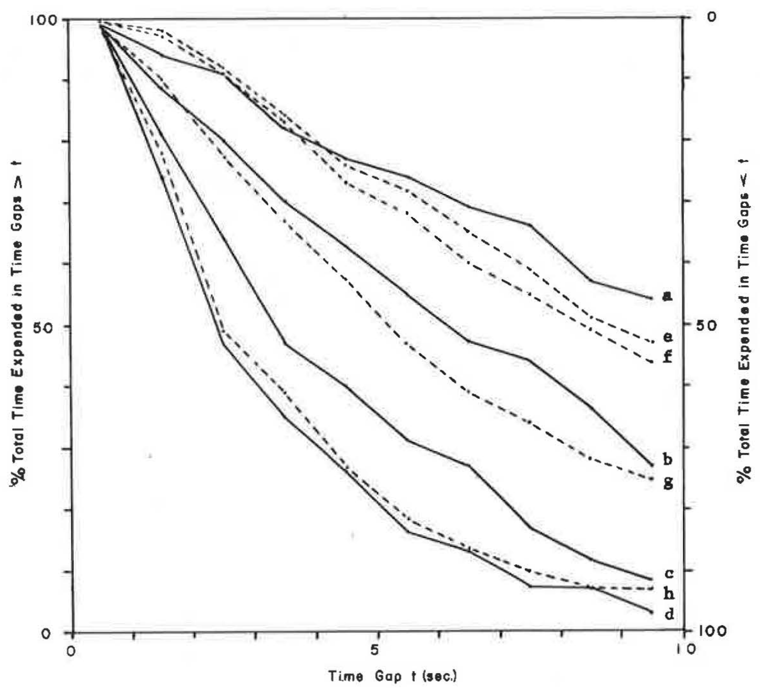
Before discussing the results of this study, it should be noted that the analysis in its present form is somewhat limited in scope. At each study location, observations were restricted solely to the ramp nose. No attempt was made to study the variation in the size of individual time gaps over the length of the acceleration lanes. Similarly, all observations were made during periods of free flow on the expressway. No analyses were made of gap availability during periods of high-density forced flow,

ability at the entrance ramp nose.

With these qualifications accepted, the following statements may be made concerning the distribution of time headways and the availability of time gaps in the lanes adjacent to the two ramps studied:

1. The modal time-gap size (at all volume levels) in the left lane adjacent to the Harlem Ave. left-hand entrance ramp was 1 to 2 sec. This mode became more exaggerated as the total three-lane volume increased. The total amount of time expended in such gaps, however, was very small, less than 5 percent of the total study time at all volume levels. By comparison, the modal value for time gaps in the adjacent right lane at the First Ave. right-hand entrance ramp varied from 3 to 4 sec at low total volumes to 1 to 2 sec at high volumes. Again, the total amount of time expended in such gaps was very small.

2. At all except high total volume levels, there was a significant difference (at the 5 percent level) between the total amount of time expended in time gaps less than t in the adjacent lanes at the two locations. During periods of very low flow (< 40 vpm), a significantly larger proportion of time was expended in gaps of less than 5 sec in the lane adjacent to the left-hand entrance ramp than in the comparable lane at the right-hand entrance ramp. During periods of low (≤ 54 vpm) and medium (55-84 vpm) total flow, however, the position was reversed and a significantly higher proportion of time was expended in time gaps of less than 5 sec at the right-hand entrance ramp than at the left-hand entrance ramp (Fig. 14). If a value of approximately 5 sec is assumed for the minimum acceptable gap size at each location, the results indicate that the probability of an entering driver encountering an acceptable gap was higher at the right-hand ramp during periods of low and medium flow and at the left-hand ramp during periods of very low flow. At high total flows (> 84 vpm), there was no significant



a Harlem Ave. LH On-Ramp, V. Low Flow (<40 vpm)
b Harlem Ave. LH On-Ramp, Low Flow (≤54 vpm)
c Harlem Ave. LH On-Ramp, Medium Flow (55-84 vpm)
d Harlem Ave. LH On-Ramp, High Flow (≥85 vpm)

e First Ave. RH On-Ramp, V. Low Flow (<40 vpm)
f First Ave. RH On-Ramp, Low Flow (≤54 vpm)
g First Ave. RH On-Ramp, Medium Flow (55-84 vpm)
h First Ave. RH On-Ramp, High Flow (≥85 vpm)

Figure 14. Time-gap distributions in adjacent lane at Harlem Ave. EB left-hand entrance ramp and First Ave. WB right-hand entrance ramp, Eisenhower Expressway, Chicago.

difference between the time-expended distributions at the two locations (Fig. 14). During this flow condition, therefore, the probability of an entering driver finding an acceptable gap was approximately the same at each location.

3. At the right- and left-hand ramps studied, the proportion of acceptable gaps (i.e., gaps ≥ 5 sec in the adjacent lane) decreased with increase in total three-lane volume.

Lane Changing

The intensity of lane changing in the vicinity of the left- and right-hand entrance ramps studied is summarized in Table 2. On the basis of these data it would appear that:

1. Immediately upstream of the nose of the entrance ramps, the intensity of lane changing (measured in terms of the total number of lane changes between all lanes per 1,000 ft/min) was 1.6 times higher approaching the left-hand entrance ramp than on the approach to the right-hand entrance ramp. Values of the ratio:

$$\frac{\text{Avg. No. lane changes per 1,000 ft/min upstream of left-hand entrance}}{\text{Avg. No. lane changes per 1,000 ft/min upstream of right-hand entrance}}$$

for different interlane movements were as follows:

TABLE 2

LANE CHANGES IN VICINITY OF HARLEM AVE. EB LEFT-HAND ENTRANCE RAMP AND FIRST AVE. WB RIGHT-HAND ENTRANCE RAMP, EISENHOWER EXPRESSWAY, CHICAGO, AS FUNCTION OF RAMP AND MAINSTREAM MINUTE VOLUME LEVELS

Ramp Type	Ramp Vol.[a]	Lane Changes (No./1,000 ft/min)											
		Low Fwy. Vol.[b]				Med. Fwy. Vol.[b]				High Fwy. Vol.[b]			
		L-C	C-R	R-C	C-L	L-C	C-R	R-C	C-L	L-C	C-R	R-C	C-L
(a) Within 1,000-ft section of freeway immediately upstream													
RH	Low	1.10	0.59	0.98	0.82	0.65	0.42	0.91	0.85	0.47	0.41	0.62	0.76
LH		1.37	1.20	0.96	1.13	1.70	1.48	0.75	0.86	1.35	1.28	0.68	0.39
RH	Medium	0.91	0.68	1.21	0.97	0.62	0.39	0.99	0.48	0.69	0.67	0.76	0.88
LH		1.43	1.38	1.19	0.93	1.76	1.66	1.22	1.33	1.44	1.33	1.03	1.33
RH	High	0.82	0.41	1.15	0.81	0.65	0.51	1.04	0.51	0.52	0.46	0.83	0.61
LH		1.38	0.83	1.11	0.55	1.55	0.83	0.42	0.37	1.27	0.61	0.42	0.37
(b) Adjacent to acceleration lanes													
RH	Low	1.00	0.80	1.16	1.05	0.82	0.73	0.99	0.91	0.68	0.67	0.79	0.71
LH		3.00	1.16	0.79	1.04	1.43	1.30	1.56	1.17	1.29	0.92	0.68	1.01
RH	Medium	0.75	0.90	1.27	0.98	1.01	1.12	2.13	1.07	0.71	0.89	1.21	0.90
LH		3.78	1.21	0.68	1.53	2.91	2.89	1.14	0.86	1.29	0.81	0.62	0.73
RH	High	0.69	0.91	1.72	1.21	0.63	1.15	2.78	1.42	0.61	1.07	2.30	1.14
LH		5.91	1.21	0.45	0.76	4.80	1.14	0.45	1.60	3.75	0.52	0.38	1.35

[a]Low, ≤ 5 vpm; medium, 6-15 vpm; and high, ≥16 vpm.
[b]Low, ≤54 vpm; medium, 55-84 vpm; and high, ≥ 85 vpm.

From center to right lane = 2.3/1,
From right to center lane = 0.8/1, and
From center to left lane = 1.2/1,
for an overall average of 1.6/1.

2. The predominate lane-changing movement upstream of the left-hand entrance was to the right (i.e., from the left lane to the center lane and from the center lane to the right lane) at all volume levels. Upstream of the right-hand ramp, there was a more even amount of lane changing between all lanes, though again there was a slight predominance of movements away from the ramp. At both locations, the intensity of lane changing first increased and then decreased with continuing increases in freeway flow. Individual maneuver lengths (not illustrated here) varied from 70 to 500 ft and tended to be shorter at higher total flows.

3. There were 1.8 times as many lane changes per 1,000 ft/min adjacent to the acceleration lane of the left-hand ramp as there were adjacent to the acceleration lane of the right-hand ramp. Values of the ratio:

$$\frac{\text{Avg. No. lane changes per 1,000 ft/min adjacent to left-hand ramp}}{\text{Avg. No. lane changes per 1,000 ft/min adjacent to right-hand ramp}}$$

for different interlane movements in this case were:

From left to center lane = 4.3/1,
From center to right lane = 1.3/1,
From right to center lane = 0.6/1, and
From center to left lane = 1.1/1,

for an overall average of 1.8/1. The predominate movements at both locations were again away from the entrance ramps. Again the intensity of lane changing increased and then decreased with increase in freeway volume. Movements away from both ramps increased directly as ramp volumes increased. During peak volumes, a separate analysis indicated that there was a net lane changing over the length of the left-hand ramp acceleration lane of 12.8 lane changes per 100 ft/hr, compared with a net figure of 2.3 lane changes per 100 ft/hr adjacent to the right-hand ramp. At lower volumes these figures increased to 16.2 and 12.3 lane changes per 100 ft/hr, respectively. (These figures include movements between all mainstream lanes.)

