Traffic Behavior and On-Ramp Design

ICHIRO FUKUTOME and KARL MOSKOWITZ
Assistant Traffic Engineers,
California Division of Highways

Three ramp terminal designs were painted successively at one on-ramp location. The first sequence of observations was made with the ramp curb encroaching on the shoulder (2 ft from edge of freeway pavement) and a second sequence was observed with the ramp curb offset shoulder width from the freeway pavement (in this case 8 ft), resulting in six separate studies. Speed and placement of vehicles were recorded and movies were taken during each phase. Freeway volume varied from 2,400 to 6,000 vph, while ramp volume varied from 240 to 1,200 vph. Findings include the following:

1. All three designs resulted in similar vehicle paths, because essentially they were all liberal designs and traffic was able to drive a natural path. When the nose was offset, a long gradual taper (50:1) appeared to cause vehicles to use a greater portion of the ramp than a parallel ramp of the same length.
2. Somewhat more length was used at low volumes than at high volumes, except during the 8-ft offset 50:1 taper phase, where the length used was approximately constant for all volumes.
3. Merging distance required at high turning speed is as great as that required at low speed.
4. The natural path of nearly all vehicles is contained within a 50:1 taper, and this design provides sufficient acceleration distance for all turning speeds.

It is concluded that ramp terminal design should be standardized and a tentative standard is offered together with supporting data and reasoning.

●IN CALIFORNIA, where more than 600 traffic interchanges have been constructed, the shape of on-ramp terminals has gone through an evolutionary process through the years. In general, this process has been in the direction of more liberal design to provide greater smoothness in merging operations. There is still discussion, however, as to how liberal the design should be. On one hand is the requirement of liberality as determined through experience to date, and on the other are the limitations of cost and space.

The objective of the present study was to provide a factual background regarding traffic behavior as affected by ramp geometry.

SITE

At the Ashby Avenue Interchange on the Eastshore Freeway (US 40) just across the Bay from San Francisco (Fig. 1), there was an entrance ramp

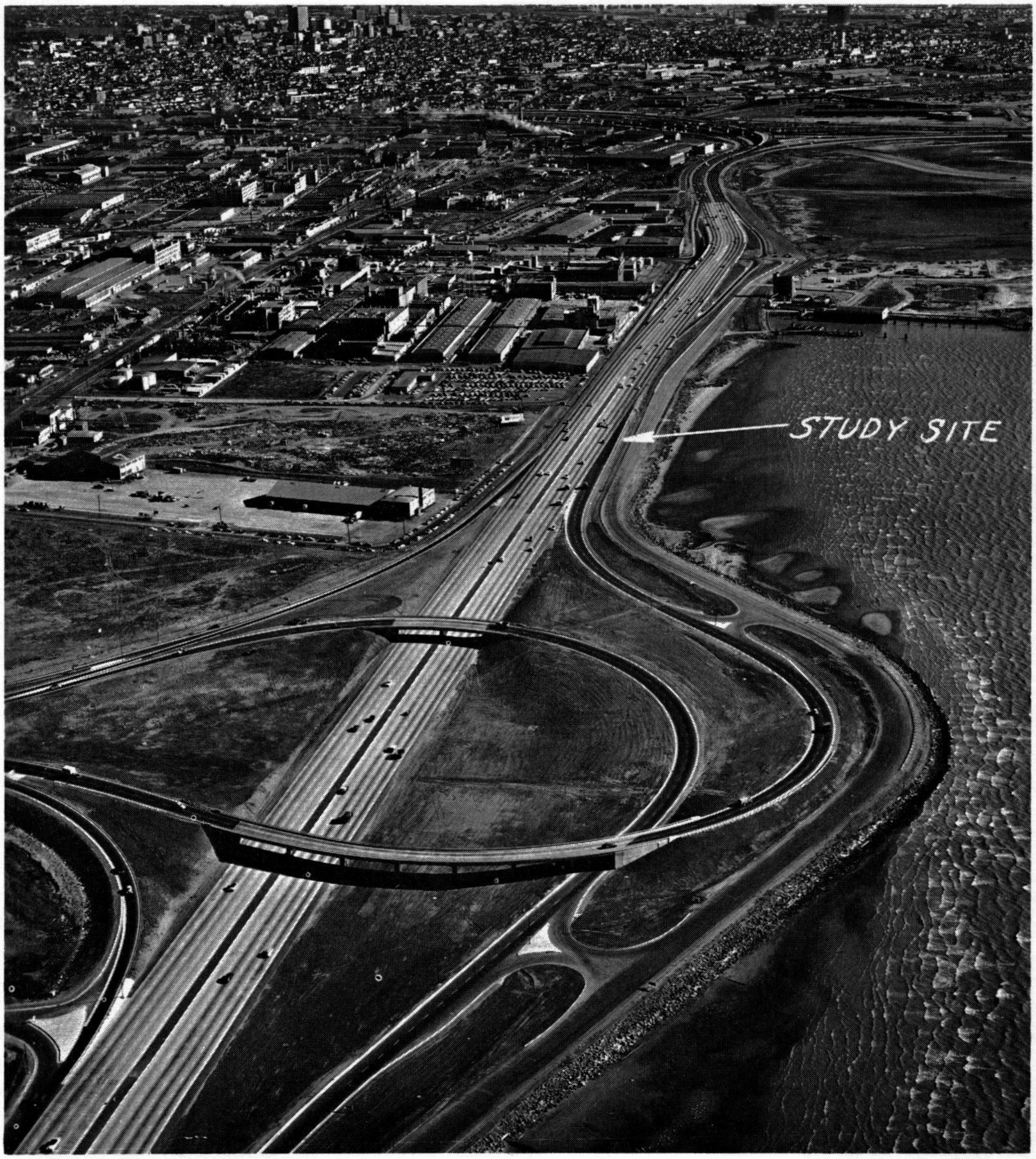

Figure 1. Looking south on Eastshore Freeway. Ashby Avenue Interchange in foreground with study site noted. This picture was taken before studies began and shows a two-lane entrance ramp terminal.

originally designed as a two-lane ramp. This design resulted in a triangular area beyond the ramp nose 840 ft long and 28 ft wide at the nose (Figs. 2, 3 and 4). This unusual paved area provided an opportunity for testing several different shapes of ramp terminal while other variables remained constant. The freeway is level tangent and has 4 lanes in each direction.

It would have been desirable, for study purposes, to select a loca-

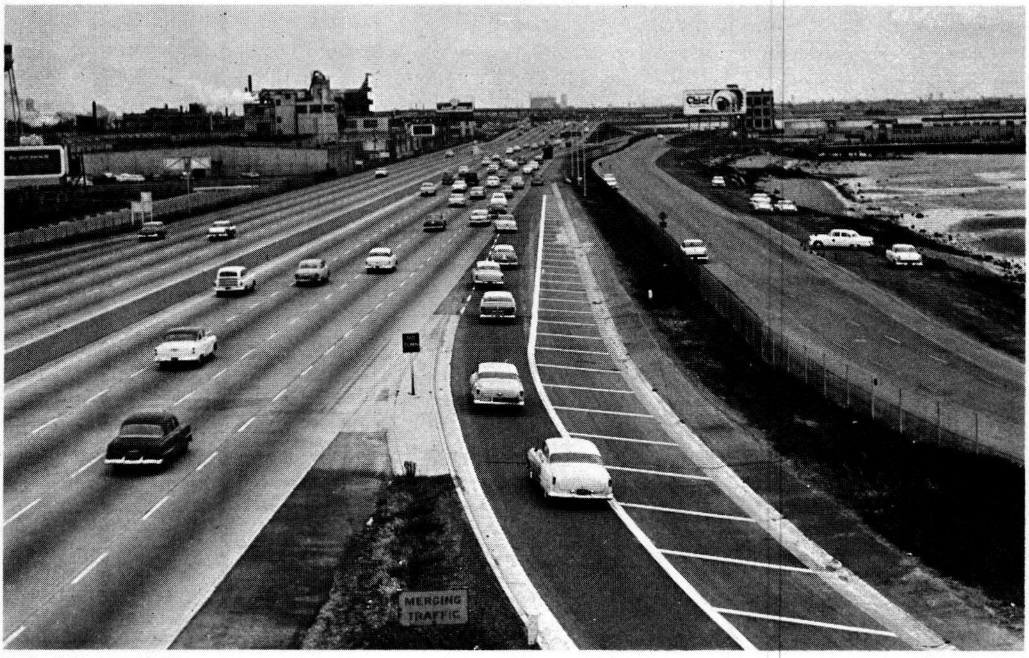

Figure 2. Test site with ramp curb encroaching on shoulder (2 ft from edge of freeway pavement).

Figure 3. Test site with ramp curb offset shoulder width (in this case 8 ft from freeway pavement).

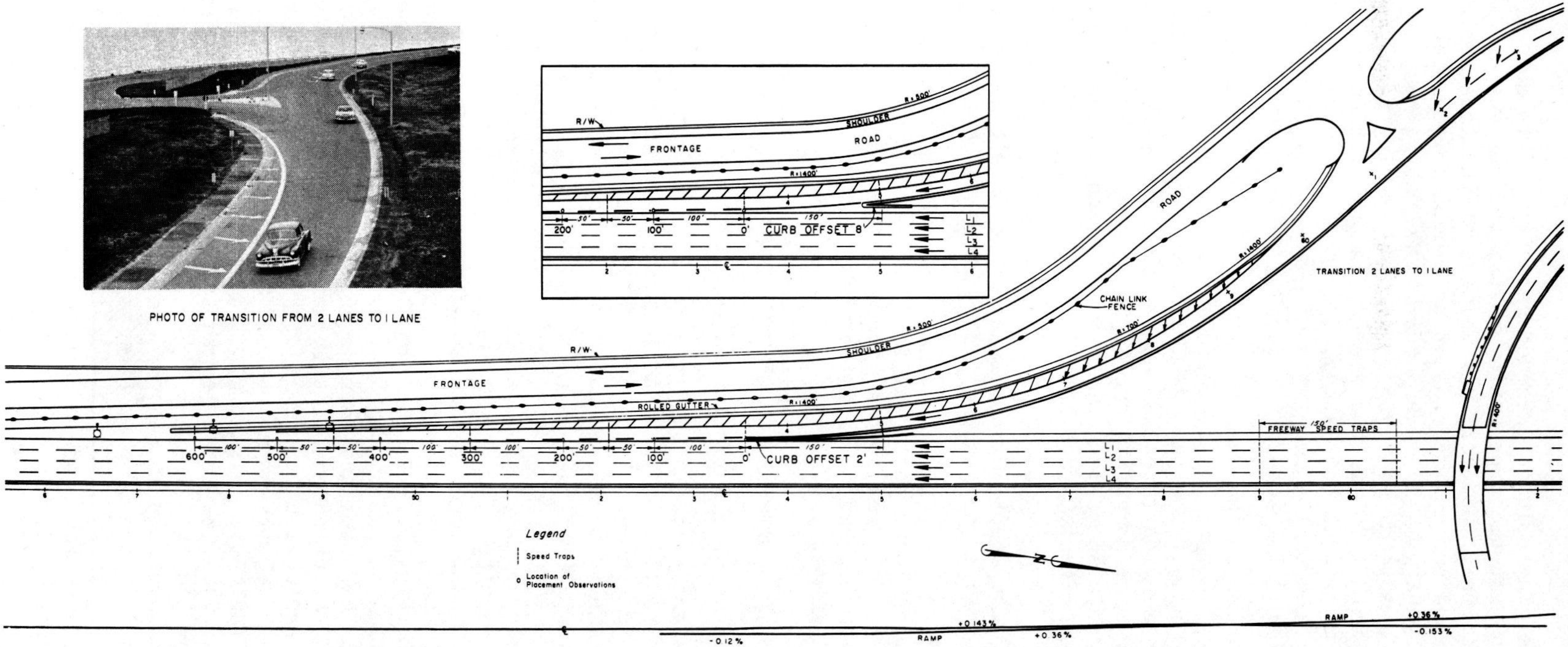
PHOTO OF TRANSITION FROM 2 LANES TO 1 LANE

Figure 4. Diagram of test site—southbound Ashby Avenue on-ramp on Eastshore Freeway.

tion where merging volumes exceeded capacity. Some such locations exist in California, but the opportunity to try various shapes does not occur at these locations. However, the volumes at the location selected are substantial, and the maximums observed exceed commonly accepted values for "practical capacity." The peak hour volume on the ramp is 900, merging with 4,800 for a total of 5,700 vph in the morning peak, and 800 on the ramp merging with 3,000 on the freeway in the evening peak. During the peak hours observed in this study, the hourly rate on the four lanes going away from the end of the merging area exceeded 5,800 vph for about 30 min out of the hour. The total includes 7.7 percent trucks.

The vehicles on the ramp do not come at random intervals (as they do on the freeway) because of signal controls on the street system about 4,000 ft before the nose. The ramp vehicles, which come in platoons, make the instantaneous merging rate much higher than the 5-min volumes indicated and result in some momentary congestion. However, these momentary accordions last such a short length of time that no backup occurs and the average speed is affected very little.

The speed of on-ramp vehicles is controlled by a 700-ft radius curve, which is good for about 50 mph; in other words, it can be assumed that the distance required after passing the nose is needed for merging and not for acceleration.

Observations were spaced at least one week apart to permit the traffic to become accustomed to the geometric changes. The location and method of study were chosen to minimize the effect of variables other than ramp terminal geometry.

