EVALUATION OF FREEWAY TRAFFIC FLOW AT RAMPS, COLLECTOR ROADS, AND LANE DROPS

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This study was designed to evaluate freeway traffic flow characteristics for several high-standard geometric design features. The study evaluates and compares the effect of different ramp types, spacing, and volumes on freeway capacity and operation. Collector-distributor roads, auxiliary lanes, and lane drops are included. The primary measure of effectiveness used for this study was density (vehicles per lane-mile). Density was chosen rather than speed because it is a better indication of driving conditions. The major finding of this study is that freeway designs that offer greater flexibility (freedom of choice to the drivers) will result in smoother and more efficient operation. For example, a freeway with auxiliary lanes has greater flexibility than a freeway with a collector road system with the same total number of lanes. It also has greater capacity and more efficient operation.

•SINCE the first freeway was built, an evolution in design has been in progress that has caused standards to be continually changed. With better standards, such as wider lanes, wider medians, longer ramp tapers, special weaving areas, large radius curves, increased lateral clearance, and reduction in grades, newer freeways carry larger volumes of traffic faster and safer than ever before.

In densely populated urban areas, freeways tend to become overloaded during peak periods of the day. These freeways carry such high volumes of traffic that geometric configurations become critical controls of their operation. Improper design causes increased congestion and excessive delay to the motorist.

As always, the adequacy of present design standards is being questioned. What freeway geometric designs, from an operational point of view, will give the highest level of service (least congestion) and carry the maximum volume of traffic? This study was designed to help answer this question by making an evaluation of traffic flow characteristics for several high-standard geometric design features. Traffic flow characteristics are simply volume, lane distribution, and average speed or density as well as variability in speed or density. The study evaluates and compares the effect of different ramp types, spacing, and volumes on freeway capacity and operation. Collector-distributor roads, auxiliary lanes, and lane drops are included in the analysis.

STUDY LOCATIONS

Eleven study sites were used in the Los Angeles area on the San Diego, Santa Monica, and Hollywood Freeways (Fig. 1). The design characteristics of each are as follows:

1. Medium-volume multiple on-ramps,
2. A high-volume standard on-ramp,
3. Medium-volume multiple off-ramps,
4. High-volume multiple off-ramps,
5. A high-volume standard off-ramp,
6. Merge of collector-distributor road onto freeway,
7. Slip-ramp from collector-distributor road to freeway,
8. A high-volume off-ramp with parallel auxiliary lane,

9. A high-volume on-ramp with parallel auxiliary lane,
10. Freeway merge from four to three lanes, and
11. A medium-volume two-lane on-ramp.

At all of the off-ramp locations, an upstream straight pipe section was observed, and, at most of the on-ramp locations, a downstream straight pipe section was observed.

METHODOLOGY

The primary measure of effectiveness used for this study was that, for a given rate of flow, one section of freeway operates better than another if the traffic density is less or if it is more uniform at the same average density. Density was chosen as the primary measure of quality of operation rather than speed because it is thought that density (which, if volume is known, can be translated into average speed) is a better indication of driving conflicts or tension than speed per se.

Time-lapse photography was used to obtain density and volume by individual lanes at every location. Photographs were taken at the rate of one frame per sec. Spot densities were determined by counting the number of cars in a known length of road in every fifth frame. Knowing density and volume by lane permitted analysis of different sections of roadway with varying volumes and geometric conditions.

The findings of this study are based on observations of freeways carrying capacity or near-capacity volumes. This is the volume level when the quality of flow tends to be unstable and geometric conditions have a major effect on the operation of the freeway.

The 90th percentile density (a value that density is equal to or less than 90 percent of the time) was used as a paramter for the quality of flow. The 90th percentile density can be used to show the variance in operation at a location or between locations. The general method or form this analysis took can be illustrated in the following example taken from the data.

Say we are concerned with sections of freeway with four lanes in one direction with a total 5-min flow rate of 7,500 vehicles per hour (Appendix). To get a statistical sample, we dealt with 5-min periods that had flow rates between 7,400 and 7,600 vph.