4. Table 3 summarizes the intensity of lane changing within the 1,700 ft of roadway separating the left-hand exit and entrance ramps at the Harlem Ave. EB interchange. It is apparent that there was no tendency for time gaps created in the left-lane traffic stream due to vehicles exiting at the left-hand exit ramp to fill up between the nose of the exit ramp and the nose of the entrance ramp 1,700 ft downstream. This conclusion is based on a total sample of 4 hr of lane-changing data.

Hazardous Maneuvers

A qualitative analysis of the incidence of hazardous maneuvers was performed at each of the ramps studied. For the purposes of the analysis a hazardous maneuver is defined as a maneuver by an entering vehicle which caused the driver of a following through vehicle to change his speed or direction violently. Although no attempt was made to develop a precise quantitative definition of a hazardous maneuver, errors of definition were kept to a minimum by insuring that the same individual performed all of the analyses.

There was very little difference in the overall incidence of hazardous maneuvers at the left- and right-hand ramps studied. No significant relationship could be developed between the incidence of hazardous maneuvers and traffic volume for the range of daytime volumes studied. At the four left-hand ramps, an average of 18.7 hazardous entries per 1,000 ramp vehicles were observed. At the two right-hand ramps, the comparable average figure was 17.6/1,000 ramp vehicles.

At the four left-hand entrances, an average of three hazardous maneuvers per ramp per hour were observed in which through vehicles made use of the acceleration lane to pass other through vehicles. At the right-hand entrance ramps, only one such maneuver was observed during a period of 8 hr. A relatively large percentage of the hazardous direct entries (i.e., entering maneuvers in which the entering vehicle cut directly across one or more lanes of traffic) observed at all of the left-hand entrance ramps studied involved trucks. This was due primarily to a regulation requiring trucks to use the two extreme right-hand lanes on the freeway. No such tendency was observed at the right-hand ramps.

TABLE 3

LANE CHANGES WITHIN 1,700-FT SECTION OF FREEWAY[a]

Fwy. Vol.[b]	Lane Change Direction	Lane Changes (No./min)
Low	L-C	2.37
	C-R	2.80
	R-C	2.18
	C-L	2.11
Medium	L-C	3.20
	C-R	2.92
	R-C	2.71
	C-L	2.88
High	L-C	2.96
	C-R	2.66
	R-C	2.16
	C-L	2.79

[a]Between noses of Harlem Ave. EB left-hand exit and entrance ramps, Eisenhower Expressway, Chicago.
[b]Low, ≤ 54 vpm; medium, 55-84 vpm; and high ≥ 85 vpm.

Zone of Entry Onto Through Lanes

Figure 15 illustrates the variation of point of entry onto the main freeway lanes (the point at which a vehicle's front near-side wheel finally crosses from the acceleration lane onto the adjacent through lane) for the Harlem Ave. EB left-hand entrance ramp, the First Ave. WB right-hand entrance ramp and the Sayre Ave. SB right-hand entrance ramp. In each case, the data are subdivided into conditions of peak and off-peak flow in the mainstream. Congested and uncongested observations were combined in the case of the peak flow condition.

At the Harlem Ave. left-hand entrance ramp, the zones of entry were concentrated mainly in the first 400 ft during off-peak

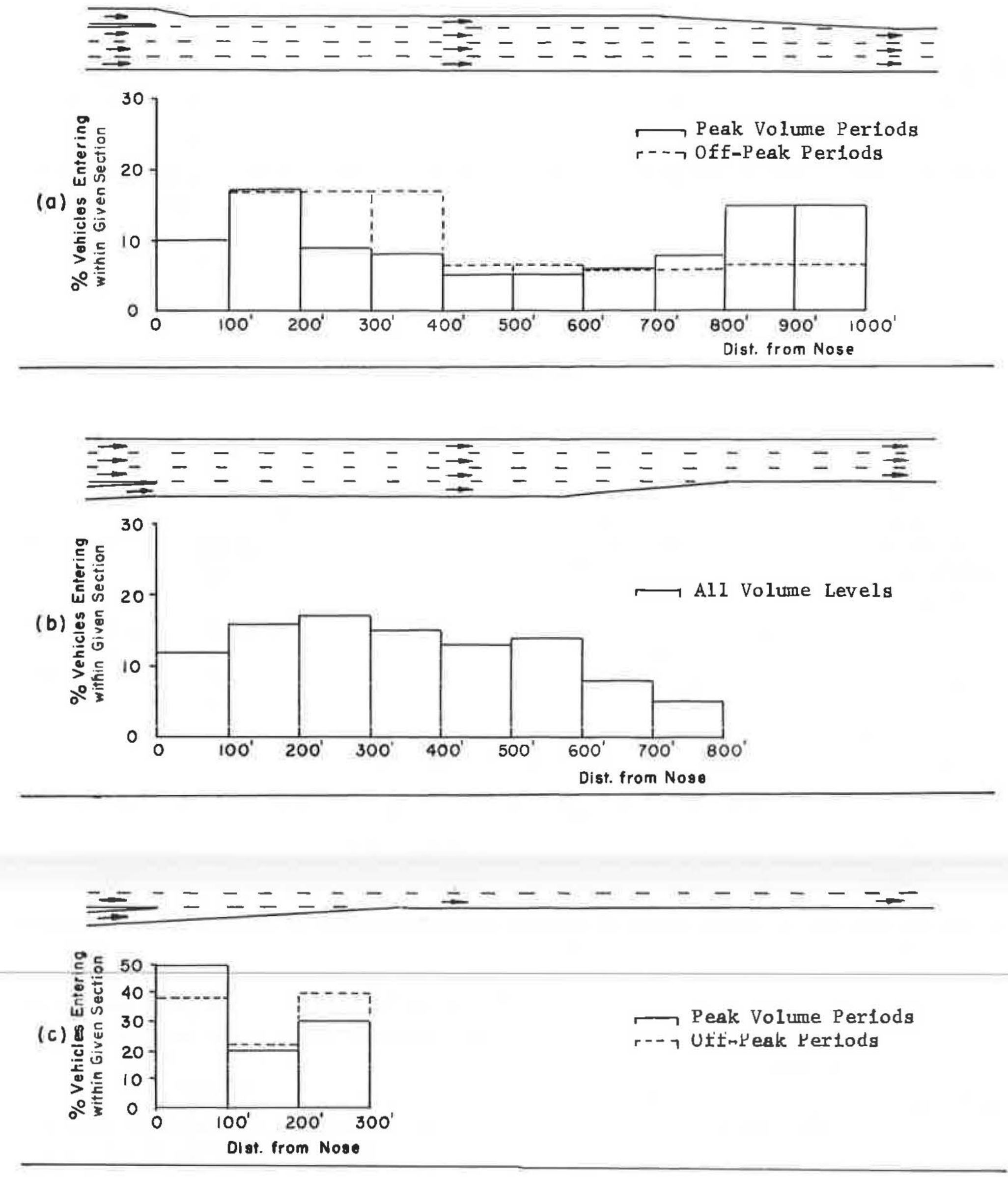


Figure 15. Zone of entry distributions: (a) Harlem Ave. EB left-hand entrance ramp, Eisenhower Expressway; (b) Sayre Ave. SB right-hand entrance ramp, Kennedy Expressway; and (c) First Ave. WB right-hand entrance ramp, Eisenhower Expressway.

periods and in the first 200 and last 350 ft during the peak periods. The equivalent distributions at the First Ave. right-hand entrance ramp, which has a very short acceleration lane, were more uniform for both volume conditions. The absence of an adequate acceleration lane, however, encouraged a number of drivers to stop at the nose of the ramp to wait for an acceptable gap, thereby creating an increased number of early entries. The Sayre Ave. entrance ramp observations, for a right-hand ramp provided with an 800-ft long acceleration lane, showed an even distribution of points of entry at all volume levels.

The results of the Harlem Ave. zone-of-entry studies, when considered in isolation, indicate that the use of a long acceleration lane by no means guarantees satisfactory operation of a left-hand entrance ramp. At high total volumes, a large number of drivers were forced to the end of the acceleration lane without finding an acceptable gap and were then brought to a complete halt. Obviously, such a procedure reduces the efficiency of ramp operation. It should be noted, however, that the acceleration lane was sufficiently long to prevent backups due to such stoppages from extending up the ramp proper.

During off-peak periods, relatively few entering vehicles made full use of the extra length of acceleration lane provided for their benefit, whereas a number of through vehicles utilized the speed-change lane as a fourth through lane to pass other vehicles. This latter practice clearly constitutes a hazardous maneuver that might be dealt with by reducing the length of the acceleration lane. Such a proposition, however, is in conflict with the conclusions of the preceding paragraph. A more satisfactory solution might be to extend the ramp nose by some 200 ft beyond its present position.

SYSTEM STUDY—EISENHOWER EXPRESSWAY EB

Figure 16 illustrates a 2-mi section of the eastbound Eisenhower Expressway in west suburban Chicago. This section of freeway contains two internal diamond interchanges, at Harlem Ave. and Austin Blvd., spaced about 7,300 ft apart.

Traffic operations within this section of freeway were studied on four separate occasions in the spring and summer of 1964, during the evening inbound peak period (between 4:00 and 6:30 p.m.). The condition during this period was studied to avoid congestion backing up into the study area from downstream, as occurred regularly in the morning peak period.

Data were collected by means of coordinated time-lapse movie photography. Films were taken simultaneously from each of eight locations illustrated in Figure 16. Each series of films was synchronized by stopwatch timing supplemented by a series of timed runs through the study section in a marked vehicle. All cameras were equipped with synchronous electric motors connected to the main freeway lighting circuit, giving a constant film speed in each case of 60 ft/min. Shoulder markings 25 ft apart were laid down at each study location to provide a distance scale for the analysis.