DESCRIPTION OF RAMP SHAPES STUDIED

The sequence of observation was as follows:

1. One-lane 50:1 (in this report, a ramp terminal described by a ratio such as "50:1" is a constantly tapering area, with the ratio representing the cotangent of the angle of convergence between the outer edge of the ramp terminal and the pavement edge of the freeway) on-ramp with lane stripe on left and a painted hatched area on right (Fig. 5). The right-hand edge tapers from 18 ft at the curb nose of the on-ramp to 8 ft in a distance of 500 ft. An imaginary projection of this right-hand edge would go another 400 ft, making a total of 900, to an intersection with the right-hand edge of the through lane.
2. One-lane parallel on-ramp with lane stripe on left and hatched area on right (Fig. 6). In the parallel ramp, the right-hand edge was carried parallel to the through pavement, and 12 ft wide, up to a point 500 ft beyond the nose, and then squeezed off on a 30:1 (rolled gutter) taper for 120 ft, at which point it was 8 ft from the through pavement. An imaginary projection of the right-hand edge would intersect the pavement in another 240 ft, or a total of 860 ft from the nose.
3. One-lane 30:1 on-ramp with lane stripe on left and hatched area on right (Fig. 7). The total length to the imaginary intersection of the right edge was 540 ft.
4. The above ramp shapes were repeated with the ramp curb reconstructed at a distance of 8 ft (freeway shoulder width) from the edge of the through traffic lanes, resulting in six separate studies. Reconstructing the curb moved the curb nose back 130 ft as shown in the inserts in Figures 4, 5, 6 and 7.

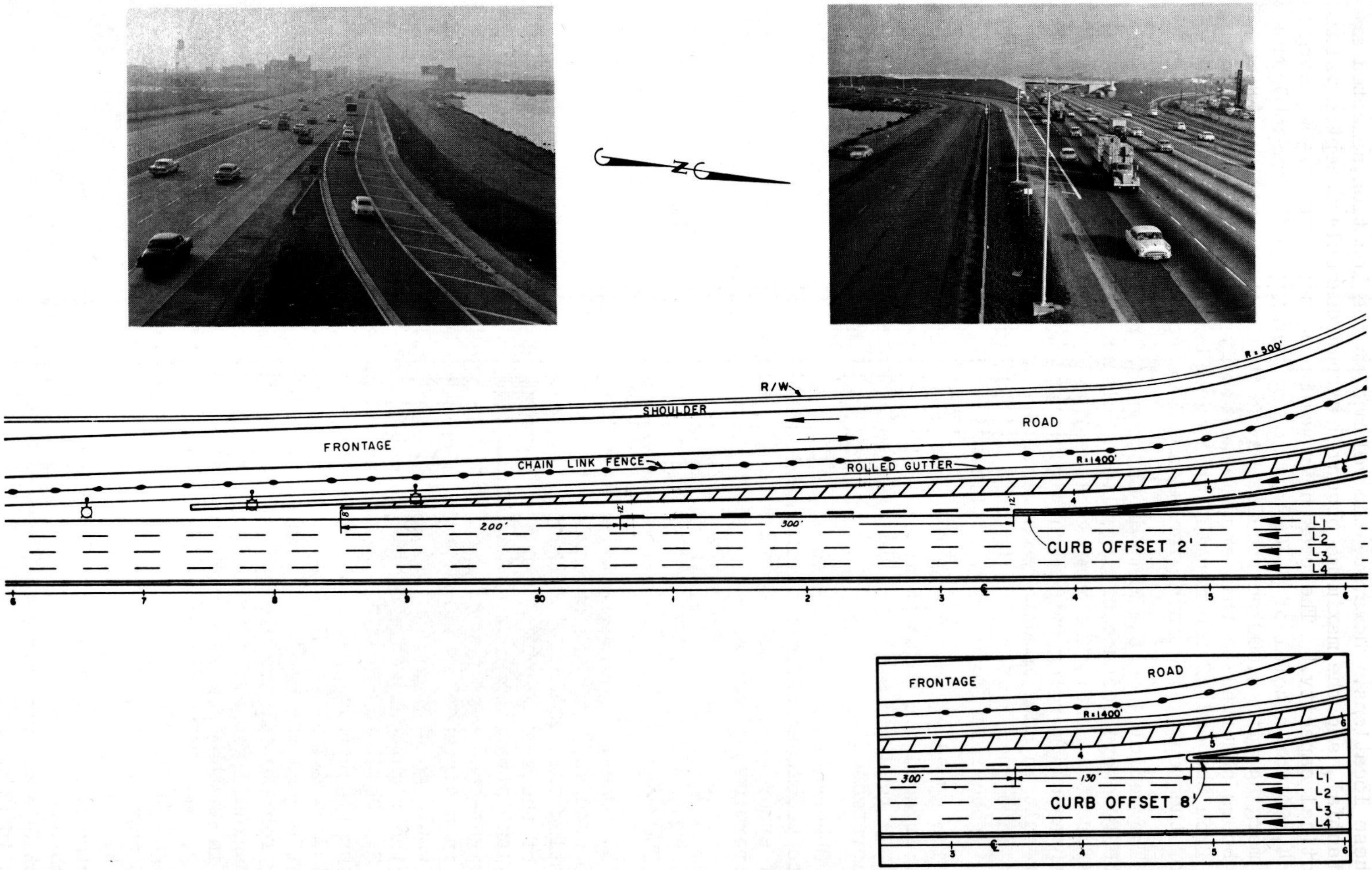

Figure 5. Plan—50:1 tapered on-ramp.

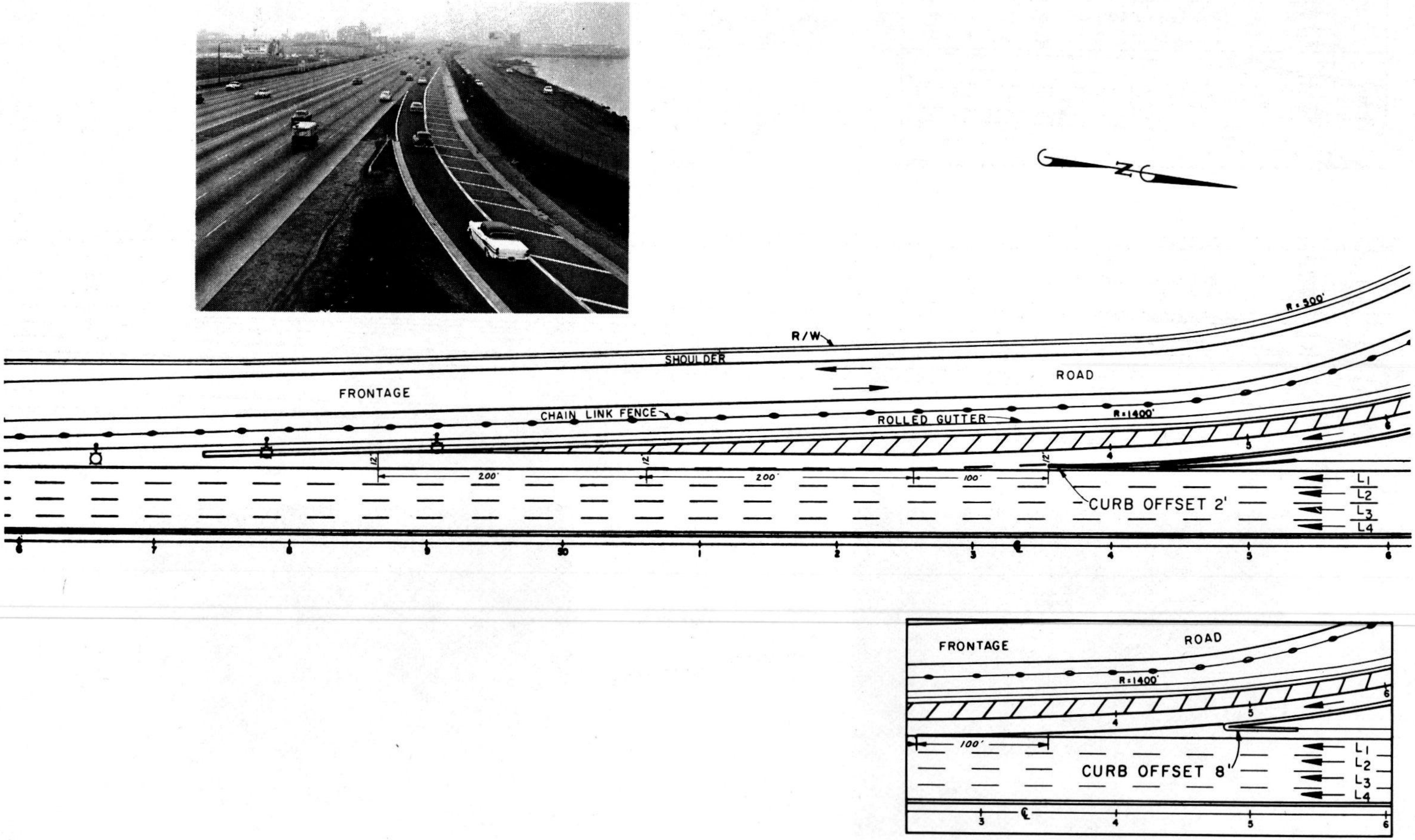

Figure 6. Plan—parallel on-ramp.

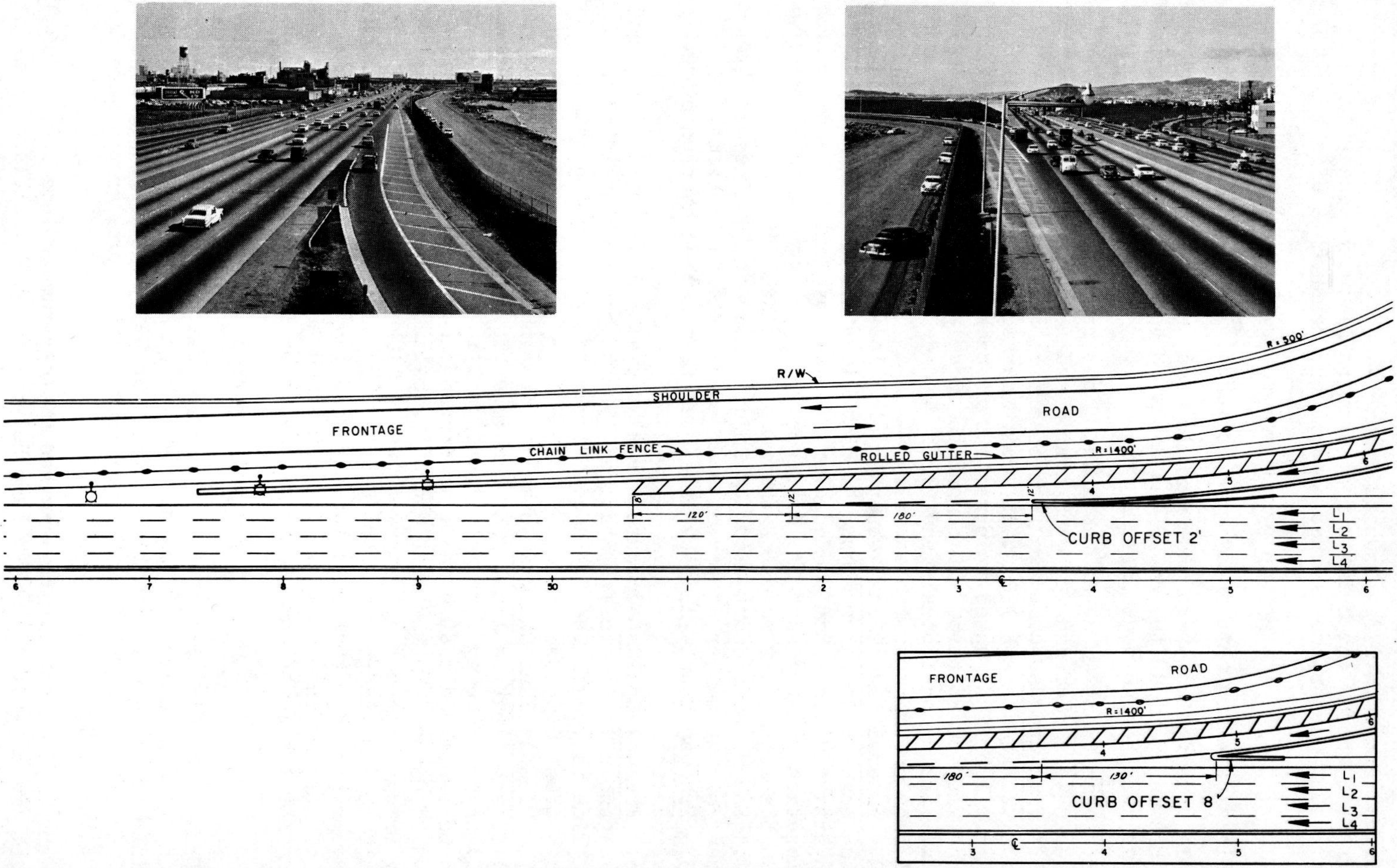

Figure 7. Plan—30:1 tapered on-ramp.

The transition from 2 lanes to 1 and the delineation of the various sequences in the study were by means of white traffic paint. The transition from 2 lanes to 1 is shown in Figure 4.

Traffic obeyed the paint almost universally. The exceptional car that traveled across the hatched area had no measurable effect on the data.

METHOD OF COLLECTING DATA

Field data for this study were collected in the following manner:

All observations were made manually and based on 5-min counts with 2 min between periods to record the data. Observers were located on the frontage road behind a chain link fence.