Then, on a four-lane section with no ramps in the vicinity or any other unusual features, a typical 5-min time-slice, representing 60 data points for a given time of day on one of the graphs, would be as given in Table 1. This table basically shows that, at this section when the 5-min flow rate is 7,500 vph, the mean density is 125 vehicles per mile, which is an average calculated speed of 7,500/125 or 60 vph. (This is a calculated speed for a short duration of time.) It also shows that 10 percent of the time density in lane 3 exceeds 48 vehicles per mile. This represents queuing effects and is an adverse feature.

Next we look at a merging section where there is a single on-ramp and where the total freeway 5-min flow rate is 7,500 vph (Table 2). Data given in Table 2 show that, for this circumstance with a total flow rate of 7,500 vph and a ramp flow rate of 925 vph, mean density is 126 vehicles per mile, which is an average calculated speed of 59.5 mph. The table also shows that 10 percent of the time the merging density is greater than 55 vehicles per mile. (It is entirely possible to have equal mean densities or speed; then the variability factor becomes more important in determining operational difference.) It can be seen that the merging section does not operate so well as the through section to the extent shown.

Graphs have been developed (Fig. 2) that show the relationship between volume and density with respect to time for the different locations. Speed was calculated with volume and density and shown on the graphs also. Figure 2 shows volume, lane distribution, density, and speed all with respect to time of day. This makes it possible to compare the quality of operation for different locations at similar flow rates. The graphs also obviate the difficulty in interpreting the meaning of standard "q-k" curves, which are plotted without relation to time and which fail to distinguish upstream from downstream of bottlenecks.

Figure 2 vividly shows when operation breakdown occurred. Using the term "breakdown" is really a misnomer. Even though the drivers are experiencing stop-and-go

Figure 1. Study sites.

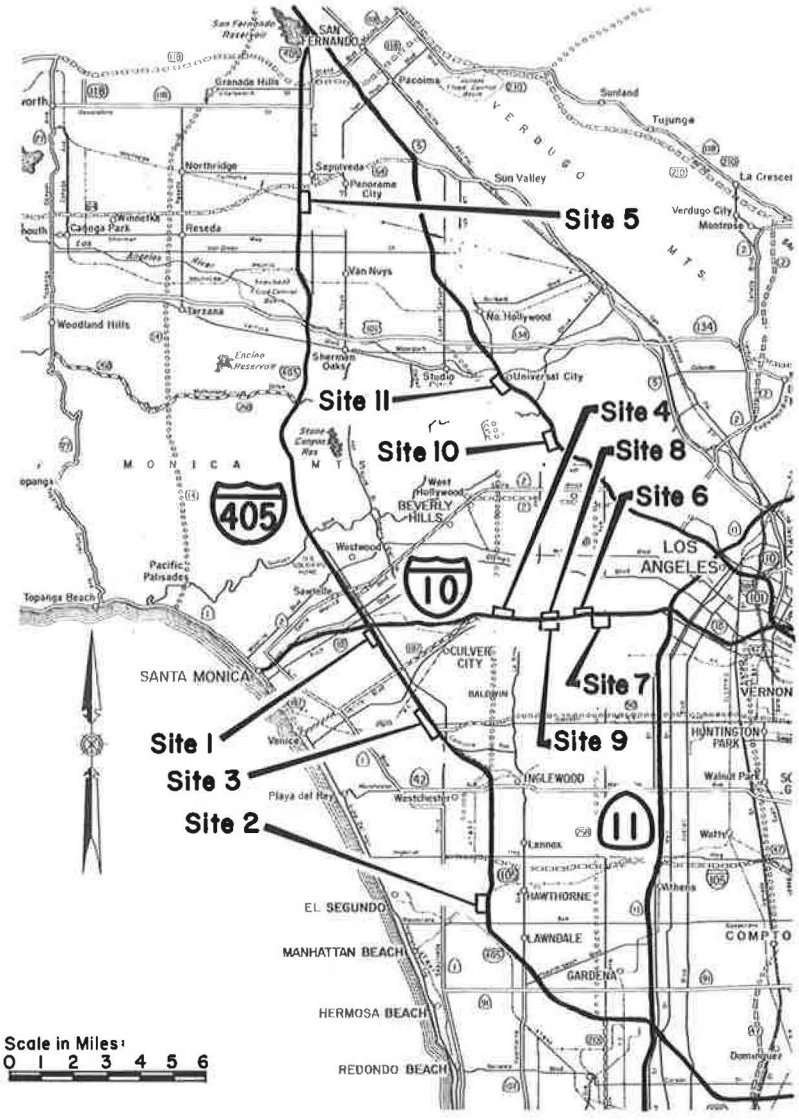


Table 1. Flow rate and density on four-lane section with no ramps.