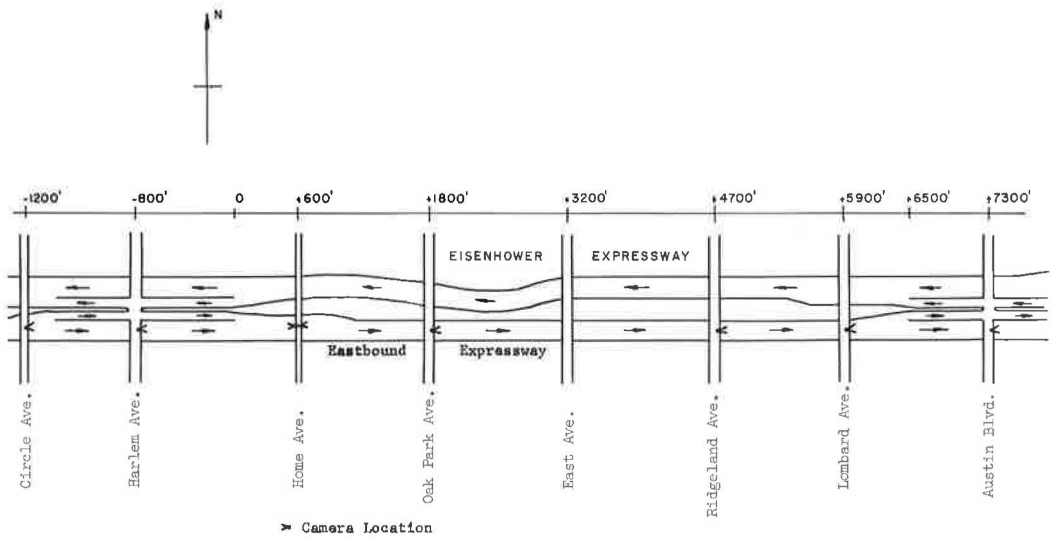


Figure 16. Eisenhower Expressway EB system study—map of study section showing eight camera locations.

Entrance Ramp Merge Rates and Development of Congestion in Adjacent Freeway Section

At each camera location a speed/volume profile was prepared for each lane and ramp, showing the variation of average-minute-volumes and average-minute-speeds with time throughout the study period. Figure 17 reproduces a section of one of these diagrams, covering a period of 40 min during which a shock wave was propagated in the vicinity of the Ridgeland Ave. overpass and reflected back along the expressway beyond Harlem Ave. Figures 18 and 19 illustrate the variation of speeds upstream of the same ramp for two separate periods of 50 min during which high average merge rates were sustained at the left-hand entrance ramp.

On the basis of these diagrams, it may be concluded that:

1. Extremely high merge rates (i.e., ramp volume plus through volume in left lane) were maintained throughout the study period at the Harlem Ave. entrance ramp. These rates ranged from a 2-hr average flow rate of 1,968 vph to an average 50-min rate of 2,034 vph to sporadic peaks maintained for only a few minutes in excess of

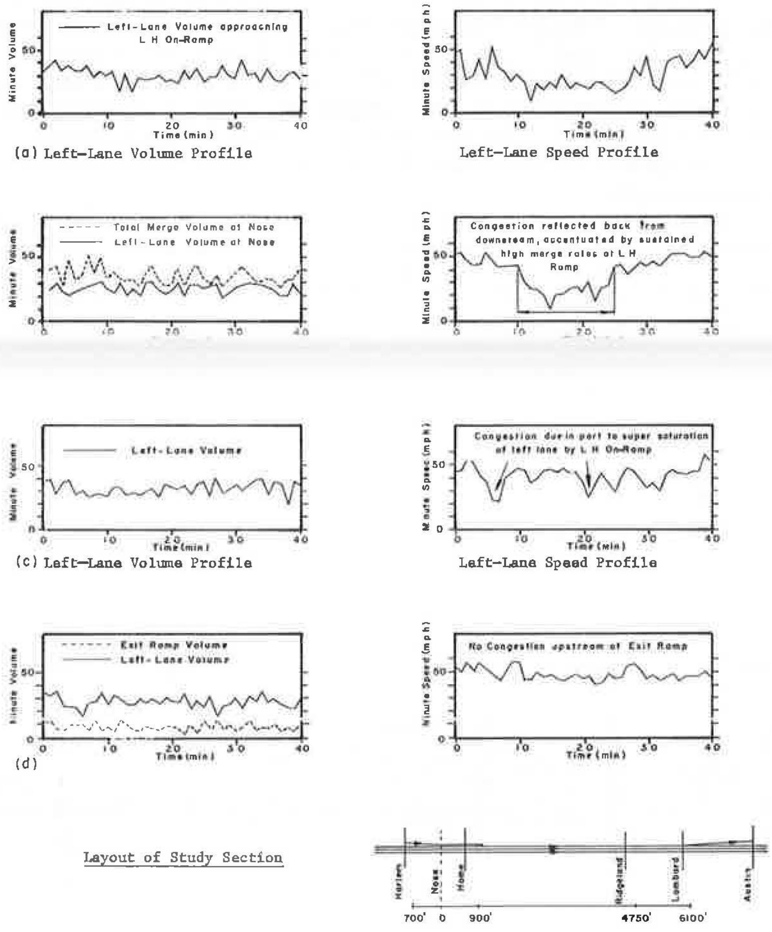


Figure 17. Volume/speed profiles within study section—left lane only: (a) Harlem Ave. overpass, 700 ft upstream of nose of left-hand entrance ramp; (b) Home Ave. overpass, 600 ft downstream of nose of left-hand entrance ramp; (c) Ridgeland Ave. overpass, 4,750 ft downstream of left-hand entrance ramp; and (d) Lombard Ave. overpass, 6,100 ft downstream of left-hand entrance ramp, 600 ft upstream of nose of left-hand exit ramp.

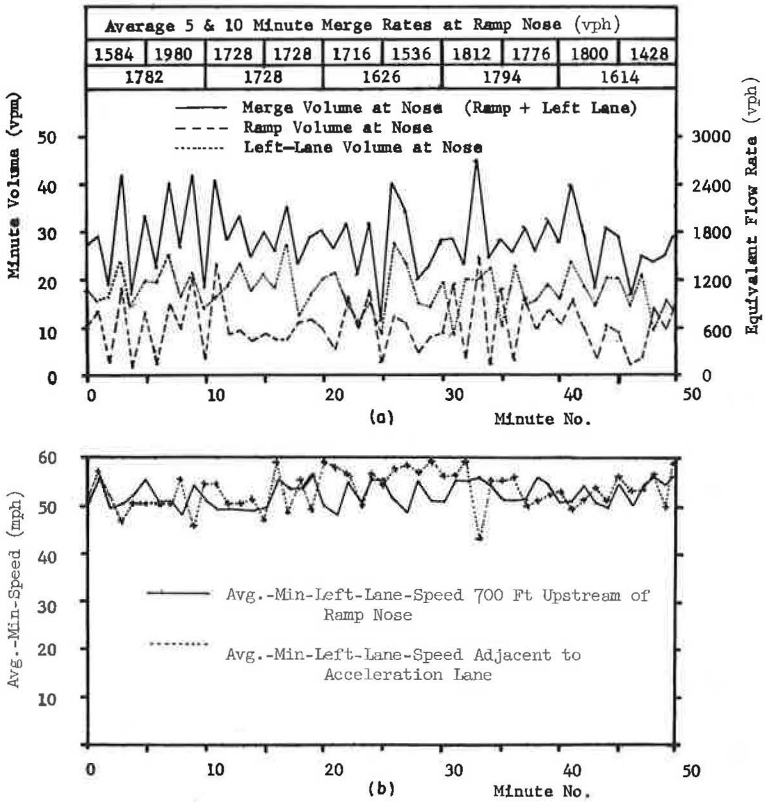


Figure 18. Entrance ramp merge rates (uncongested condition) at nose of Harlem Ave. left-hand entrance ramp, Eisenhower Expressway, Chicago: (a) minute merge volume profiles; and (b) minute speed profiles for left lane in vicinity of ramp.

2,200 vph. Average-minute-speeds in the left lane at a point 700 ft upstream of the ramp nose varied from 10 to 58 mph and, in the same lane at a point immediately downstream of the merge area, from 12 to 52 mph. At no time during the entire study period did the sustained high merge rates result directly in a total breakdown of flow upstream of the ramp. The 10-mph average speeds mentioned and shown in Figures 17 and 19 resulted not from congestion backing up from the merge area, but from a shock wave propagated at a point some 6,000 ft downstream of the ramp (see paragraph 3).

2. For a period of over 50 min, an average merge rate in excess 1,700 vph was maintained at the left-hand entrance ramp without average-minute-speeds in the left lane upstream of the ramp ever falling below 45 mph (Fig. 18). During this period, there was one 5-min merge rate of 1,920 vph and a series of intermittent 1-min merge rates of over 2,000 vph. Throughout the 50 min, the average rate of flow in the left lane approaching the ramp nose was 1,100 vph, with a minimum minute flow rate of 660 vph and a maximum minute flow rate of 1,680 vph.