1. Ramp Count—made at the nose of the ramp. The number of autos and trucks were recorded for each period and each break between periods.
2. Ramp Speeds—computed from observations with stop watches and 5 consecutive speed traps 150 ft in length marked with road tubes across the ramp. The first speed trap was 150 ft back of the ramp nose and the last one was 450 ft to 600 ft beyond the nose as shown on Figure 4. Samples were taken continuously and times recorded for sample vehicles to travel from one mark to the other.
3. Lateral Placements—observed at 5 locations at 100-ft intervals from the nose as shown on Figure 4. Each location was marked by 5 lines 1 ft apart, starting from the edge of freeway pavement. One man observed each location and recorded the distance from the edge of the freeway pavement to the right rear wheel of the ramp vehicles.
4. End of Ramp Count—made at location 600 ft from nose. Counts were made of the number of vehicles in Lane 1 and on the ramp.
5. Freeway Count—made by lanes before the merging area of the acceleration lane.
6. Freeway Speeds—computed from stopwatch observations of speed traps as shown in Figure 4. Stations 150 ft apart were painted in each lane. Time to travel the distance between the two stations was estimated to the nearest 0.05 sec.
7. Freeway Lane Changes—observed from the location of freeway count to end of acceleration lane. The lane changes made by traffic that was already on the freeway were not significant in the study. However, it should be mentioned that a major interchange having a 3-lane branch connection to Oakland on the left and a three-lane branch to the San Francisco Bay Bridge on the right was located $1\frac{1}{4}$ mi beyond the observation site. For this reason, there was a noticeable tendency for many of the ramp cars to weave right on across into Lanes 2 or 3 (and occasionally Lane 4) instead of merging into Lane 1. It is assumed that most of these cars were heading for the left-hand branch of the major interchange.

ANALYSIS OF DATA

Due to the wide range of ramp and freeway volumes during the study of each on-ramp design, it was necessary to classify placement and speed data into volume groups so that comparisons between the three designs could be made for equal volume conditions. The volume groups were divided as given in Table 1.

Thus a group labeled R1 - F2 has a 5-min ramp volume between 20-39 vehicles and a 5-min freeway volume between 200-299 vehicles. Freeway volume distribution by lane is given for all volume groups in Table 2.

TABLE 1

VOLUME GROUP CLASSIFICATION

Ramp Group	5-Min Volume	Hourly Rate	Freeway Group	5-Min Volume	Hourly Rate	Hourly Rate in Lane 1[a]
R 1	20-39	240-479	F 1	100-199	1,200-2,400	190-380
R 2	40-59	480-719	F 2	200-299	2,400-3,600	380-580
R 3	60-79	720-959	F 3	300-399	3,600-4,800	580-770
R 4	80-100	960+	F 4	400-500	4,800-6,000	770-960

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[a] Hourly rate in Lane 1 based on 16 percent of freeway volume (see Table 2). This volume does not include ramp vehicles.

TABLE 2

DISTRIBUTION BY LANE AT APPROACH TO ON-RAMP MERGING AREA

		Lane 1		Lane 2		Lane 3		Lane 4	
Volume Group	Ramp Design	2-ft Curb Offset (%)	8-ft Curb Offset (%)	2-ft Curb Offset (%)	8-ft Curb Offset (%)	2-ft Curb Offset (%)	8-ft Curb Offset (%)	2-ft Curb Offset (%)	8-ft Curb Offset (%)
R1-F1	50:1	19.1	17.0	26.0	26.7	31.8	31.4	23.1	24.9
	Parallel	19.1	17.9	27.4	25.6	30.7	30.4	22.8	26.1
	30:1	16.0	14.8	29.7	27.9	32.5	32.1	21.8	25.2
R1-F2	50:1	16.5	16.0	24.2	23.9	31.9	31.6	27.4	28.5
	Parallel	17.1	x	23.1	x	31.1	x	28.7	x
	30:1	12.6	17.0	25.2	23.5	29.7	31.3	32.5	28.2
R2-F1	50:1	17.6	15.6	25.6	25.8	31.9	32.4	24.9	26.2
	Parallel	16.1	16.0	25.0	25.8	31.8	30.7	27.1	27.5
	30:1	16.2	14.6	28.8	24.9	30.8	33.2	24.2	27.3
R2-F2	50:1	15.8	14.8	25.3	25.4	29.9	30.2	29.0	29.6
	Parallel	16.6	14.9	25.4	24.2	30.5	31.0	27.6	29.9
	30:1	15.1	15.2	25.1	24.2	31.6	31.2	28.0	29.4
R2-F3	50:1	15.7	15.4	26.6	22.2	29.1	28.7	29.6	33.7
	Parallel	15.0	15.2	24.0	26.5	30.4	30.2	30.6	28.1
	30:1	15.5	x	23.9	x	30.0	x	30.6	x
R3-F2	50:1	15.1	15.5	24.4	23.9	30.6	29.9	29.9	30.7
	Parallel	14.5	14.1	26.1	24.1	30.2	31.0	29.2	30.8
	30:1	16.7	16.4	24.8	21.8	30.1	28.7	28.4	33.1
R3-F3	50:1	15.8	15.7	24.8	23.3	29.3	29.7	30.1	31.3
	Parallel	16.0	14.8	22.1	24.0	29.4	28.2	32.5	33.0
	30:1	16.7	15.0	24.1	24.2	28.4	28.9	30.8	31.9
R3-F4	50:1	15.6	14.6	24.7	23.0	29.0	27.9	30.7	34.5
	Parallel	14.8	13.2	24.5	22.2	28.4	30.7	32.3	33.9
	30:1	15.7	14.7	24.1	22.6	28.4	27.8	31.8	34.9
R4-F2	50:1	15.1	13.6	24.4	29.1	30.6	30.1	29.9	27.2
	Parallel	13.1	13.8	25.3	22.2	33.2	30.0	28.4	34.0
	30:1	16.7	14.1	24.8	25.9	30.1	28.7	28.4	31.3
R4-F3	50:1	15.7	14.8	25.1	24.0	28.9	28.6	30.3	32.6
	Parallel	16.4	16.7	24.4	23.3	29.1	28.4	30.1	31.6
	30:1	16.3	13.8	24.3	22.8	24.7	29.7	32.0	33.7
R4-F4	50:1	15.6	16.4	24.0	22.3	28.3	29.0	32.1	32.3
	Parallel	15.9	14.6	21.5	22.9	30.8	29.1	31.8	33.4
	30:1	16.0	13.4	22.8	22.9	29.0	29.6	32.2	34.1

NOTE: x indicates insufficient data.

TABLE 3

NUMBER OF RAMP VEHICLES OBSERVED IN EACH VOLUME GROUP

Ramp Volume Rate (vph)	Ramp Design	One-Way Freeway Volume Rate Prior to Ramp (vph)							
		F1 1,200-2,400		F2 2,400-3,600		F3 3,600-4,800		F4 4,800-6,000	
		2-ft Curb Offset	8-ft Curb Offset	2-ft Curb Offset	8-ft Curb Offset	2-ft Curb Offset	8-ft Curb Offset	2-ft Curb Offset	8-ft Curb Offset
R1 240-480	50:1	210	335	39	206	x	x	x	x
	Parallel	172	315	71	x	x	x	x	x
	30:1	132	333	39	108	x	x	x	x
R2 480-720	50:1	360	227	450	768	210	105	x	59
	Parallel	279	460	321	769	160	57	56	114
	30:1	497	223	551	869	158	x	99	57
R3 720-960	50:1	x	x	341	345	767	330	405	432
	Parallel	x	x	265	384	280	423	206	70
	30:1	x	x	340	263	492	608	294	212
R4 960-1,200	50:1	x	x	x	101	259	437	184	84
	Parallel	x	x	186	92	82	90	264	806
	30:1	x	x	199	172	254	348	514	520

NOTE: x indicates insufficient data.

It is to be noted that the distribution for the various ramp designs is very similar and can be minimized as a variable affecting the study.

In this study, some combinations of volume groups were eliminated due to insufficient data. The groups used in the analysis and the number of observations in each group are given in Table 3.

RESULTS

Placement

Paths of the right rear wheels of observed vehicles are shown in Figures 8, 9 and 10 for the 2-ft curb offset studies and Figures 12, 13 and 14 for the 8-ft curb offset studies. The diagrams on these figures are drawn on a scale that exaggerates the lateral distance in a ratio of 5 to 1 as compared with the longitudinal distance. Each figure represents one ramp terminal shape, and the four diagrams on each figure represent the four ramp-volume groups, with the lowest ramp-volume at the top.

1. It will be noted that the variation in wheel paths for changing freeway volumes with any given ramp volume is small. This fact does not necessarily show that freeway volume is unimportant in determining ramp length, but it does suggest that when adequate length is available, it will be used during light volumes as much as during heavy volumes.

Because the paths for varying freeway volumes were similar, two additional drawings were made (Figs. 11 and 15) in which freeway volumes were combined for any given ramp volume. On these diagrams it is easier to see the relationship between the paths as affected by geometry.

2. An unexpected result was to find that as the ramp volume increased, the length of ramp used decreased.

With the 2-ft curb offset, the 85th percentile did not change much but the 50th percentile decreased from about 390 ft to about 300 ft as the ramp volume increased from less than 480 vph to more than 960 vph. With the 8-ft curb offset and the 50:1 design, the 50th percentile decreased from about 480 ft to about 420 ft through this volume range and with the parallel and 30:1 designs, the 50th percentile decreased from about 430 ft to 300 ft. During the high ramp volumes, the freeway volumes were also higher.

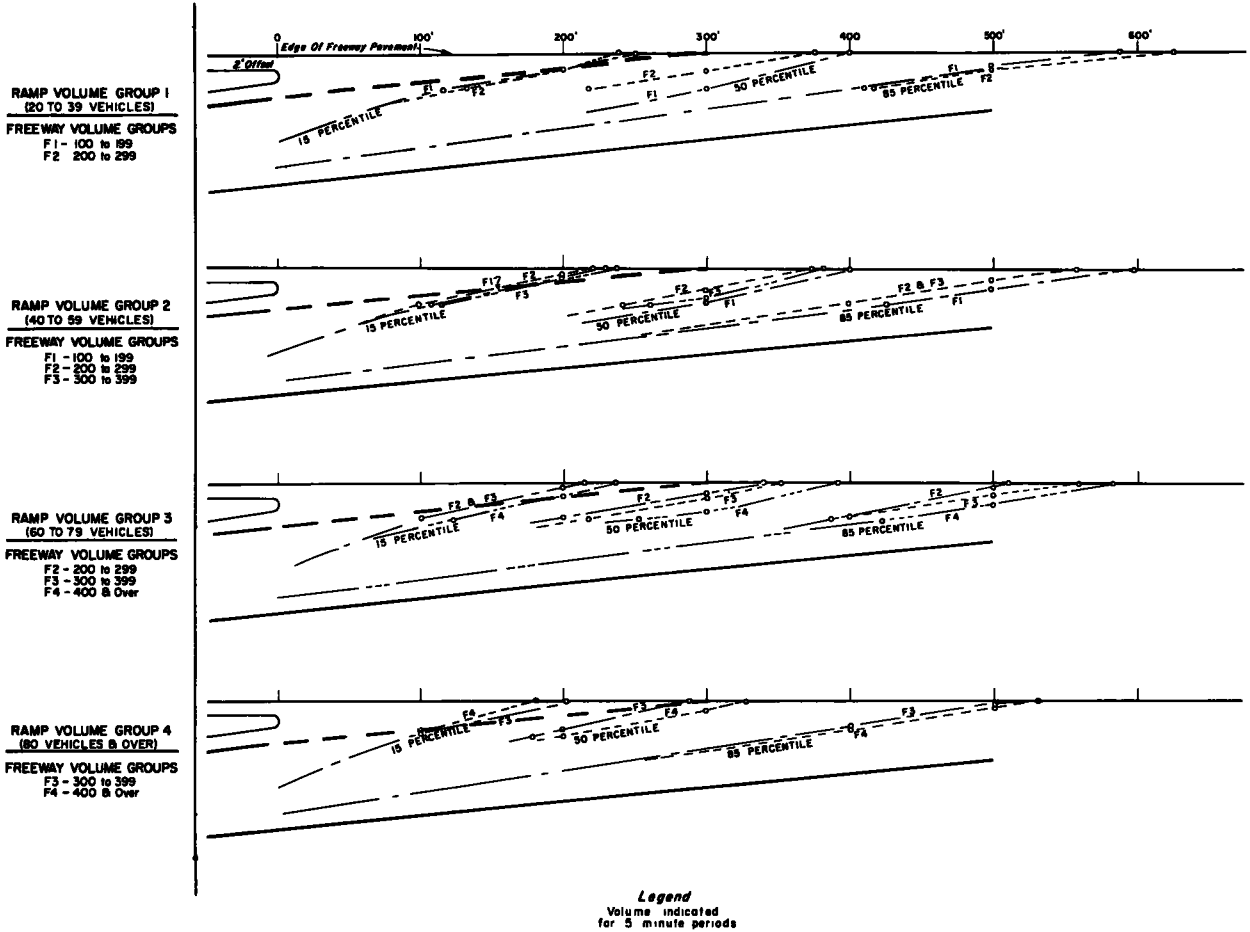


Figure 8. Right rear wheel path of 15, 50 & 85 percentile vehicles—50:1 tapered on-ramp (curb offset 2 ft).