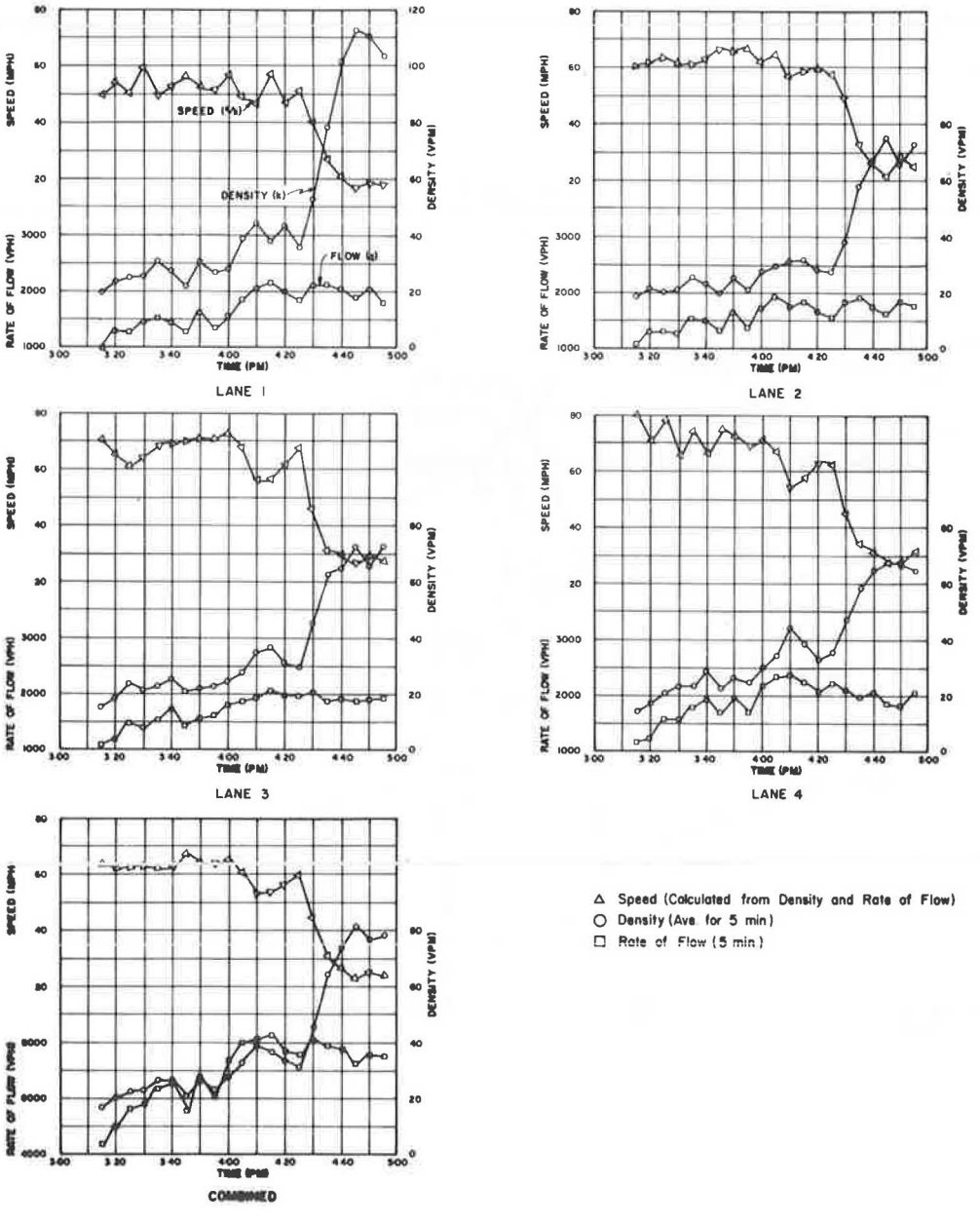
Lane[a]	5-Min Flow Rate (vph)	Mean Density[b] (vehicles/mile)	90th Percentile Density (vehicles/mile)
1	1,340	24	40
2	1,900	34	40
3	2,050	34	48
4	2,210	33	39
Total	7,500	125	