3. During a separate period of 50 min, an average merge rate of 2,034 vph was observed at the Harlem Ave. entrance ramp (Fig. 17). This period included one period of 10 min during which the average merge rate was 2,360 vph, and four separate 5-min periods during which the average merge rate exceeded 2,000 vph. At no time during the 50 min did the 5-min merge rate drop below 1,872 vph. The average left-lane flow rate approaching the ramp throughout the period was 1,469 vph. During this same period, average-minute-speeds in the left lane upstream of the entrance

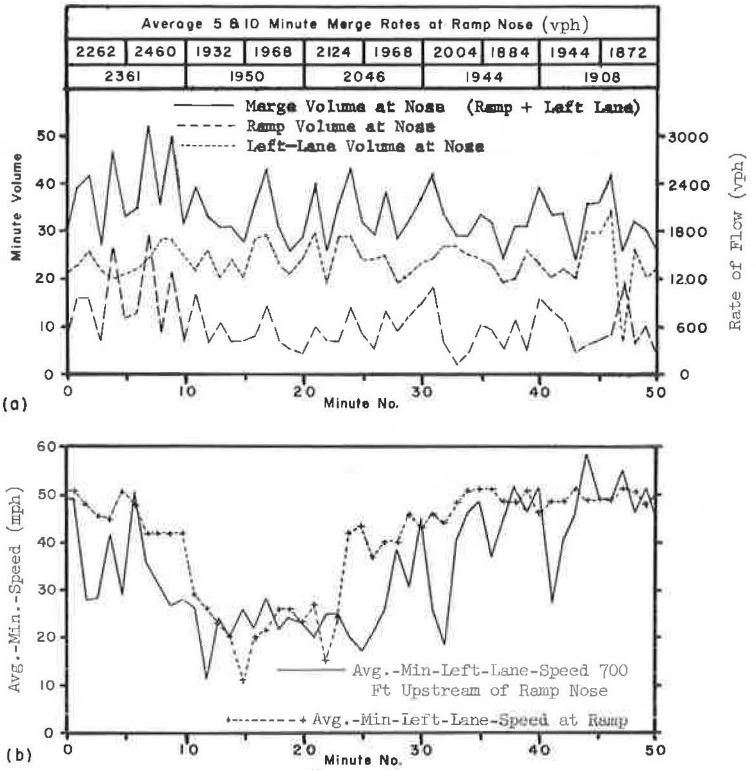


Figure 19. Entrance ramp merge rates (congested condition) at nose of Harlem Ave. EB left-hand entrance ramp, Eisenhower Expressway, Chicago: (a) minute merge volume pro-

ramp dropped to a minimum value of 10 mph (Fig. 19). This maximum slowdown was not, however, created solely by the queueing of freeway vehicles in the left lane upstream of the ramp, but was attributable in large part to the effects of a shock wave reflected back into the vicinity of the ramp from a point 6,000 ft downstream (Fig. 17).

4. During the 50-min period of high sustained merge rates previously mentioned, a condition of extreme forced flow or supersaturation was created in the left lane of the freeway downstream from the entrance ramp. In this condition, the flow in the left lane was extremely sensitive to even relatively minor disturbances. The shock wave illustrated in Figure 17 was propagated in the vicinity of Ridgeland Ave. by a series of abrupt lane changes in and out of the left lane which caused vehicles in that lane to decelerate sharply. This shock wave was reflected back along the left lane of the freeway and its effect was magnified by the sustained high merge rates at the Harlem Ave. entrance ramp, producing a 17-min period of congestion (average-minute-left-lane-speed ≤ 35 mph) adjacent to the ramp's acceleration lane and a 23-min congested period immediately upstream of the ramp nose. The total effects of this shock wave and the accompanying slowdowns caused by the sustained high merge rates at the left-hand entrance were totally dissipated and average-minute-left-lane-speeds returned to their original 45- to 50-mph level upstream of the ramp within a period of 25 min without the average 10-min merge rate ever falling below 1,900 vph.

5. Figures 18 and 19 illustrate a number of extremely high, but short-lived, merge rates in excess of 2,000 vph. Almost without exception, such a merge rate, if sustained for more than 1 min, resulted in a significant drop in the average left-lane speed upstream of the ramp nose.

6. Lane changing adjacent to the acceleration lane of the left-hand entrance ramp has already been discussed. It should be noted here, however, that throughout the study period an average net volume of approximately 125 to 150 vph moved out of the left lane over the length of the merge area. This net lane changing reduced the maximum sustained 50-min merge rate of 2, 034 vph to a left-lane flow downstream of the ramp of 1, 904 vph.

7. There was no indication (Fig. 17) that the Austin Blvd. left-hand exit ramp caused any congestion in the adjacent freeway section.

8. The analyses previously described represent the initial stages of a more detailed series of investigations which are currently in progress at Northwestern University. These investigations include analyses of gap acceptance on both a static and dynamic, basis, the study of maximal permissible merge rates and ramp capacity under all conditions of flow, and an analysis of the entire 2-mi section of freeway considered as a system.

Lane Distribution of Ramp Vehicles Upstream and Downstream of Left-Hand Exit and Entrance Ramps

Using two of the four sets of films described, an analysis was made of the lane distributions of ramp vehicles at varying distances upstream and downstream of the pair of left-hand entrance and exit ramps. The films yielded approximately 2 hr of data. The first hour encompassed primarily free-flow operations on the freeway, and the second hour primarily forced-flow or near-capacity conditions.

Entrance ramp vehicles, entering from the Harlem Ave. EB left-hand entrance ramp, were traced through the study section by means of a master chart on which were recorded the classification, make, year, color and other distinguishing characteristics of each ramp vehicle. From this chart, the number of entrance ramp vehicles traveling

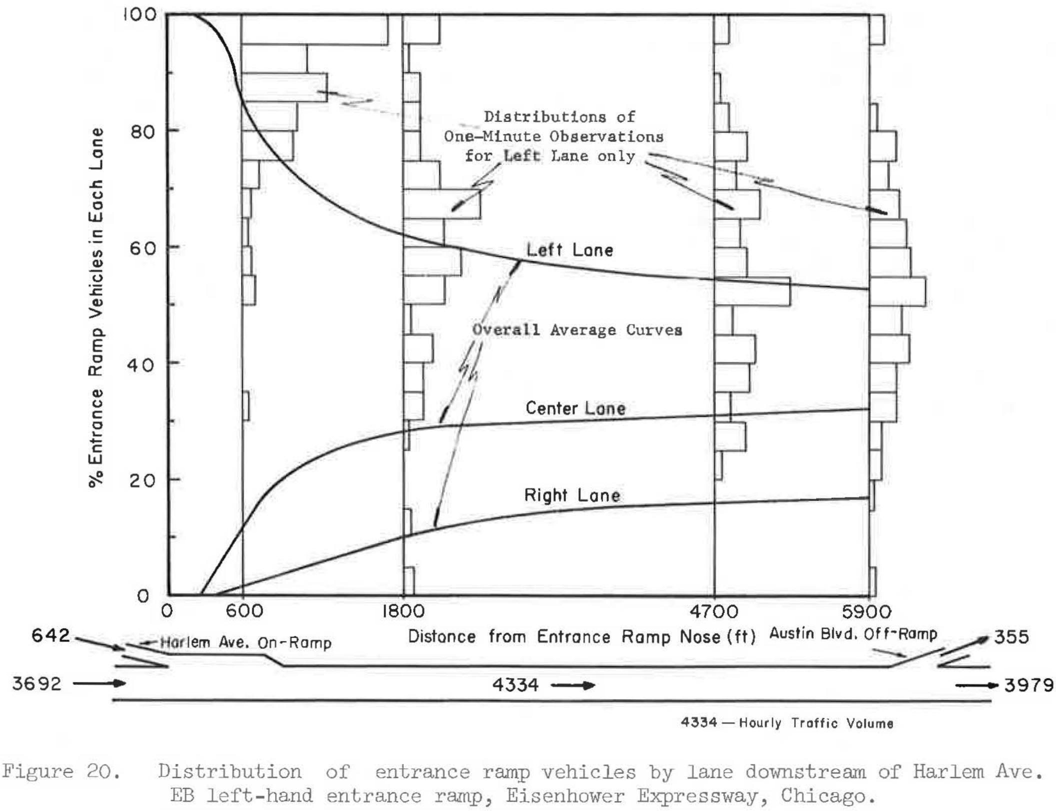


Figure 20. Distribution of entrance ramp vehicles by lane downstream of Harlem Ave. EB left-hand entrance ramp, Eisenhower Expressway, Chicago.

in each lane of the freeway was determined, on a minute-by-minute basis, at four different locations downstream of the entrance ramp nose (Fig. 20). Concurrent with these observations, classified counts of minute-lane-volumes were also made at each location. A similar analysis technique was adopted for vehicles exiting via the Austin Blvd. EB left-hand exit ramp. The average proportion of commercial vehicles within the section throughout the entire study period was 11 percent.

Figure 20 summarizes the results of the entrance ramp studies in general terms. The curves represent the overall average lane distributions of entrance ramp vehicles at varying distances downstream of the entrance ramp nose for the entire study period (i.e., the curves connect the percentage lane distributions computed at each study location on the basis, not of the average of a series of successive minute observations, but of a single aggregate observation period of approximately 2 hr). The extreme variability of the individual minute observations is indicated in Table 4. Because of this variability, it was considered more meaningful to plot a single aggregate curve for the entire study period than an average minute observation curve.

Despite the acknowledged variability of the data, it is clear from Figure 20 that the proportion of ramp vehicles remaining in the left-lane downstream of the entrance ramp fell off rapidly as the distance from the ramp nose increased. It also appears (Table 4) that the frequency distributions of the sets of minute observations became more uniform as distance from the ramp nose increased.

In an effort to develop an understanding of the variables influencing the behavior of entrance ramp vehicles, their lane distribution at varying distances from the ramp nose was analyzed as a function of total mainstream volume. In this connection, it is interesting to note that the mere separation of the second hour of data (mainstream flow rate of 5,050 vph at Oak Park, 60 min of observations) from the first hour (mainstream flow rate of 3,607 vph, 57 min of observations) revealed notable differences in lane distribution percentages.

Total three-lane volume was broken down again into the general categories of high (> 84 vpm), medium (55-84 vpm), and low (< 55 vpm) flow rates. Figure 21 illustrates the variation in the average proportion of entrance ramp vehicles remaining in the left lane, at varying distances downstream of the ramp nose, for each different level

in form to those illustrated for the left lane. The curves for the right lane (also not illustrated) indicate virtually no variation with total volume level.

In Figure 21, the curves for high and medium total volume levels almost coincide, both tending towards an asymptotic value of approximately 50 percent at a distance of 6,100 ft downstream of the ramp nose. The low-volume curve indicates a more rapid transition to this asymptote, at a point in this case some 2,200 ft downstream of the ramp nose. The subsequent increase in the proportion of ramp vehicles traveling in the left lane is simply a reflection of normal weaving and lane-changing maneuvers on a six-lane freeway. Throughout the study period, less than 5 percent of the traffic entering the freeway via the Harlem Ave. left-hand entrance ramp was destined for the Austin Blvd. left-hand exit ramp. All of this traffic remained in the left lane throughout the study section.