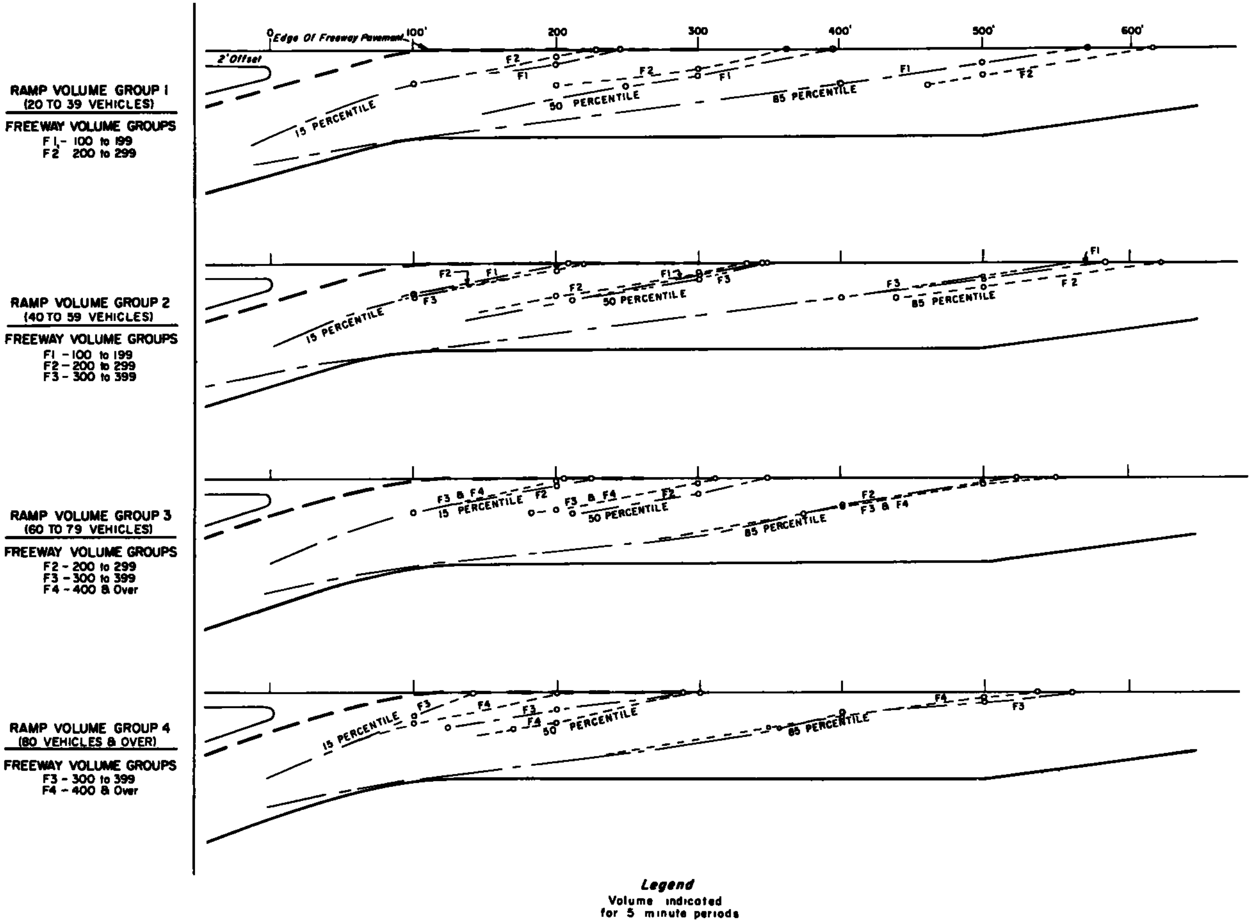


Figure 9. Right rear wheel path of 15, 50 & 85 percentile vehicles—parallel on-ramp (curb offset 2 ft).

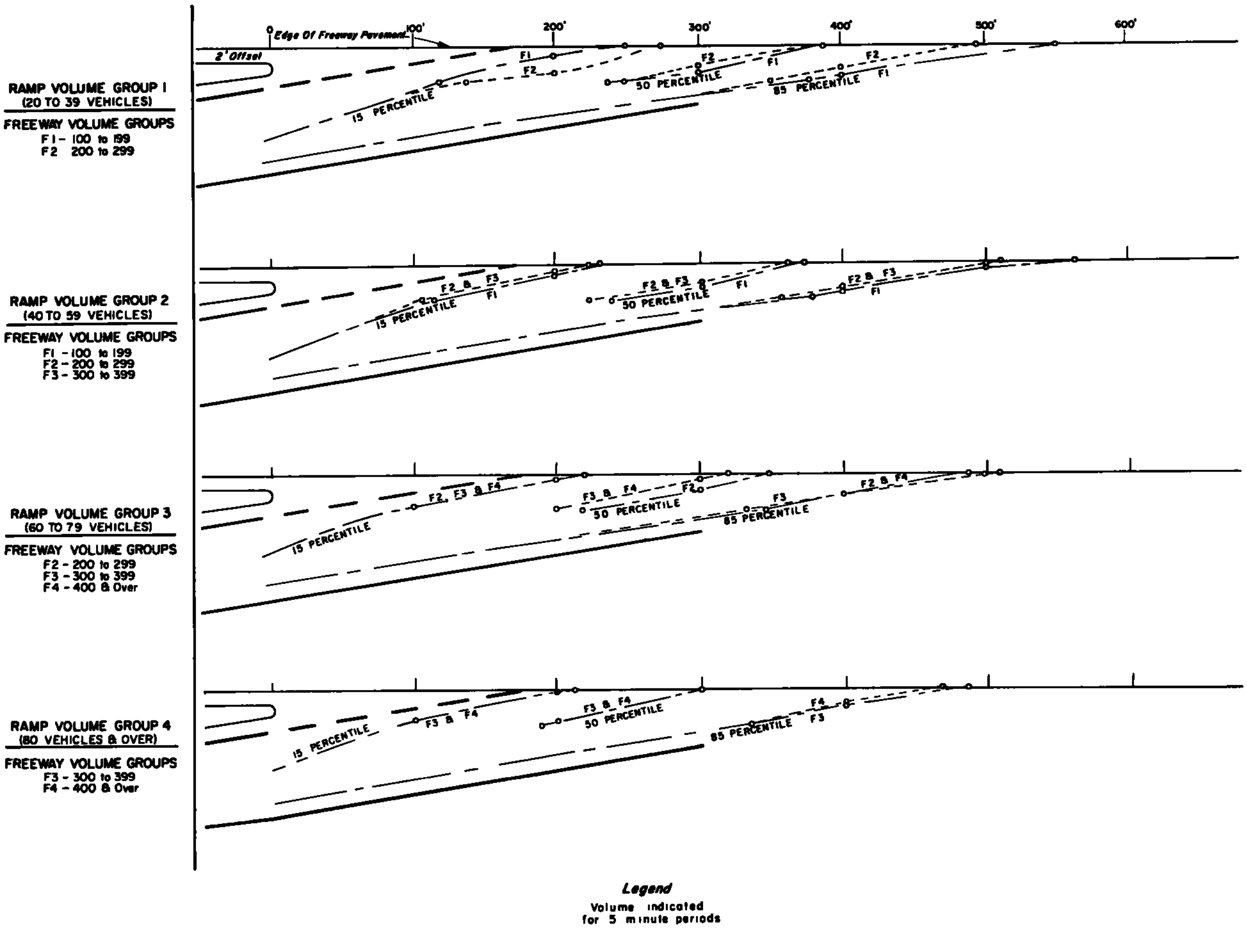


Figure 10. Right rear wheel path of 15, 50 & 85 percentile vehicles—30:1 tapered on-ramp (curb offset 2 ft).

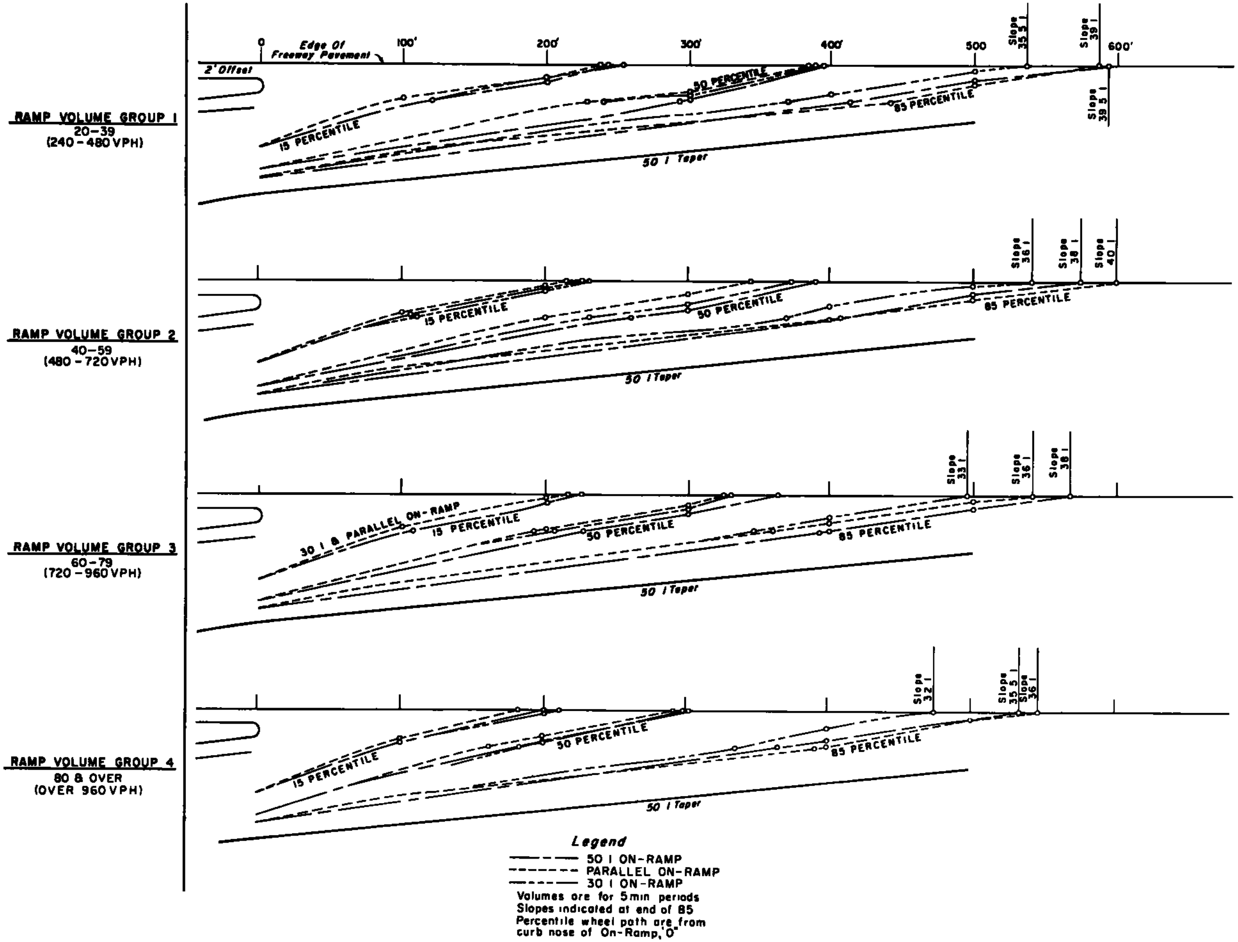


Figure 11. Right rear wheel path of 15, 50 & 85 percentile vehicles—various on-ramps (curb offset 2 ft).

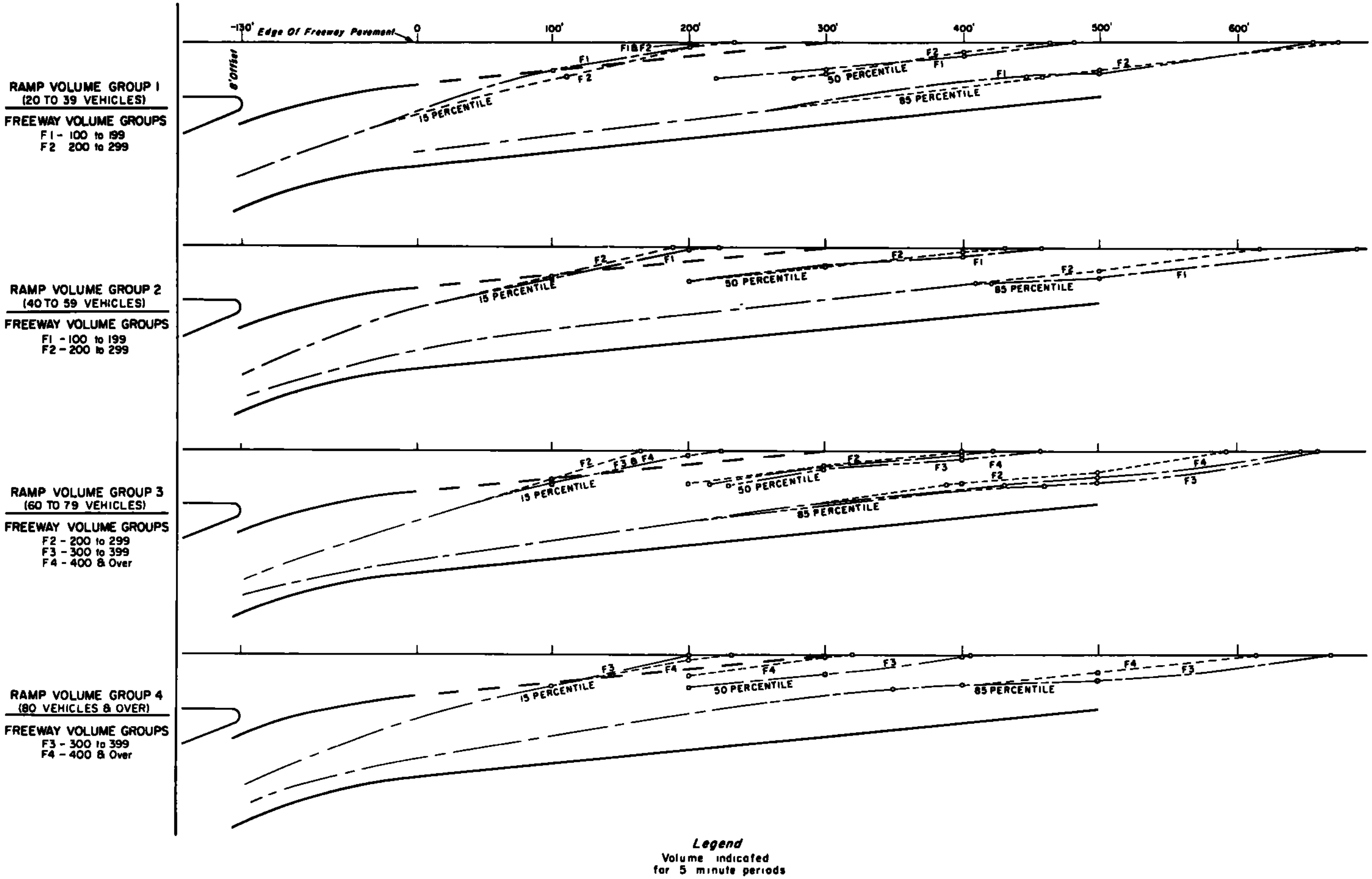
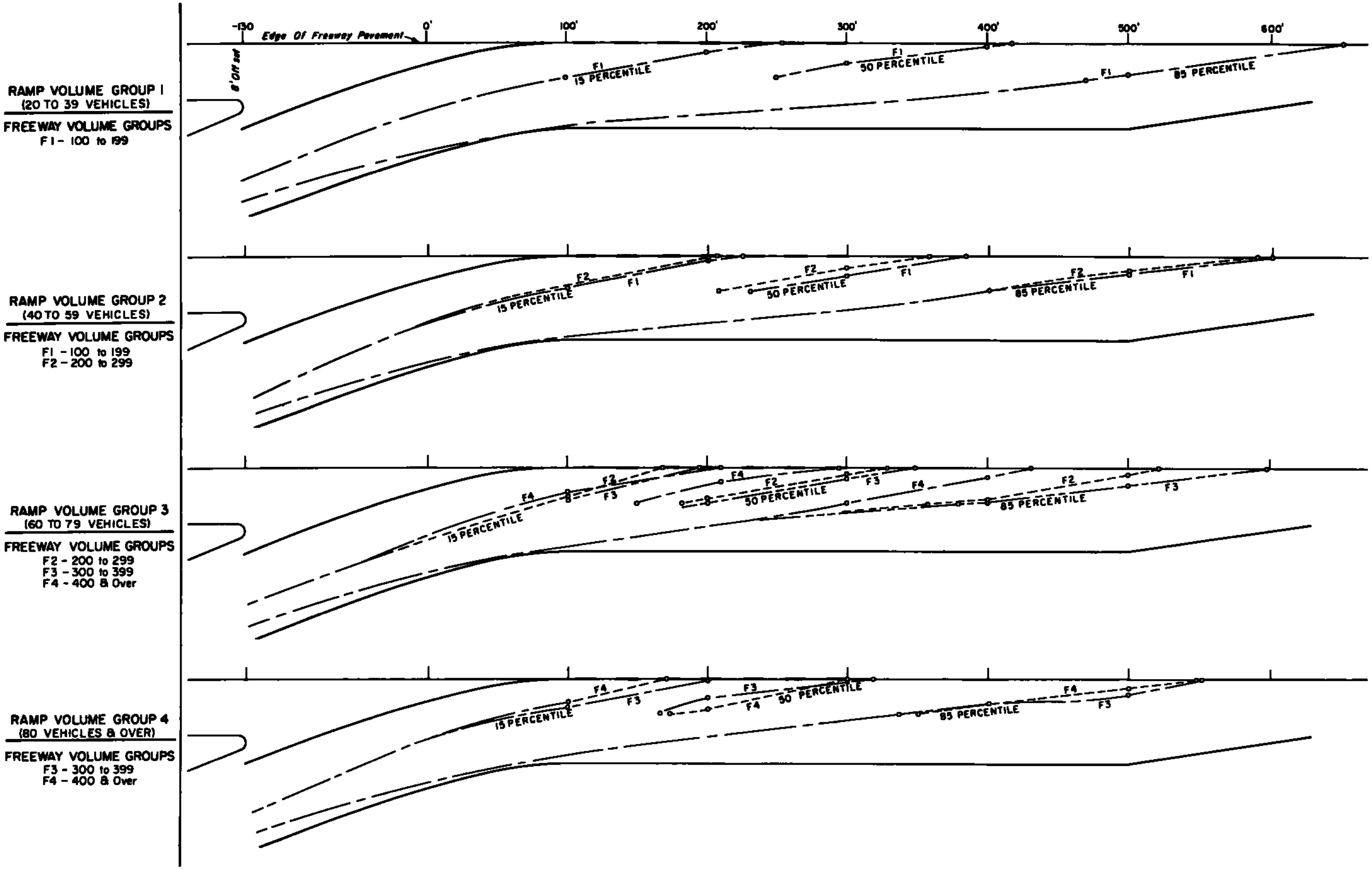


Figure 12. Right rear wheel path of 15, 50 & 85 percentile vehicles—50:1 tapered on-ramp (curb offset 8 ft).



Legend
Volume indicated
for 5 minute periods

Figure 13. Right rear wheel path of 15, 50 & 85 percentile vehicles—parallel on-ramp (curb offset 8 ft).

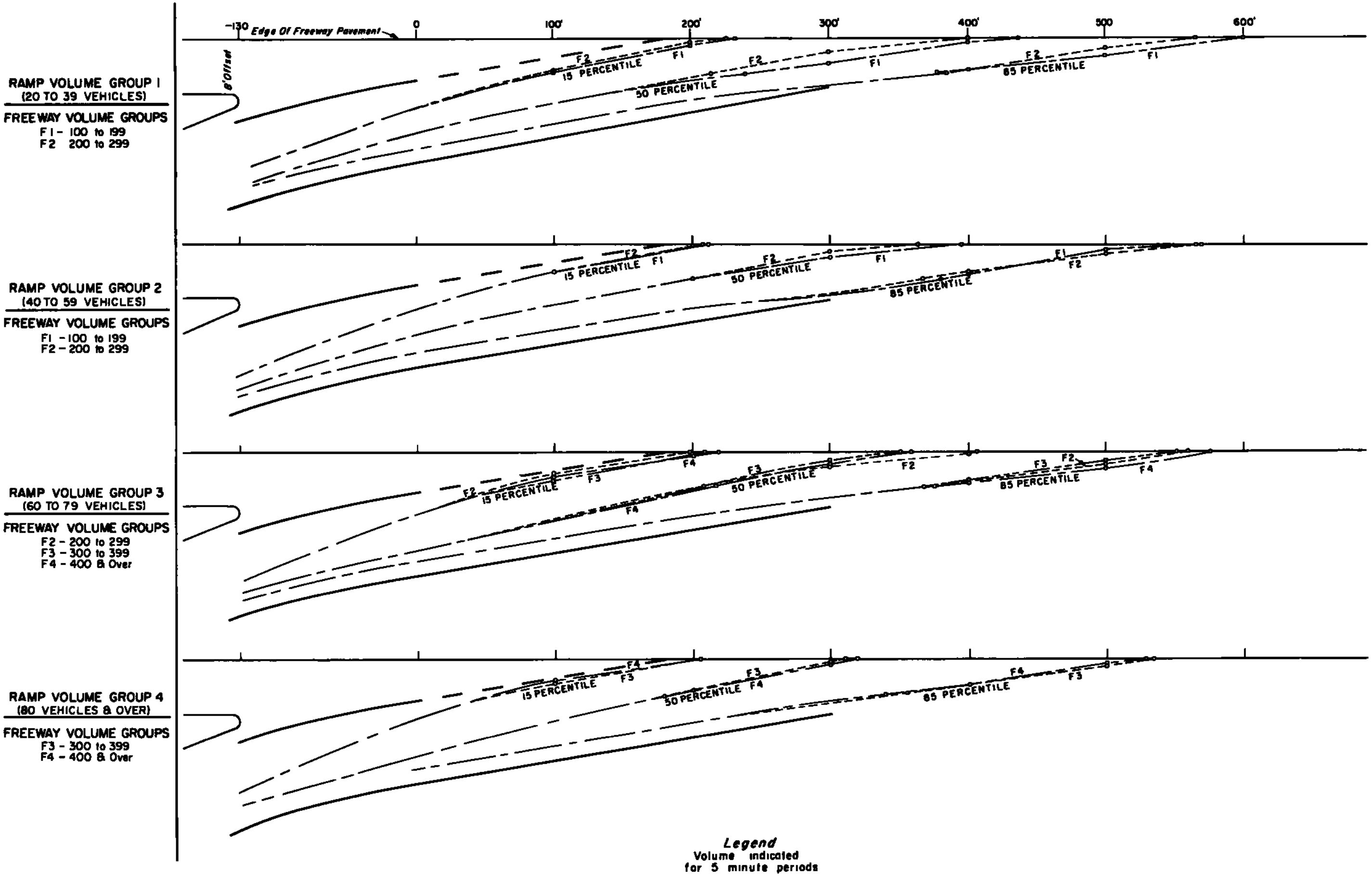


Figure 14. Right rear wheel path of 15, 50 & 85 percentile vehicles—30:1 tapered on-ramp (curb offset 8 ft).

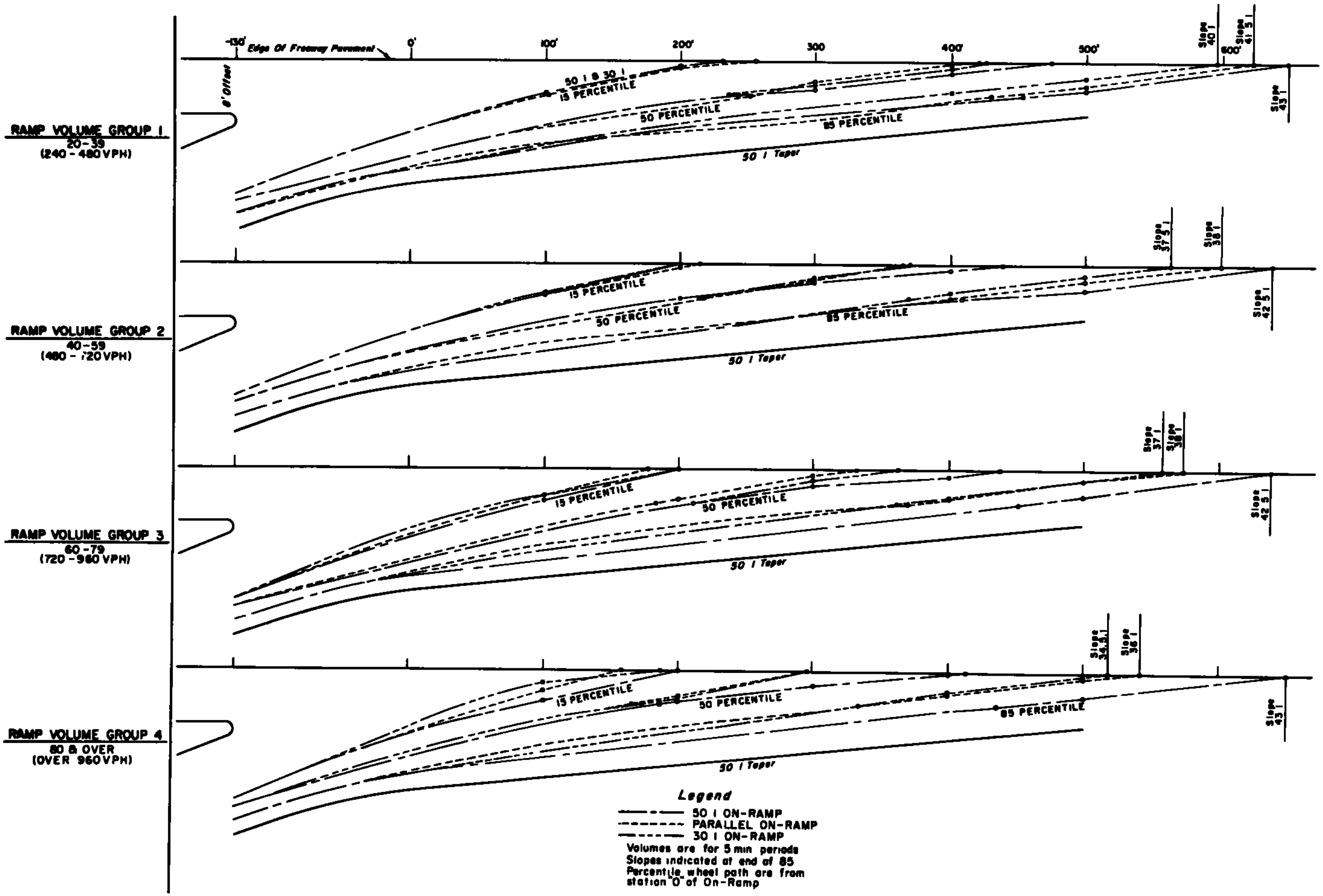


Figure 15. Right rear wheel path of 15, 50 & 85 percentile vehicles—various on-ramps (curb offset 8 ft).