TABLE 4

LANE DISTRIBUTION OF LEFT-HAND ENTRANCE RAMP VEHICLES[a]

Location	Dist. Downstream of Ramp Nose (ft)	Sample Size (min)	% Veh in Lane[b]			Std. Dev.[c] (%)			Range[c] (%)		
			Left	Center	Right	Left	Center	Right	Left	Center	Right
Home Ave.	600	117	86	12	2	13	12	4	33-100	0-67	0-17
Oak Park Ave.	1,800	118	62	28	10	20	20	12	0-100	0-100	0-67
Ridgeland Ave.	4,700	112	54	30	16	18	16	12	20-100	0-80	0-50
Lombard Ave.	5,900	102	52	31	17	18	16	12	0-100	0-80	0-50

[a]At selected points downstream of Harlem Ave. EB left-hand entrance ramp, Eisenhower Expressway.
[b]Mean of minute sample observations.
[c]Of minute observation percentages.

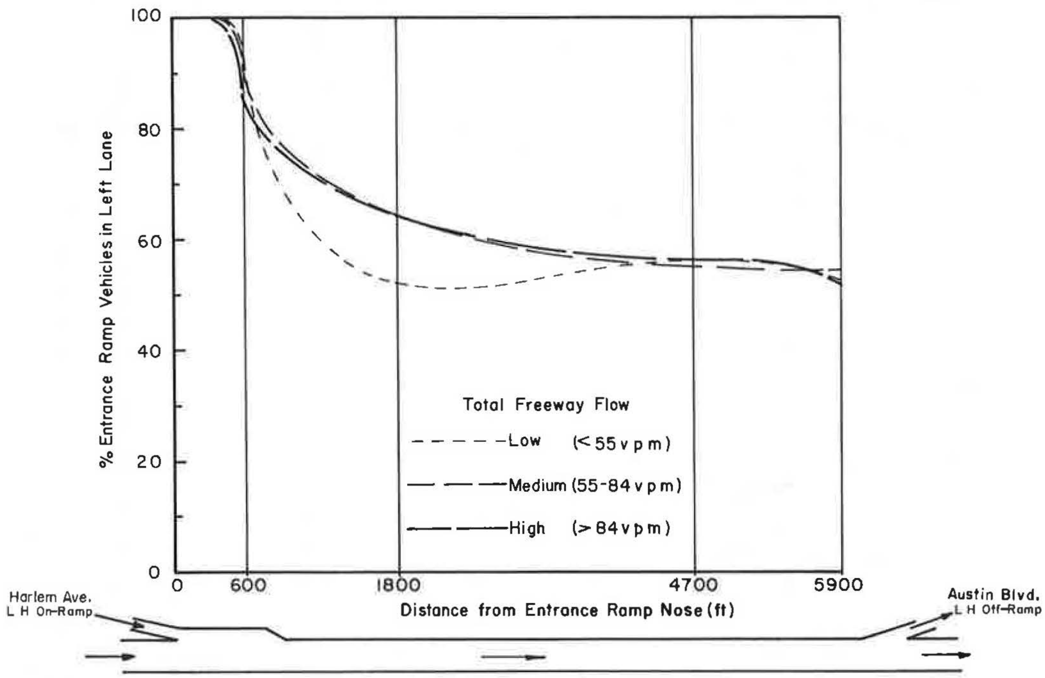


Figure 21. Distribution of entrance ramp vehicles remaining in left lane of expressway downstream of Harlem Ave. EB left-hand entrance ramp, Eisenhower Expressway, Chicago, as function of total volume.

An analysis of the effects of ramp volume and mainstream volume level on the behavior of entering vehicles yielded only inconclusive results. There was a general tendency for the proportion of vehicles remaining in the left lane to increase at all points within the study section with increase in total volume. The behavior of ramp vehicles under conditions of forced flow in the mainstream also appeared to differ considerably from their behavior under conditions of free flow. The scatter of points was too wide, however, and the sample of data too small to permit any detailed conclusions to be drawn.

The results of the companion exit ramp studies are summarized in Table 5 and Figure 22. Figure 22 also indicates the location of directional signs at distances ½, 1 and 2 miles upstream of the exit ramp nose. All of these signs emphasized the fact that the approaching ramp was located on the left rather than the right side of the traveled way.

TABLE 5

LANE DISTRIBUTION OF LEFT-HAND EXIT RAMP VEHICLES[a]

Location	Dist. Upstream of Ramp Nose (ft)	Sample Size (min)	% Veh in Lane[b]			Std. Dev.[c] (%)			Range[c] (%)		
			Left	Center	Right	Left	Center	Right	Left	Center	Right
Harlem Ave.	7,300	104	74	21	5	20	18	11	0-100	0-67	0-50
Home Ave.	5,900	105	81	16	3	19	18	9	0-100	0-100	0-50
Oak Park Ave.	4,700	108	91	8	1	14	12	7	33-100	0-50	0-50
Ridgeland Ave.	1,800	105	97	2	1	11	9	6	50-100	0-50	0-50

[a]At selected points upstream of Austin Blvd. EB left-hand exit ramp, Eisenhower Expressway.
[b]Mean of minute sample observations.
[c]Of minute observation percentages.

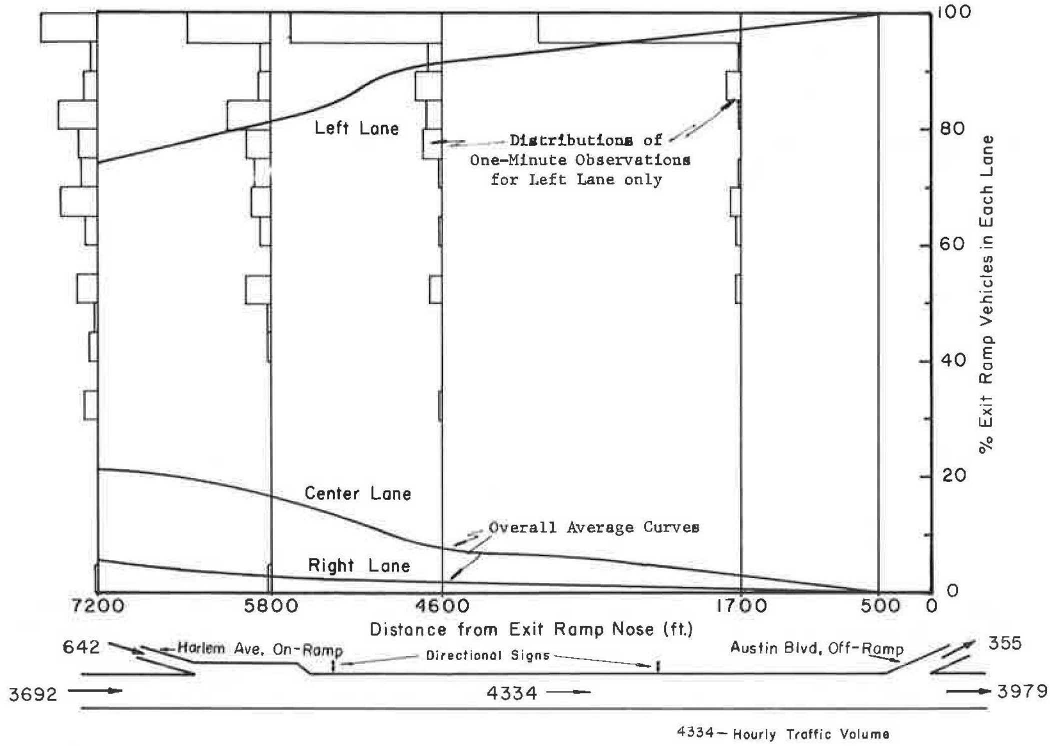


Figure 22. Distribution of exit ramp vehicles by lane upstream of Austin Blvd. EB left-hand exit ramp, Eisenhower Expressway, Chicago.

As in the case of the entrance ramp data, the distributions were again highly dispersed, due largely to the effects of a number of extremely low minute ramp volume observations. In this case, however, the arrival pattern of ramp vehicles at the exit ramp nose was relatively uniform over the entire hour. Minute volumes were low merely because the overall demand for the ramp was low.

Whereas the entrance ramp relationships tended to stable asymptotes within the study section, the exit ramp curves failed to do so. Undoubtedly, a substantial movement of exit ramp vehicles into the left lane occurred upstream of the study section, between the Harlem Ave. camera location and the first directional sign located approximately 1 mi farther upstream. The curves indicate clearly that drivers wishing to use the left-hand exit tended to move into the left lane far in advance of the ramp nose, perhaps as a result of the directional signing or perhaps for fear of missing the ramp completely. Over 70 percent of all exiting vehicles were positioned in the left lane of the freeway at a point 7,250 ft upstream of the left-hand exit ramp. Total freeway volume had no apparent effect on the lateral placement of exit ramp vehicles at any point in the section. These results all tend to confirm those of a previous more limited study (1).

ACCIDENT STUDIES

A number of previous studies (2, 3, 4, 5) have indicated that the average accident rate at left-hand ramps is generally higher, and frequently more severe, than that observed at comparable right-hand terminals. None of these studies, however, was based on more than a very limited sample of study locations, and none of them included any detailed statistical comparison of the two design types.

The final section of this paper describes a series of comparative accident studies, conducted over a 2-yr period at 75 entrance and exit ramps (20 left-hand and 55 right-hand ramps) on urban expressways in the Chicago area. The studies include analyses of the simple frequency of occurrence of ramp accidents at left- and right-hand ramps, of the characteristics of these accidents, of the factors contributing to them and of the effect of different ramp configurations on the pattern of mainstream accidents.

Selection and Description of Study Locations and Sources of Data

A total of 20 left-hand (16 entrances and 4 exits) and 55 right-hand ramps (26 entrances and 29 exits) were selected for study (Fig. 23). To reduce errors resulting from differential levels of accident reporting, the selection of study locations was restricted to three intensively patrolled urban freeways in the Chicago area.