This result (decreased distance with increased volume) was not expected. However, it is easy to explain and should have been expected. It is simply because more cars come on simultaneously when volume is high, and while the car (or truck) at the head of the platoon behaves very much like the ones at the head of the line during the low-volume periods, there are more "following" cars that are anxious to get into the main stream in the same gap as the lead car than there are during low-volume periods.

3. Wheel paths were similar for all designs except the 50:1 design with an 8-ft curb offset, which resulted in a more gradual path at high ramp volumes than the other designs.

In retrospect, it is not hard to see why this result was observed. It is because all designs studied actually provided ample room, especially if the 8-ft paved shoulder continuing beyond the end of the taper was used, as it was used by more than 15 percent of the vehicles in the 30:1 study. The 50:1 and "parallel" shapes, as pointed out in the introduction, actually were within 40 ft of being the same length. When the study was being planned, however, the lack of variability was not foreseen. It was thought, instead, that drivers would be influenced by the shape. This thought was based on the common knowledge that ramps of many shapes are working fairly well, and it was assumed that drivers comform to what is provided. The important finding here is that they tend to drive one way regardless of ramp shape, within the limits, of course, of what is available to drive on.

It would, of course, be possible to think of endless combinations of geometry and try them with many combinations of ramp and freeway volumes and also with several different turning speeds. It would not be prudent, however, to experiment with public traffic on a design more restrictive than the 30:1 study. Despite the lack of variation between the three designs, some principles have been evolved which will be discussed later.

4. For the low ramp volumes, the 85th percentile calls for a merging distance of about 600 ft from the point where the left edge of the ramp is 6 ft from the edge of the freeway to the point where the right wheels enter the through lane. Because the right-hand edge of the ramp is 18 ft away at the beginning and can be assumed to be 3 ft away from the right wheel at the point where the right wheel enters the freeway, this represents a taper of 15 ft in 600, or 40:1. At higher ramp volumes, the distance for the 85th percentile was slightly reduced, but this is mainly because at the higher volumes, the vehicles using more than 600 ft comprised a smaller percentage of the total.

Unfortunately, the free-running vehicles (as opposed to those caught in platoons) were not identified during the study so it is not possible to make a quantitative statement about free-choice paths. However, observation in the field, confirmed by study of the movies, showed that the vehicles caught in a platoon felt obliged to sidle on over into the freeway at an earlier location than did the vehicles at the head of a platoon or those running by themselves.

5. The percentile paths, as plotted, indicate that vehicles drive nearly a straight line instead of zigzagging. It was observed in the field and is demonstrated in the movies that this is the case, although it must be pointed out that it would have been possible for them to zigzag and still the lines connecting equal percentiles could have come out straight. With five observation stations, however, it would be extremely unlikely that a straight line for a given percentile could be drawn through more than two stations if many of the individual cars comprising that percentile zigzagged.

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	44			
R2	37	42		
R3		39	35	28
R4			34	

D

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	41	42		
R2	38	40	34	
R3		36	36	32
R4			33	34

C

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	43	42		
R2	41	42	39	
R3		40	38	38
R4			38	39

B

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	44	43		
R2	43	43	43	
R3		42	40	40
R4			38	39

A

Ramp Vol Group	Fwy. Vol Group F1	F2	F3	F4
R1	45	41		
R2	45	46	44	
R3		45	42	42
R4			38	39

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	41			
R2	38	39	33	
R3		35	36	33
R4			33	38

R1	44			
R2	41	43	39	
R3		40	36	39
R4			38	39

R1	45	43		
R2	43	44	46	
R3		41	41	40
R4			37	38

R1	44			
R2	43	46	41	
R3		46	42	40
R4			37	36

AVERAGE VEHICLE SPEED APPROACHING IN OUTSIDE FREEWAY LANE (L_1)

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	45	50		
R2	46	46	44	
R3		45	46	46
R4			47	50

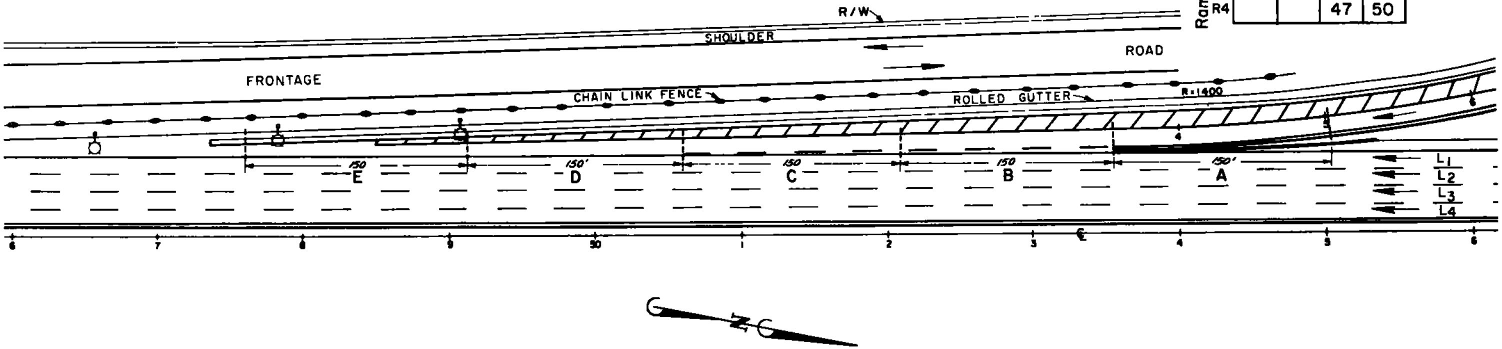


Figure 16. Ramp speeds—50:1 tapered on-ramp (curb offset 2 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1				
R2	39		28	
R3		30		
R4				

D

Fwy Vol Group

	F1	F2	F3	F4
R1	36	41		
R2	38	44	36	
R3		32	41	34
R4			44	34

C

Fwy Vol Group

	F1	F2	F3	F4
R1	40	40		
R2	42	42	40	38
R3		38	41	40
R4		46	39	39

B

Fwy Vol Group

	F1	F2	F3	F4
R1	43	42		
R2	42	44	43	42
R3		42	42	43
R4		42	39	39

A

Fwy Vol Group

	F1	F2	F3	F4
R1	46	43		
R2	45	44	45	42
R3		44	44	45
R4		43	42	43

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	36			
R2	39	43	36	
R3				33
R4		47	44	33

R1	41	39		
R2	42	41	41	43
R3		39	41	39
R4		45	32	40

R1	45	43		
R2	42	44	44	45
R3		43	42	44
R4		41	35	38

R1	42			
R2	46	44	44	
R3		44	44	43
R4		39	41	41

AVERAGE VEHICLE SPEED APPROACHING
IN OUTSIDE FREEWAY LANE (L_1)

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	46	45		
R2	46	46	45	
R3		45	48	48
R4			46	49

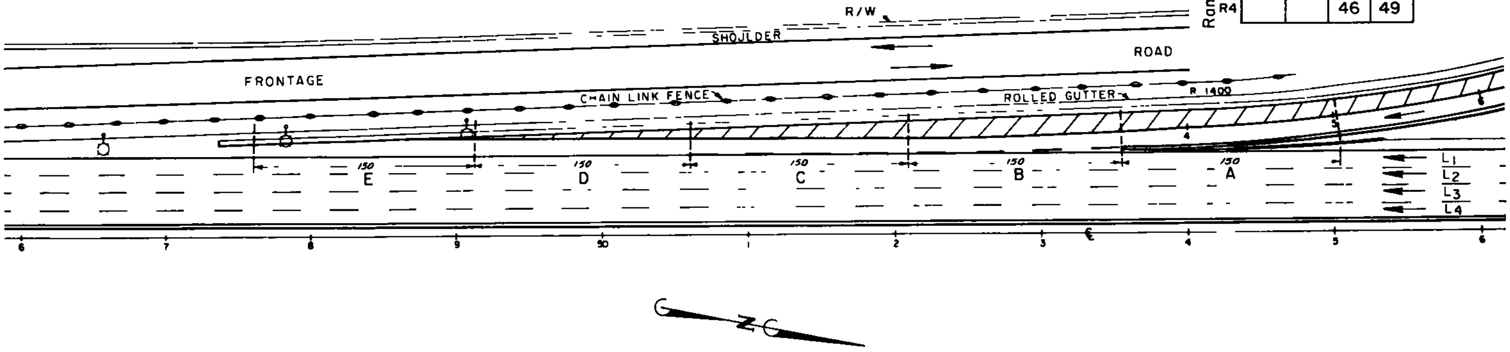


Figure 17. Ramp speeds—parallel on-ramp (curb offset 2 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Fwy Vol Group

Ramp Vol. Group	F1	F2	F3	F4
R1				
R2	45			
R3			36	
R4				36

D

Fwy Vol Group

	F1	F2	F3	F4
R1	36			
R2	37	36	39	
R3		38	36	37
R4			32	33

C

Fwy Vol Group

	F1	F2	F3	F4
R1	39	44		
R2	40	41	42	40
R3		41	38	38
R4		39	37	37

B

Fwy Vol Group

	F1	F2	F3	F4
R1	41	41		
R2	41	41	41	41
R3		40	37	39
R4		40	38	38

A

Fwy Vol Group

	F1	F2	F3	F4
R1	39	39		
R2	40	40	39	41
R3		40	38	38
R4		39	37	38

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	37			
R2	36	35	38	
R3		37	35	37
R4			31	33

R1	40	44		
R2	40	41	42	41
R3		41	38	37
R4		39	37	37

R1	43	37		
R2	40	40	39	41
R3		38	36	38
R4		41	39	38

R1	40			
R2	39	40		
R3		41	37	35
R4		39	36	34

AVERAGE VEHICLE SPEED APPROACHING IN OUTSIDE FREEWAY LANE (L_1)

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	46	46		
R2	45	46	48	
R3		45	48	46
R4			48	47

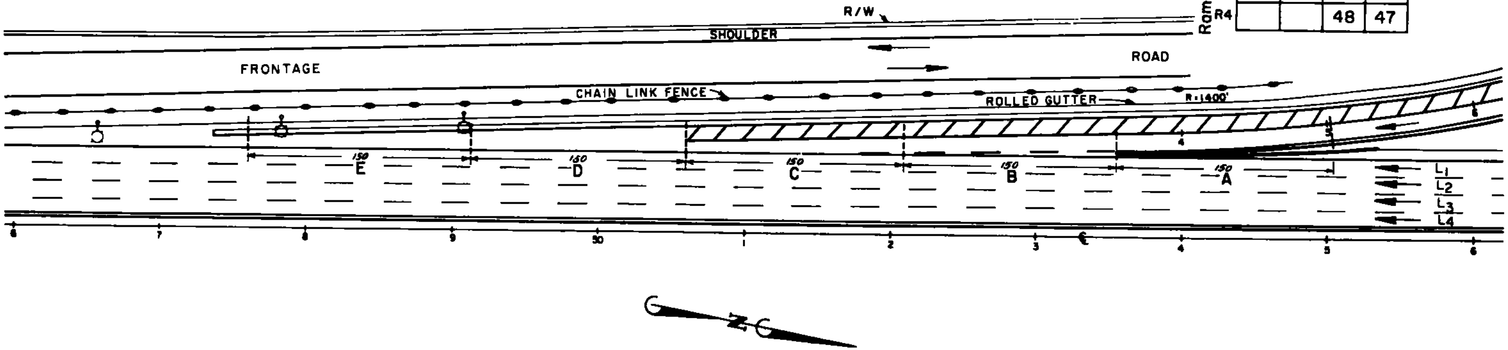


Figure 18. Ramp speeds—30:1 tapered on-ramp (curb offset 2 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	39	38		
R2	38	38	40	
R3		40	37	38
R4		38		

D

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	41	42		
R2	40	41	40	
R3		41	40	42
R4		41	42	

C

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	42	42		
R2	41	42	41	40
R3		40	40	40
R4		41	40	38

B

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	44	43		
R2	42	42	42	44
R3		43	42	41
R4		41	42	42

A

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	42	42		
R2	41	42	43	44
R3		43	40	40
R4		42	43	45

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	39	43		
R2	40	41		
R3		41	39	41
R4			42	

R1	42	41		
R2	39	44		39
R3		43	40	38
R4			40	37

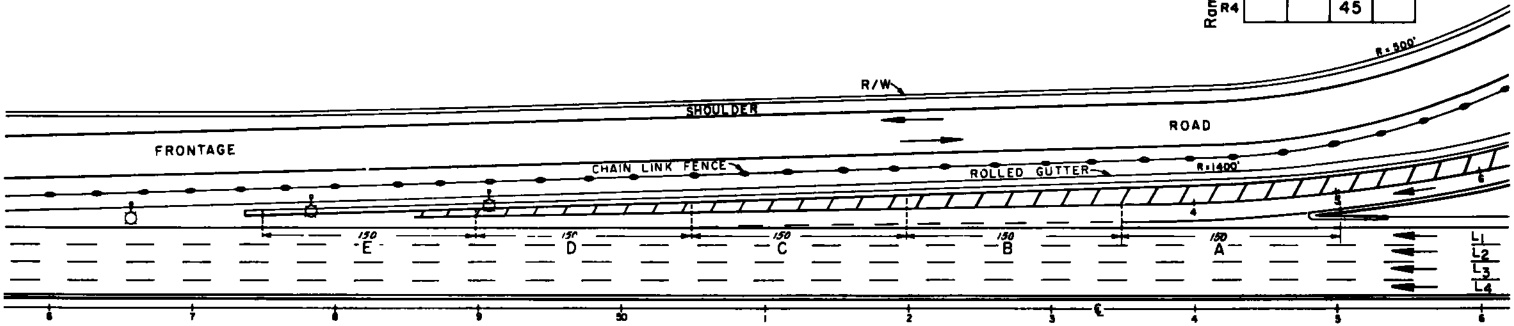
R1	44	42		
R2	42	42	40	
R3		40	45	40
R4			41	

R1	44	52		
R2		43		
R3		47	42	39
R4			46	

AVERAGE VEHICLE SPEED 500' AHEAD OF CURB NOSE

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	43	44		
R2	41	44	46	
R3		43	47	47
R4			45	



AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	43	44		
R2	42	43	44	44
R3	43	43	42	42
R4		42	42	45

AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION A

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	45	45		
R2	43	45	43	46
R3		46	45	45
R4			43	42

Figure 19. Ramp speeds—50:1 tapered on-ramp (curb offset 8 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E
Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	39			
R2	39	38		
R3		36	39	
R4				38

D
Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	41			
R2	41	41		43
R3		41	39	
R4		41	37	40

C
Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	43			
R2	42	42	43	37
R3		41	40	40
R4		44	37	40

B
Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	44			
R2	43	43	41	40
R3		42	42	42
R4		43	38	40

A
Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	41			
R2	40	41	39	41
R3		40	40	40
R4		42	36	39

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	41			
R2	41	41		44
R3		41	36	
R4				38

Ramp Vol Group				
R1	44			
R2	42	43	44	30
R3		41	40	
R4		47		40

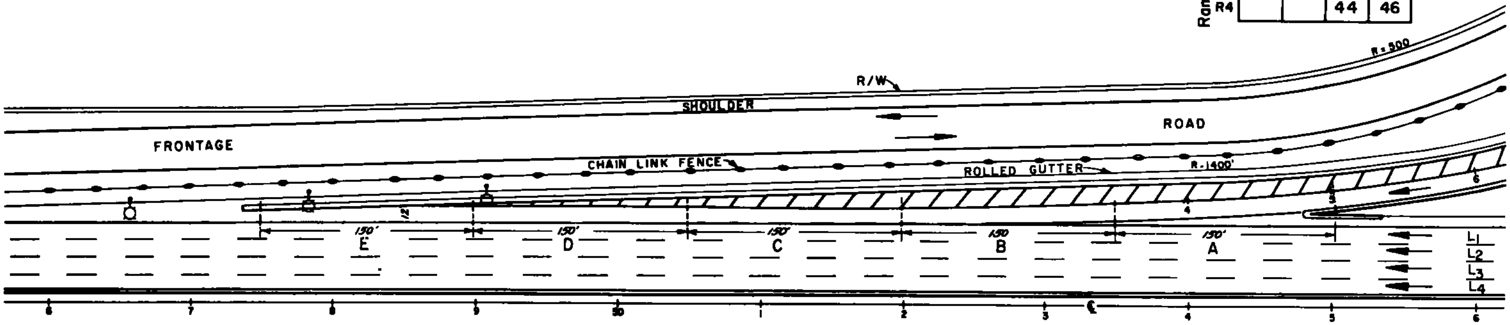
Ramp Vol Group				
R1	43			
R2	43	45		41
R3		42	43	43
R4		42	38	39

Ramp Vol Group				
R1	47			
R2	41	42		
R3		40	46	
R4				39

AVERAGE VEHICLE SPEED 500' AHEAD OF CURB NOSE

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	46			
R2	45	45	45	
R3		44	46	45
R4			44	46



AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	44			
R2	43	43	43	
R3	44	43	43	42
R4		41	43	43

AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION A

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	42			
R2	43	45	49	
R3	42	45	48	44
R4			46	46

Figure 20. Ramp speeds—parallel on-ramp (curb offset 8 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	39			
R2	40	40		
R3			39	36
R4			38	39

D

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	40	38		
R2	41	42		
R3		41	42	38
R4		40	40	36

C

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	42	42		
R2	43	43		42
R3		44	41	39
R4		42	40	39

B

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	43	43		
R2	44	43		42
R3		44	42	39
R4		46	40	39

A

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	40	42		
R2	42	42		40
R3		44	38	38
R4		47	37	35

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	40	40		
R2	41	42		
R3		42	42	39
R4			38	36

42	45		
39	43		
	45	40	39
	42	39	39

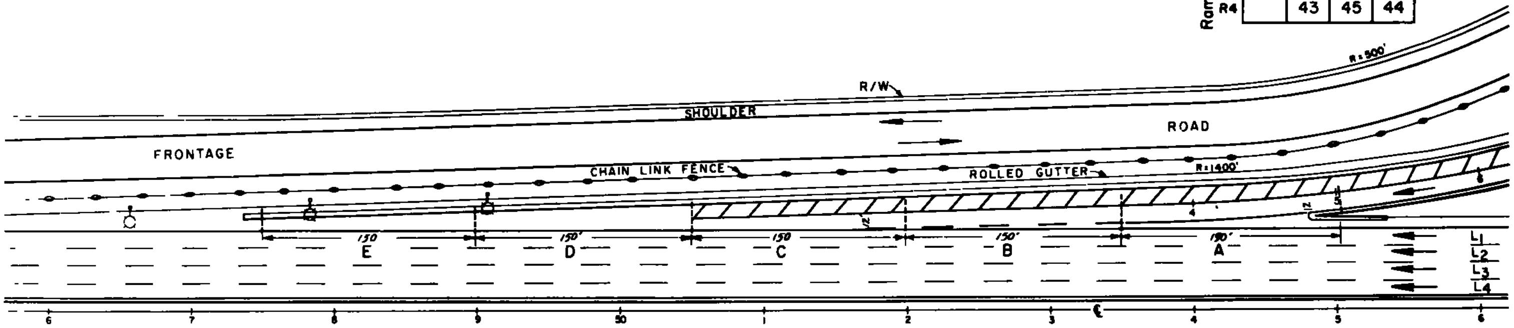
44	40		
43	41		41
	43	41	37
	48	37	39

43			
46	43		
	42	38	
	51	36	34

AVERAGE VEHICLE SPEED 500' AHEAD OF CURB NOSE

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	43	43		
R2	42	44		45
R3		45	45	46
R4		43	45	44



AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	43	41		
R2	44	43		44
R3		43	43	40
R4		43	41	40

AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION A

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	44	45		
R2	45	43		44
R3		45	45	43
R4		42	43	41

Figure 21. Ramp speeds—30:1 tapered on-ramp (curb offset 8 ft).

This point is made because the "parallel" design calls for the vehicles to drive a zigzag path if they are to follow the outlines of the ramp.

6. A comparison of Figure 11 with Figure 15 shows that the distance from the physical nose is increased just about the same amount as the nose was moved back. This shows that the nose should not be used as a control in computing length required, but that a distance of about 6 ft from the edge of the through lanes to the left edge of the ramp marks the real beginning of the merging area. It may also be implied that angle of convergence is a more significant control than distance from the physical nose.

Speed

Figures 16 to 21 show the speeds observed for each ramp shape and volume group. The upper row of boxes on each figure shows the speed of ramp vehicles for each speed trap labeled on the plan, but does not include vehicles which have already entered the freeway. The lower row of boxes shows the average speed of entering vehicles at the point of entry indicated. Blank squares in the boxes indicate a lack of sufficient measurements to establish a reliable estimate for the particular volume combination. The lower right-hand box shows the average speed approaching from Lane 1 of the freeway. For studies made with the curb offset 8 ft, additional average speeds for Lane 1 of the freeway at the beginning and end of the on-ramp are shown in the two boxes at the bottom of Figures 19, 20 and 21.

1. With a 700-ft radius approach lane (turning lane), the turning speed (box A in upper row) was in most cases higher than the merging speed. This does not necessarily mean that the ramp area was not used for accelerating. But it does indicate that when drivers attained the speed they thought necessary, they drove on in to the freeway without accelerating.
2. With ramp curb offset 8 ft, the ramp and freeway speeds were similar for all ramp designs.
3. The difference between entering speed and speed of the approaching traffic in Lane 1 was from 2 to 8 mph, and speeds of both the ramp vehicles and freeway vehicles in the right-hand lane are in the 40-50 mph range.
4. The freeway speeds, 45 to 50 mph, were higher than expected for Lane 1 which included 35 percent trucks during the off-peak hours and 10 percent trucks during the peak hours.

CONCLUSIONS

As a result of the present study and previous experience of the authors in the design of interchanges and in making freeway capacity studies, it is concluded that entrance ramp terminal design should take into consideration the following requirements:

1. A direct alinement should be provided. This study reaffirmed findings reported elsewhere (1) that drivers tend to follow a straight line from the point where ramp curvature ends until they have entered the freeway traffic lane.

Merging vehicles can be broadly classified as: (a) individual unobstructed vehicles, and (b) vehicles in platoons. The individual vehicles almost invariably drive a direct line, and if the outline of the ramp terminal is a series of curve, then diagonal, then parallel, then squeeze-off, these drivers cut across the convex corners which appear alternately on the left and right. Vehicles in platoons frequently execute a "left-oblique" maneuver in which each vehicle can execute either a zigzag motion or a direct line. If the left-oblique is performed zigzag, the azimuths of each path will be equal, whereas if each vehicle on reaching the nose assumes a different azimuth (with the rear vehicle taking the greatest angle of convergence), the same effect will be achieved. At high volumes, this effect is to be desired, because it results in any long gap in the freeway traffic being filled. At low volumes, a direct but gradual approach will give the freeway traffic more "notice" that the entering car is encroaching, and thus provide an opportunity for cooperative adjustment of speeds.

The direct alinement, or constant taper design, makes it possible to perform any of these desirable maneuvers. Although the zigzag design will, if long enough, usually provide space for the same maneuvers, it is always possible that the designer may leave a nose or a corner in such a place that traffic will have to cut across it, and at best the zigzag design will waste pavement on one side while restricting clearance on the other.

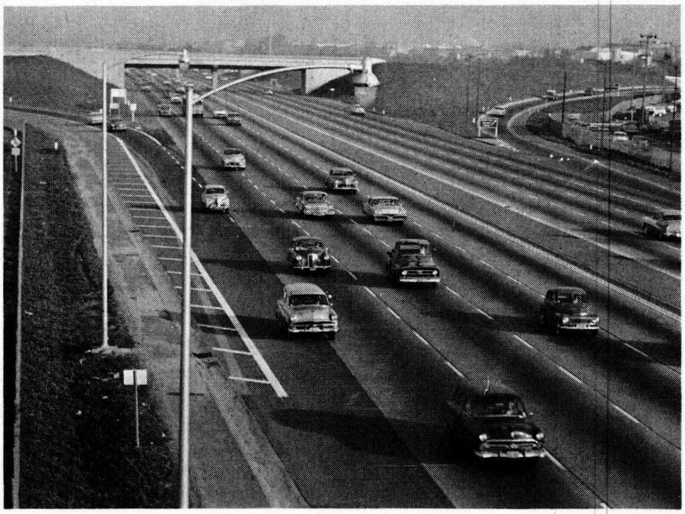
2. The angle of convergence is an important control. Drivers should be encouraged to merge at a small angle of convergence (Figs. 22A, 22B, 22C and 22D).

A ramp terminal is essentially an elongated intersection. If the intersection area is short, as on a conventional highway, freeway operating characteristics are not present and as a result both capacity and safety suffer. The difference between traffic operation at an ordinary intersection and that at a freeway ramp terminal is primarily in the angle at which the entering traffic and the through traffic converge, which in turn controls the lateral speed at which the entering vehicle approaches a vehicle on the through highway.

If the lateral speed of approach is slow enough, it is almost impossible for two cars to collide. One of them will adjust his speed so as to fall in behind the other. If both cars are in the centers of the 12-ft lanes at the point where the left edge of the ramp lane intersects the right edge of the freeway lane, there will be 6 ft between them and the convergence angle should be such that they have about 300 ft in which to adjust.

There is no mathematical formula nor psychological test that can be cited to show that 300 ft is the amount of distance needed for this adjustment; neither is there any to show that 1 sec, 2 sec, or any particular length of time is required. However, a distance such as 300 ft is much easier for the driver and, for that matter, for the engineer to visualize. A distance of 300 ft for a lateral movement of 6 ft results in a 50:1 taper. With this taper, the entering driver can confidently accelerate continuously, secure in the knowledge that he will see any freeway vehicle before he hits it, and soon enough to avoid hitting it. Vice versa, the freeway driver will see the entering vehicle before hitting it and in time to adjust his speed to avoid it.

A parallel ramp with a sudden squeeze-off at the end forces a decision on the driver: Shall I go on down and take a chance when I get there, or shall I cut in short? A constant taper design makes it easy for the driver to do what he is supposed to do, because he has a line to follow. When properly delineated by pavement markings, it also gives notice to the freeway driver that he is in a merging area.



Foreground ramp car is merging into a 166-foot, 2.7-sec. gap in Lane 1. Average headway between merged vehicles is 1.35 sec. Note that third car in Lane 1 is moving to Lane 2, anticipating that traffic in Lane 1 will slow down slightly. The four cars now occupying 275 feet (4.3 sec.) will stretch out to about 5.4 sec. or 400 feet.