Of the 20 left-hand ramps selected for study, eight (four exits and four entrances) were elements of two internal diamond interchanges, located 1½ mi apart on a six-lane section of the Eisenhower Expressway in west suburban Chicago. Another isolated left-hand entrance ramp was located on the eight-lane section of the Kennedy Expressway, some 8 mi northwest of the Loop. This was the only left-hand entrance

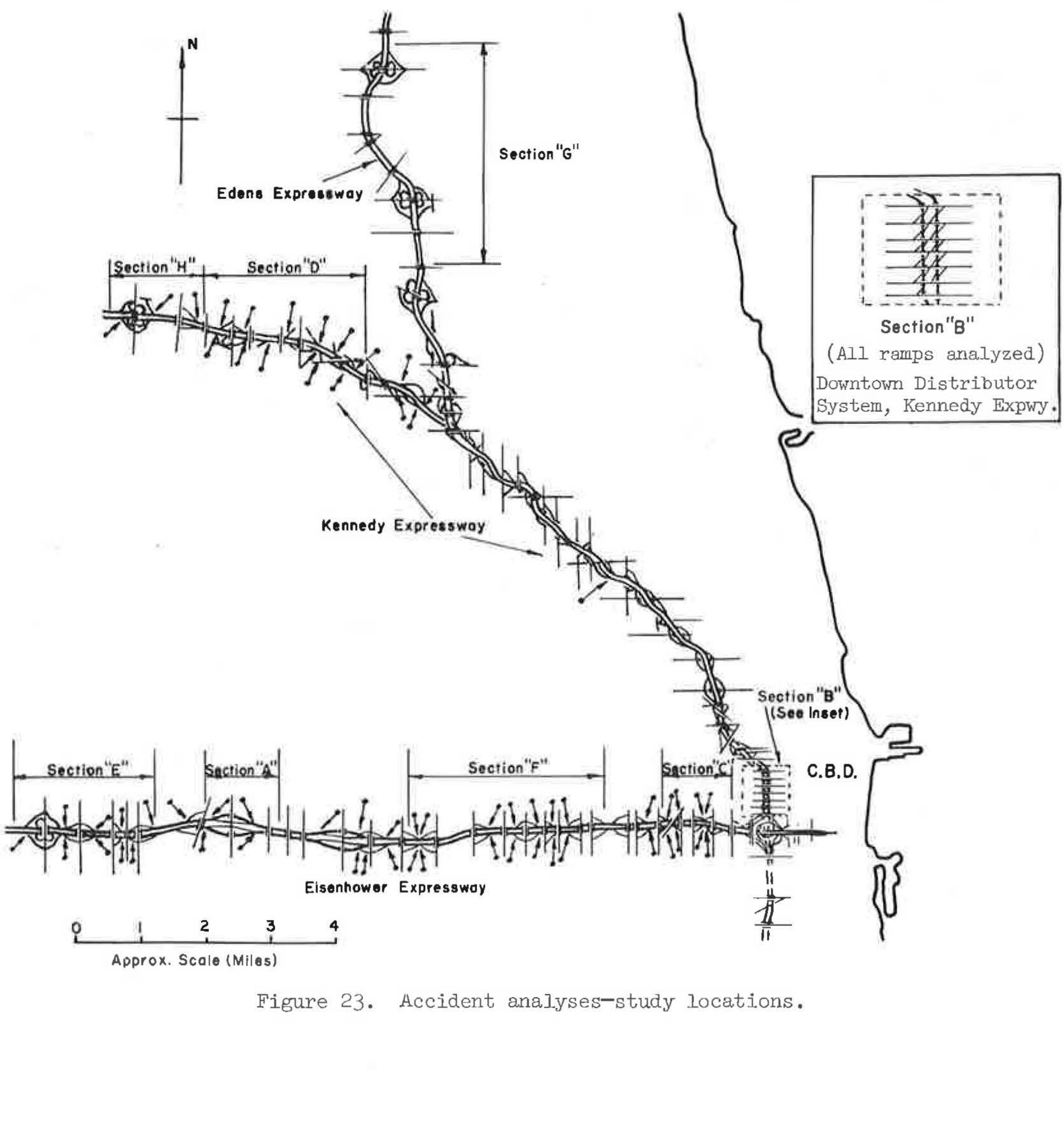


Figure 23. Accident analyses—study locations.

studied whose approach to the freeway was located on an upgrade. The remaining 11 left-hand ramps (all entrance ramps) composed part of a compact downtown distributor system leading from the Kennedy Expressway immediately to the west of the Loop. These 11 entrance ramps, together with a parallel set of 11 right-hand exits, provide the main distributory system linking the expressway with the downtown street network. The entire system occupies slightly less than 0.8 mi of expressway.

The general design and volume characteristics of the 20 left-hand ramps differed considerably. The two internal diamond interchanges and the single isolated left-hand entrance ramp were all designed to high standards (Table 1). The minimum acceleration lane length was 800 ft and minimum deceleration length 450 ft. Ramp grades were approximately ±3 percent and ramp widths 16 to 18 ft. Adequate directional signing was provided at all locations. The 11 downtown left-hand entrance ramps, in contrast, were substandard in design. They were provided with very short acceleration lanes (350 ft), had extremely poor sight lines and, as already mentioned, were "nested" together into a compact ramp system that paralleled a similar compact sequence of right-hand exits. All of the 11 ramps were single-lane designs with grades of -3 percent. Average weekday daily traffic (AWDT) volumes at the various locations varied from 1,200 to 10,700 veh on the entrance ramps, and from 4,300 to 10,700 veh on the exit ramps. The adjacent freeway sections carried between 48,500 and 54,800 AWDT (three-lane sections) and between 63,600 and 91,600 AWDT (four-lane sections).

In selecting the sample of right-hand ramps for comparison, it was not possible to choose locations which reproduced exactly the characteristics of the left-hand ramps described. Instead, a sample of right-hand ramps was selected that encompassed, as far as possible, the entire range of volume and design characteristics to be found at the left-hand ramps.

As in the case of the left-hand ramps, the sample of right-hand locations ranged from high standard designs with 1,000-ft speed-change lanes to substandard facilities spaced very closely together. Of the 26 entrance ramps studied, nine had parallel acceleration lanes, eight had direct taper designs and nine had acceleration lanes which were continuous with the deceleration lane of an adjacent off-ramp. Of the 29 exit ramps, 21 had direct taper deceleration lanes and eight were continuous-lane designs [illegible] and from 300 to 850 ft for deceleration lanes. Ramp gradients varied from +3 to -3 percent (all but one of the entrance ramps were either level or on a downgrade and all but two of the exit ramps were on an upgrade). Ramp widths varied from 14 to 18 ft; all the ramps studied were again single-lane designs. Approximately 50 percent of both entrance and exit ramps were located on eight-lane sections of freeway, and 50 percent on six-lane sections. All but three of the 55 ramps were elements of diamond interchanges. Traffic volumes again varied considerably: from 1,300 to 12,000 AWDT on the entrance ramps, from 1,100 to 13,800 AWDT on the exit ramps, and from 53,600 to 60,900 (three-lane) and 54,800 to 84,400 (four-lane) on the adjacent freeway sections.

Data for the accident analyses were obtained from copies of original police accident reports, filed by the City of Chicago Police Department and the Illinois State Highway Patrol for the 2-yr period from January 1962 to December 1963. Further general data were obtained from a series of punched card summaries of individual freeway accidents, prepared for Illinois by the Chicago Area Transportation Study. Twenty-four-hour volume data for 1961 and 1963 were provided for each location by the Illinois Division of Highways. These data were corrected to yield average, 24-hr weekday volume figures for 1962 and 1963 for each ramp and for each adjacent freeway section. Approximate annual volumes were then computed by multiplying these 24-hr figures by 340 to allow for weekends and holidays (7).

Analysis Techniques

The annual number of accidents occurring both on the ramp itself and also within the ¼-mi section of freeway immediately upstream of and adjacent to the ramp's speed-change lane were computed separately for each study location for 1962 and

1963. These computations yielded a total of 32 "ramp-years" of data for the left-hand entrance ramps and 8 "ramp-years" for left-hand exit ramps. Ramp accidents were defined for the purposes of this study as all those accidents which occurred either on the ramp itself, on the speed-change lane, or that involved vehicles in the act of either entering or leaving a speed-change lane. They were further subclassified according to whether they occurred at the upper or lower terminal of the ramp or on the body of the ramp proper.

A final series of analyses were made to determine the annual number of accidents occurring within each of the eight "sections" of freeway defined in Figure 23.

Each set of data was broken down according to the severity of the individual accidents, the type of collisions, and the class and number of vehicles involved. Data on the major factors which contributed to the cause of each accident (such as lane changing, failure to yield right-of-way, and speed) were unfortunately not reported in sufficient detail to warrant any form of rigorous analysis.

Annual ramp and freeway accident rates were computed for each location, using six different "exposure indices" as denominators:

$$\text{Exposure index 1} = \frac{\text{Avg. annual ramp volume}}{\text{Avg. annual freeway volume}};$$

$$\text{Exposure index 2} = \frac{\text{Avg. annual ramp volume}}{\text{Avg. annual lane volume on freeway}};$$

$$\text{Exposure index 3} = \frac{\text{Avg. annual ramp volume}}{\text{Avg. annual merge volume}};$$

$$\text{Exposure index 4} = \frac{\text{Avg. annual ramp volume} \times \text{avg. annual freeway volume}}{\text{No. of freeway lanes}};$$

$$\text{Exposure index 5} = \frac{\text{Avg. annual freeway volume}}{\text{No. of freeway lanes}} + \frac{1}{\text{freeway volume}}; \text{ and}$$

$$\text{Exposure index 6} = \frac{\text{Peak hour ramp volume}}{\text{Avg. peak hour lane volume on freeway}}.$$

None of these relatively complicated exposure indices were any more significantly related to accident occurrence than were simple stratified combinations of average daily ramp volume and average daily freeway volume. For this reason, the following simple volume classification system was adopted for the purposes of statistical analysis:

Freeway Volume—Low, 45,000 AWDT; medium, 45,000-70,000 AWDT; and high, 70,000 AWDT.