Instantaneous rate-of-flow in this picture is:

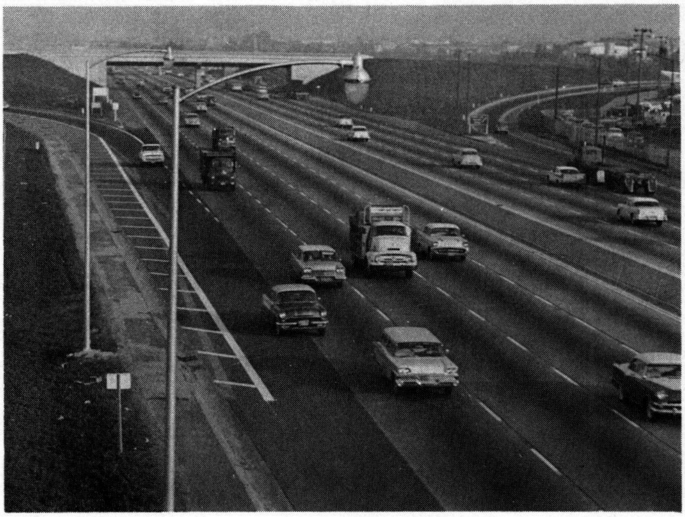
Ramp	960 vph
Freeway Lane 1 (near lane)	860 vph
Lane 2	950 vph
Lane 3	1400 vph
Lane 4	220 vph
TOTAL	4390 vph

Figure 22A. Light Traffic—merging maneuvers with a 50:1 tapered on-ramp (heavy white stripe is 50:1 taper).

Another reason why rate of convergence should be a control is capacity. It has been observed in capacity studies elsewhere (2,3) that "saturated flow" can only be obtained where the squeeze-off distance is about 500 ft or more. The only way saturated flow (usually more than 2,000 vph per lane) can be obtained is to have more lanes coming in to a point than go away from it (as is typical of an entrance ramp), and in order to convert the stop-and-go motion behind the point of convergence into steady flow, the convergence has to be gradual.

3. Adequate merging distance should be provided for low volumes as well as high volumes.

It has been shown in this study that vehicles entering at low ramp and freeway volumes use as much as or more distance than those entering at higher volumes. The R1-F1 group of observations was taken when freeway



Foreground ramp car is merging into a 75-foot gap (1.2 second) in Lane 1. This shows that even with very light traffic, a gradual merge is necessary. After the merge, the average headway of the 3 cars in the foreground will be 0.6 sec., for a short length of time.

Instantaneous rate-of-flow in this picture is:

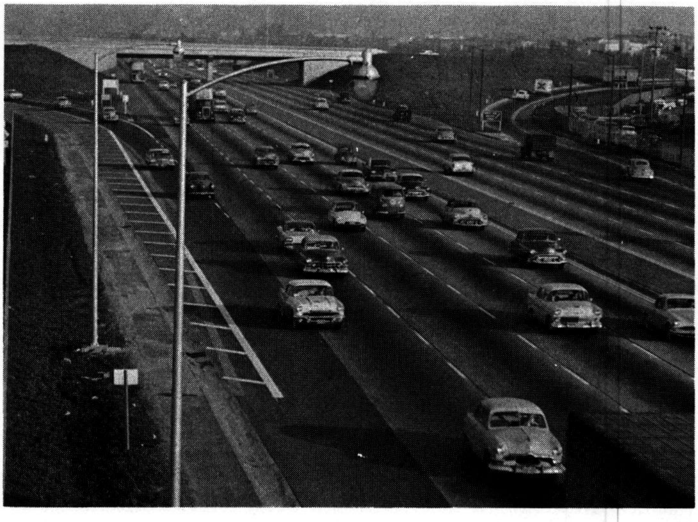
Ramp	600 vph
Freeway Lane 1 (near lane)	690 vph
Lane 2	760 vph
Lane 3	800 vph
Lane 4	680 vph
TOTAL	3530 vph

Figure 22B. Very light traffic—merging maneuvers with a 50:1 tapered on-ramp (heavy white stripe is 50:1 taper).

volume was less than 600 per lane per hour. Conversely, it has been shown that with a taper which is adequate for proper merging of a single pair of vehicles, there is adequate length for any combination of ramp and freeway volumes up to possible capacity. Controls which call for high volumes before providing adequate merging distance are therefore not tenable.

Furthermore, the science of predicting traffic for a 20-yr period is far from exact. Freeways cost so much and ramp terminals so little that it would seem only sensible to design for maximum conditions, especially when considering ramp traffic. One industrial plant, unforeseen at the design stage, not only can change the ramp volume but can radically change the design hourly volume on the freeway itself.

4. Adequate merging distance should be provided for high speeds as well as low speeds.



Foreground ramp car is merging into a 150-foot, 2.5-sec. gap. Judging by the space between 2nd and 3rd cars in Lane 1 (about 0.3 sec.), 2nd car has yielded right-of-way to ramp vehicle. This is the only way that smooth flow can be obtained at saturated rate-of-flow.

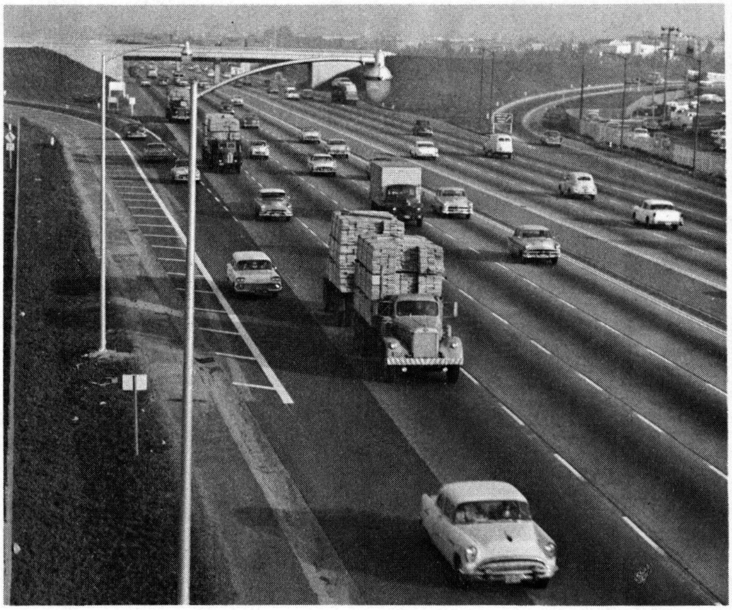
Instantaneous rate-of-flow in this picture is:

Ramp	1440 vph
Freeway Lane 1	860 vph
Lane 2	760 vph
Lane 3	1600 vph
Lane 4	<u>2250</u> vph
TOTAL	6910 vph

Figure 22C. Heavy traffic—merging maneuvers with a 50:1 tapered on-ramp (heavy white stripe is 50:1 taper).

As previously intimated, the higher the speed of the converging traffic, the more distance is required for a given length of time in which to adjust speeds, and also the higher the lateral rate of approach will be. This seems self-evident, and yet it must be mentioned because when the length of merging area is controlled by the difference between turning speed and freeway speed, it turns out that very short merging areas are provided for high turning speeds. Another way of stating this principle is that assumed high turning speeds should not result in reduced merging distance.

At the Ashby Avenue site where the observations were made, the design speed of the freeway was 60 mph, and the turning radius was 700 ft. Assuming that this is a "high volume" highway, Table VII-10 of the AASHO policy (<u>1</u>) would provide a total length of 250 ft, including taper. Ex-



Note that by gradual angle of convergence, ramp and freeway traffic will merge like a hand in a glove.

Instantaneous rate-of-flow in this picture is:

Ramp	**1200 vph**
Freeway Lane 1	**700 vph**
Lane 2	**600 vph**
Lane 3	**1200 vph**
Lane 4	**1800 vph**
TOTAL	**5500 vph**

Figure 22D. Heavy commercial traffic, especially in Lane 1—merging maneuvers with a 50:1 tapered on-ramp (heavy white stripe is 50:1 taper).

amination of Figures 11 and 15 shows that less than 15 percent of the cars observed could have stayed within this ramp, and probably less than 5 percent could have driven with 3-ft clearance on the right.

5. In combination with the approach ramp, adequate length should be provided for entering cars to accelerate from any turning speed.

6. It would be highly desirable for every entrance ramp terminal to have the same shape. When the length of the ramp terminal is dependent on assumed design speed of the freeway and safe turning speed of the approach ramp, a driver entering a level tangent freeway can be confronted with ramp terminals varying from 250 ft to 1,200 ft in length, and unless he is a commuter, he never knows quite what to do; i.e., whether to stop and take a look, to feel his way along gingerly, or to boldly step on the gas and go on into the traffic stream as the designer intended him to.

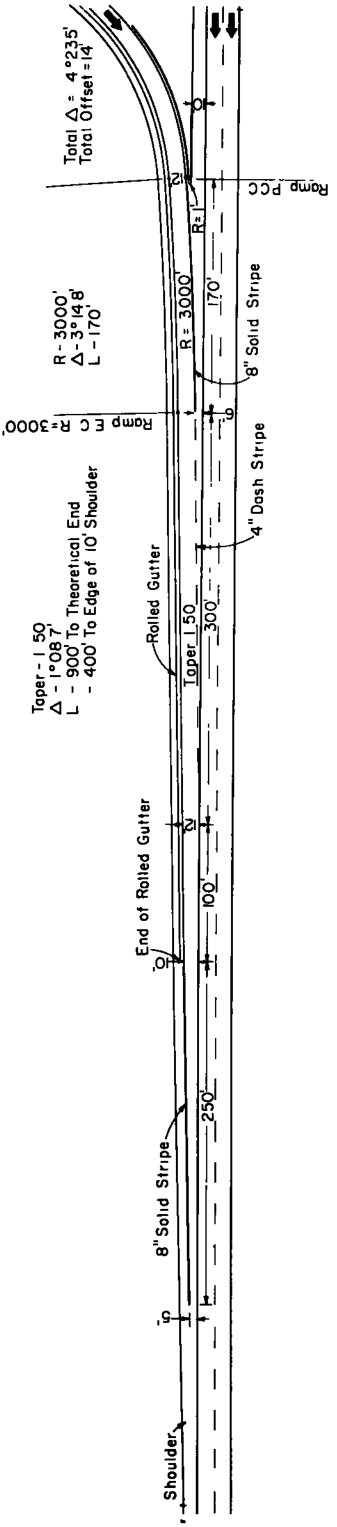


Figure 23. Suggested standard—entrance ramp.

It is obvious that a standard design for all locations would go a long way toward eliminating this confusion. A standard design would also simplify design and stake-out procedure, and would make signing, pavement marking and delineation more foolproof and uniform.

An anomaly which has arisen out of designs that vary with assumed turning speed is that the merging area is long (and adequate) at the unimportant ramps but is frequently inadequate at the important ramps, because the less important ramps are usually designed with a sharper turning radius than the more important ramps.

7. The 10-ft shoulder offset must be accommodated. Current control standards ignore the lateral space between the freeway lane and the ramp lane. Because the total length is controlled by design speeds, designs with shoulder offsets provide a sharper approach angle and a shorter merging distance than those with narrow shoulders or curb noses adjacent to the freeway lane.

8. Pavement area must not be excessive.

9. A "natural" or unforced appearance should be achieved.

A ramp design that meets all of the above requirements is offered in Figure 23. This design can be used for any typical application and has been adequately tested and observed under traffic at the Ashby Avenue site for level tangent freeways with high turning speeds.

Subjective tests have been made showing that a 1952 model 6-cylinder medium-priced car with 60,000 miles since the last overhaul, and a 1958 6-cylinder low-priced car can merge smoothly with heavy freeway traffic from a 10 mph start at the nose (marked "ramp PCC" on the drawing). It may be noted that the length of the proposed standard ramp, using the definition of length given in Fig. VII-20 (p. 494) of the AASHO

Policy (1) is 1,070 ft. Accepting the tabular values of the Policy, this makes it sufficiently long for all turning speeds on "main" highways regardless of design speed of the latter, and for "high volume" highways having design speeds of 60 mph. It is long enough for "high volume" highways with a 70 mph design speed provided that the turning radius is 150 ft or better.

It may be reasoned that the tabular values in the Policy are conservative because of the increase in auto acceleration during the past few years, a trend which is not likely to reverse. It follows that the proposed ramp design is sufficient for low turning speeds as well as the high turning speeds observed.

The data collected in the present study would warrant a 40:1 taper instead of 50:1 if the 85 percentile vehicle path is accepted as being all that should be accommodated, but 50:1 is recommended, first because of the margin of safety, and for two other reasons: it makes the ramp terminal long enough to accommodate all the lengths in the AASHO table, and this in turn makes it possible to use a uniform shape at all locations. The difference between a 40:1 and a 50:1 taper amounts to 35 sq yd of pavement and 107 sq yd of shoulder, outside of the 10-ft shoulder of the through roadway.

The 3,000-ft radius curve shown in Figure 22 was arrived at because it was desired to lose width as rapidly as possible for the sake of economy, and yet not introduce so much delta that a straight ramp from a diamond interchange would require a reverse curve.

Any offset between nose and through pavement can be fitted to this curve without changing the design. The 8-in. solid stripe has proven very effective in guiding traffic into the desired 50:1 taper.

EFFECT OF GRADES

Although no quantitative observations were made of traffic behavior on ramps having grades, the logic of the relation between grade and length may be examined. It is obvious, of course, that for a given increase in speed, more length is required by a car (on the ramp) going uphill than on the level. But it is also true that vehicles in the right-hand lane of a freeway going uphill are on the average moving much less than 50 mph. "Design speed" here becomes meaningless. Passenger cars on the entering ramp can easily overtake the slow vehicles on the freeway with less acceleration distance than they need on the level, and the time rate of convergence is less than it would be on the level with the same taper. Passenger cars in the right-hand lane of the freeway will have less difficulty avoiding entering cars than they will have avoiding slow trucks that are already on the freeway and which they encounter continuously on the main line. It therefore seems that the design shown in Figure 23 will work on any grade.

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