Ramp Volume—Low, 4,000 AWDT; medium, 4,000-8,000 AWDT; and high, 8,000 AWDT.

Detailed ramp accident rates were not computed for the 11 left-hand entrance ramps on Kennedy Expressway for 1962 because of the considerable fluctuations which occurred during that period in individual ramp volumes.

A number of serious problems arose in the analysis of the accident data because of inaccuracies or incompleteness in the original accident reports. Of these, by far the most serious was that of accurately locating the point of occurrence of an accident on the freeway. Very few of the original reports specified locations to an accuracy of more than half a block length (i.e., approximately 100 to 125 yd) and most were considerably less accurate. It was possible, however, to determine from the information in the original accident report whether a ramp accident occurred at the upper or lower terminal of the ramp or on the body of the ramp itself. In the case of freeway accidents, such a procedure was not feasible and, therefore, the analysis was restricted to a general study of the number and general characteristics of all accidents occurring over an approximate two-block length (i.e., approximately ¼ mi) upstream of each ramp.

Detailed Ramp Accident Studies. —Average corrected annual ramp accident rates for the left-hand and right-hand ramps studied are given in Table 6, classified according to the three levels of ramp and freeway volume defined previously:

Corrected annual ramp accident rate = Annual No. ramp accidents per millions of ramp vehicles per year

In every case (for both entrance and exit ramps) the average corrected accident rate at the left-hand ramps exceeded that at the right-hand ramps carrying equivalent traffic volumes. Averaged over all volume levels, the respective rates were 1.55 for left-hand vs 0.97 for right-hand entrance ramps (60 percent higher) and 1.52 vs 0.80 for left-hand and right-hand exits (90 percent higher). For each ramp volume/freeway volume combination for which data on both left- and right-hand ramps were available, a student's "t" test was run to determine whether any significant difference in average corrected accident rates existed between left- and right-hand designs. Table 6 summarizes the results of these statistical tests.

Of the 17 combinations for which comparisons were possible, seven showed differences that were significant at the 20 percent level or higher (five significant at the 10 percent level and three at the 5 percent level). The remaining ten combinations showed no significant difference in average accident rates, although, as previously noted, the rates at the left-hand ramps were consistently higher than those at the comparable right-hand ramps. It is also interesting to note that entrance-ramp accident rates, though by no means consistently higher, tended to be slightly greater than comparable exit-ramp accident rates. This latter statement applies equally to both left- and right-hand ramps. The incompleteness of the matrix in Table 6 precluded the performance of any more rigorous statistical tests.

Figure 24 illustrates some of the major characteristics of ramp accidents observed at the sample of right- and left-hand ramps. In terms of accident severity, it would appear that apart from a slightly higher proportion of personal injury accidents at left-hand exits, there was virtually no difference between the left- and right-hand entrance ramps studied. This increase in personal injury accidents at left-hand exits

was an increased proportion of sideswipe accidents (39 percent vs 18 percent for entrance ramps, 24 percent vs 11 percent for exit ramps). Only in the case of the entrance ramps, however, was this difference statistically significant (at the 10 percent

TABLE 6

AVERAGE ANNUAL RAMP ACCIDENT RATES PER MILLION RAMP VEHICLES FOR RIGHT- AND LEFT-HAND ENTRANCE AND EXIT RAMPS

Ramp Vol. (AWDT)	Accident Data	Accident Rate															
		<45,000 AWDT				45,000-70,000 AWDT				>70,000 AWDT				All Volumes			
		On-Ramps		Off-Ramps		On-Ramps		Off-Ramps		On-Ramps		Off-Ramps		On-Ramps		Off-Ramps	
		Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
<4,000	Accident rate	—	0.84	—	0	1.32	1.11	—	1.22	2.13	1.09	—	0	1.85	1.05	—	0.94
	sample, RH vs LH	0	4	0	4	3	14	0	17	6	4	0	1	9	22	0	22
						No sig. diff.				Diff. sig. at 20% level				No sig. diff.			
4,000-8,000	Accident rate	—	—	—	0.60	2.33	0.59	0.97	0.74	0.93	0.86	—	0.60	1.43	0.77	0.07	0.64
	sample, RH vs LH	0	0	0	5	3	12	4	10	5	6	0	7	8	18	4	22
						Diff. sig. at 5% level		No sig. diff.		No sig. diff.				Diff. sig. at 10% level		No sig. diff.	
>8,000	Accident rate					1.34	1.19	2.17	0.85	—	1.15	—	1.04	1.34	1.17	2.17	0.92
	sample, RH vs LH	0	0	0	0	4	8	4	9	0	4	0	5	4	12	4	14
						No sig. diff.		Diff. sig. at 5% level						No sig. diff.		Diff. sig. at 5% level	
All Volumes	Accident rate	—	0.84	—	0.33	1.60	0.97	1.52	1.00	1.59	1.01	—	0.72	1.55	0.97	1.52	0.80
	sample, RH vs LH	0	4	0	9	10	34	8	36	11	14	0	13	21	52	8	58
						Diff. sig. at 10% level		No sig. diff.		No sig. diff.				Diff. sig. at 20% level		No sig. diff.	

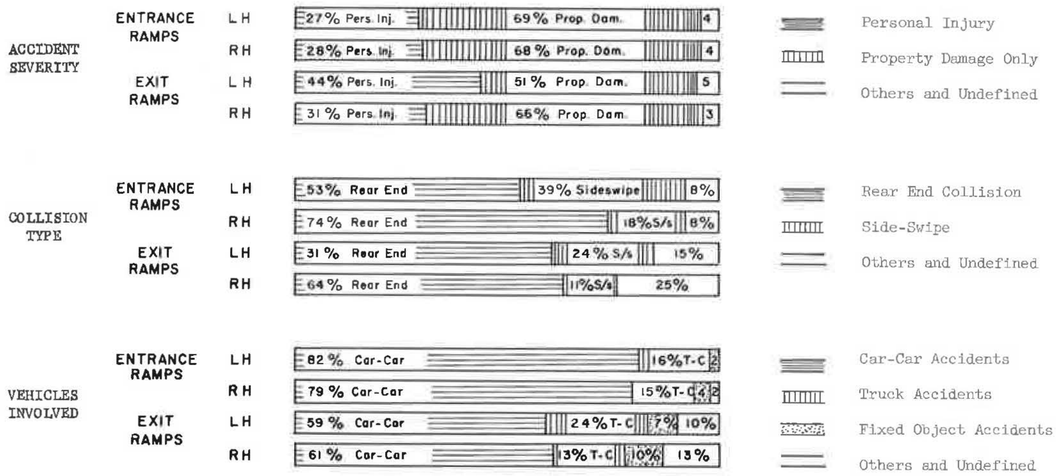


Figure 24. Characteristics of accidents at left- and right-hand ramps in Chicago area.

level). At all ramps, the major proportion of ramp accidents involved car-car collisions, with a slightly higher proportion of truck accidents at left-hand exit ramps and a higher percent of fixed object accidents at all exit ramps. Neither of these differences was significant at the 10 percent level.

A comparison of the factors contributing to the occurrence of accidents yielded a wide dispersion of results. At all ramps, whether left- or right-hand, it would appear that such features as acceleration or deceleration lane length, ramp width, ramp grade, ramp and freeway alignment and sight distance had a considerable effect on the occurrence of accidents. In no case, however, could a significant relationship be developed between any one of these variables and accident rate. A simple multiple correlation analysis indicated that, apart from volume, no one individual characteristic had a predominant effect on accident rate, and even the influence of volume was apparently subordinate to the combined effects of the other characteristics. No significant relationships could be developed between accident rate and either freeway or ramp volume level. It should be borne in mind, however, that the sample of ramps studied was somewhat small for this type of analysis and that this fact may account partially for the lack of significant results.

Studies of Mainstream Accidents Upstream of Left- and Right-Hand Entrance and Exit Ramps. —Studies also were made of the mainstream accidents occurring in the ¼-mi section of freeway immediately upstream of each entrance and exit ramp. In the case of entrance ramps, the ¼-mi section was measured from the end of the acceleration lane, and in the case of exit ramps from the ramp gore. As in the case of the ramp accident analyses, there was again no significant relationship between ramp volume, freeway volume or merge volume and accident rate. A similar series of statistical tests to those carried out on the ramp accident data indicated that for all combinations of ramp and freeway volume, there was no significant difference between the average corrected upstream accident rates at right- and left-hand terminals. There were, however, slight increases in the average severity, frequency of sideswipes and number of weaving accidents upstream of left-hand entrances and exits, as compared to right-hand entrances and exits. None of these differences was statistically significant at the 20 percent level.

In most cases it was apparent that a high upstream accident rate was dependent not as much on the type of ramp as on the alignment and profile of the through lanes. At the Austin Blvd. WB ramps, for example, the width of the freeway drops from four lanes to three, the decrease effected by the termination of the right-hand lane exactly opposite the Austin Blvd. left-hand exit. This decrease in freeway width has a far greater effect on the upstream accident rate than does the presence of the left-hand exit.

TABLE 7

SECTIONAL STUDIES—ANNUAL ACCIDENTS/MVM FOR FREEWAY SECTIONS CONTAINING DIFFERENT COMBINATIONS OF RIGHT- AND LEFT-HAND RAMPS

Section	No. Lanes	Length (mi)	No. Ramps	Ramps/ Mi	Ann. Acc./MVM	
					1962	1963
A, Eisenhower Expressway	6	1.0	2 LH on, 2 LH off, all direct ramps.	4.0 (100% left)	2.11	2.20
B, Kennedy Expressway, 400 S-299 N	8	0.9	11 LH on, 11 RH off, all direct ramps.	24.6 (50% left)	5.82	6.98
C, Eisenhower Expressway, 1100 W-1949 W	8	1.0	5 RH on, 4 RH off, all direct ramps.	9.0 (all right)	3.51	4.84
D, Kennedy Expressway, 5100 N-7500 W	6	2.2	7 RH on, 7 RH off, direct; 1 RH on, 2 RH off, loops.	6.4 (all right)	1.76	1.68
E, Eisenhower Expressway, 8200 W-9899 W	6	2.1	7 RH on, 7 RH off, direct; 1 RH on, 2 RH off, loops.	8.1 (all right)	4.10	3.21
F, Eisenhower Expressway, 2700 W-5099 W	8	2.9	8 RH on, 8 RH off, all direct ramps.	5.5 (all right)	2.70	2.15
G, Edens Expressway, 6400 N-8999 N	6	3.2	2 full clover leaves.	5.0 (all right)	1.70	2.39
H, Kennedy Expressway, 7500 W-9000 W	6	1.4	1 RH on, 1 RH off, direct; 1 full clover leaf.	7.1 (all right)	0.89	1.32

Sectional Accident Studies.—A series of eight sections of freeway, varying in length from 0.8 to 3.0 mi, were chosen (Fig. 17) on the Edens, Kennedy and Eisenhower Expressways, containing different combinations of left- and right-hand entrance and exit ramps. For each section, the total number of accidents occurring during 1962 and 1963 were computed and these totals then converted into annual accident rates per million vehicle miles (MVM). Table 7 summarizes the results of these studies; Figure 25 illustrates the monthly variation in accident rates for each of the sections between January and December 1963. From these analyses, it is apparent that the distribution of monthly accident rates along section A, containing the Harlem Ave. internal diamond interchange on the Eisenhower Expressway (but excluding the Austin Blvd. interchange where the width of the adjacent freeway section changes from four to three lanes), did not differ significantly from the average rates observed along sections D, E, F, G and H, all of which contained various combinations of right-hand ramps.

Section B, the downtown section of Kennedy Expressway containing the complex distributor system of left-hand entrances and right-hand exits, had a significantly higher distribution of accident rates than any of the other seven sections studied. However, the accident rate for section B is by no means attributable solely to the presence of the left-hand entrance ramps. The section carries consistently heavy volumes of traffic with substantial weaving and lane-changing movements and is also subjected to congestion backing up from downstream locations in both directions of travel.

The correction of the data, illustrated in Figure 21, to allow for variations in average ramp spacing within the eight sections studied resulted in a much more compact set of monthly accident distributions. In particular, the average monthly accident rate for section B dropped from 6.98 to 0.32 acc./MVM/ramp. Similar, but less

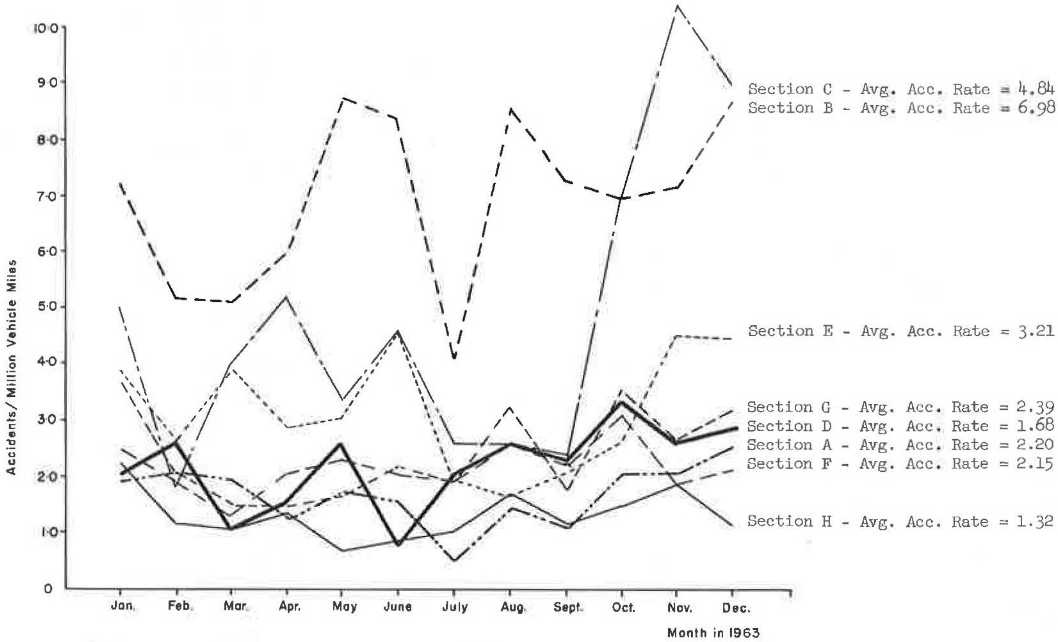


Figure 25. Monthly variations in sectional accident rates.

pronounced reductions occurred for the other seven sections. A comparison of the resultant distributions of monthly accident rates per MVM per ramp indicated that none of these corrected distributions differed significantly at the 10 percent level.

CONCLUSIONS

On the basis of the studies described in this paper, the following conclusions may be drawn concerning the operation of left-hand ramps located on six-lane tangent sections of depressed urban freeway situated in level terrain in the Chicago area. The ramps studied carried average AWDT volumes of 1,300 to 10,700 veh. (10 percent trucks) and the adjacent freeway sections AWDT volumes of 100,000 to 120,000 veh. (9 percent trucks).

1. None of the left-hand ramps studied caused any prolonged disruption of flow in the adjacent freeway lanes.
2. The distributions by lane of average-minute-volumes, average-minute-speeds, and individual time headways on the approach to a left-hand entrance forming part of an internal diamond interchange were significantly different from those observed on the approach to a comparable right-hand entrance carrying similar traffic volumes and forming part of an external diamond interchange.
3. Average merging speeds and the speed differentials between entering and through vehicles were higher at left-hand entrance ramps than at right-hand entrance ramps.
4. There was a higher incidence of mainstream lane changing in the vicinity of the left-hand entrance ramps studied than at the comparable right-hand entrances.
5. No significant difference was observed in the incidence of hazardous maneuvers at right- and left-hand entrance ramps.
6. A single low-volume left-hand entrance ramp provided with a 900-ft acceleration lane had apparently little effect on traffic behavior in the adjacent freeway section.
7. Extremely high merging rates, in excess of 1,800 vph, were observed at a left-hand entrance ramp provided with a 1,075-ft acceleration lane on a level three-lane section of depressed freeway without causing average left-lane speeds upstream of the ramp to fall below 45 mph. A 50-min average merge rate of 2,034 vph was observed

at the same entrance ramp without a prolonged drop in speeds being observed in the left lane upstream of the ramp. Periodic 1-min merge rates in excess of 2,400 vph caused brief slowdowns upstream of the ramp, but at no time caused complete breakdowns in flow. Throughout the study period the flow in the left lane approaching the ramp averaged 1,400 vph.

8. A prolonged merge rate in excess of 1,800 vph at a left-hand entrance resulted in a supersaturated flow condition in the left lane downstream of the entrance ramp. In this condition, the flow in the left lane was extremely sensitive to even small disturbances.

9. Approximately 60 percent of all vehicles entering a three-lane section of freeway via a left-hand entrance ramp were still positioned in the extreme left-hand lane at a point 2,050 ft downstream of the ramp nose. Approximately 50 percent of the vehicles still remained in the left lane at a point 6,100 ft downstream.

10. Over 70 percent of all exiting vehicles were already positioned in the left lane at a point 7,250 ft upstream of a left-hand exit ramp. The first directional sign for this ramp was located 2 mi upstream of the ramp nose.

11. Variations in total freeway volume appeared to have relatively little effect on the lateral placement of ramp vehicles upstream and downstream of left-hand entrances and exits.

12. On level sections of heavily traveled urban freeway in the Chicago area, the average reported accident rate per million ramp vehicles (MRV) was consistently higher at left-hand entrances and exits than at right-hand entrances and exits. At right-hand entrances, the average ramp accident rate was 0.97 acc./MRV, vs 1.55 at left-hand entrances; at right-hand exits the equivalent rate was 0.80 compared with 1.52 at left-hand exits. The differences in average accident rates, both overall and grouped according to ramp/freeway volume combinations, were not consistently significant at the 20 percent level.

13. At both left- and right-hand ramps, the absolute number of ramp accidents increased with increases in ramp volume. In neither case, however, could a simple relationship be found between accident rate and volume. Individual design characteristics appeared to have a more significant effect on the accident rate at [illegible]

14. There was no significant difference in the average severity of accidents occurring at left- and right-hand entrance and exit ramps.

15. There was no significant difference in the through lane accident rates upstream of left- and right-hand entrance and exit ramps.

16. Average accident rates tended to be slightly though not consistently higher at entrance ramps than at equivalent exit ramps. This statement applies to both left- and right-hand ramps.

17. With the exception of a 0.8-mi section of downtown distributor freeway containing 11 left-hand entrance ramps and 11 right-hand exit ramps (total for both directions), there was no significant difference between the distribution of monthly accident rates along sections of freeway containing primarily left-hand ramps and along sections containing exclusively right-hand ramps. For normal spacings (i.e., less than eight ramps per mile in both directions), the average spacing of ramps within the study section did not have any significant effect on the overall accident rate.

ACKNOWLEDGMENTS

The research work described here was performed in the Civil Engineering Department of Northwestern University as part of a cooperative highway research project sponsored by the Illinois Division of Highways and conducted in cooperation with the U.S. Bureau of Public Roads. Acknowledgment is made of the advice and encouragement given to the project staff by all members of the above organizations who served on the Project Advisory Committee. Acknowledgment is also made to the staffs of the Chicago (District 10) Office, Illinois Division of Highways, the Eisenhower Expressway Surveillance Project and the Chicago Area Transportation Study for their help. S. Prisant was responsible for much of the data collection and analysis in connection with the first part of the paper.

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