[a]Highway Capacity Manual nomenclature is used; lane 1 is on right side of roadway.
[b]Mean of 60 instantaneous densities observed during 5 min; 90th percentile is density equaled or exceeded in six of these observations.

Table 2. Flow rate and density on four-lane section with on-ramp.

Lane	5-Min Flow Rate (vph)	Mean Density (vehicles/mile)	90th Percentile Density (vehicles/mile)
Ramp	925		
1	895	35	55
Subtotal	1,820		
2	1,560	27	39
3	1,920	29	40
4	2,200	35	46
Total	7,500	126	

Figure 2. High-volume single-lane on-ramp (San Diego Freeway southbound at El Segundo on-ramp—site 2).



driving and are averaging speeds of approximately 30 mph, the freeway is still allowing a near-capacity rate of flow through the section. This can be seen on any of the graphs that show excessive densities and low speeds. The volume will stay at or near capacity.

All of the sites were analyzed in a similar manner to what has been discussed, and conclusions were reached from this analysis. (Detailed analysis and discussion of each study site have been omitted from this publication in the interest of brevity.)

SUMMARY OF CONCLUSIONS

The major findings of this study are as follows:

1. Where ramp layout provides adequate acceleration and deceleration tapers as well as adequate capacity on ramps and at terminals with the local street system, it was observed that off-ramps operate more smoothly and cause less congestion to the freeway than on-ramps. Bottlenecks most frequently occur downstream from an on-ramp where traffic is added to the freeway without addition of extra lanes. Because traffic signals are usually present at the ramp terminals with the city streets, traffic frequently enters the freeway in platoons, which causes severe sporadic overloading of the shoulder lane. Off-ramps relieve the freeway by taking traffic off. The vehicles usually leave the freeway at a more uniform rate; therefore, the platooning problem is greatly reduced. Platooning and overloading of the right lane do occur for off-ramps, but it takes higher volumes for platooning and overloading to become a problem.
2. High-volume single-lane standard on-ramps create operational problems on the freeway by overloading lane 1 and causing poor lane distribution of volumes on the freeway. A more efficient operation of the freeway can be obtained either by splitting the same volume into two lower volume ramps, say 1,200 to 1,500 ft apart, or by adding an auxiliary lane (as a continuation of the on-ramp) that extends to the next off-ramp or, in the absence of a high-volume off-ramp within a mile or so, for a minimum distance of 2,500 ft. Either alternative will allow the freeway to carry higher volumes with less congestion. The effect of platooning is greatly reduced.
3. If off-ramps have adequate capacity, operation will usually be smooth on the freeway near the off-ramp nose. Congestion, if present, will usually occur upstream of the off-ramp due to lane changing and overloading of lane 1 by vehicles desiring to use the off-ramp. High-volume single-lane off-ramps create operational problems to the freeway upstram of the off-ramps, i.e., excessive congestion and poor distribution of lane volumes. The use of an auxiliary lane upstream of the off-ramp will relieve congestion by allowing existing traffic to move out of the through lanes of traffic. If a capacity problem exists at the throat of the off-ramp, it can be relieved by enlarging the exit into a two-lane off-ramp and giving the vehicles in lane 1 an exit option. (A two-lane exit throat must be preceded by an auxiliary lane.) Another alternative to relieve congestion would be to split the same volume of traffic into two lower volume off-ramps, say 1,500 to 1,700 ft apart. This results in better lane distribution and reduces congestion in lane 1.
4. The use of multiple on- or off-ramps gives high volumes with less congestion to both the freeway and ramps because of better lane distribution and a more balanced use of the freeway. Multiple ramps also create a better distribution of traffic to the city street network. Merging problems are reduced.
5. The section of freeway studied that has collector-distributor roads is actually a 12-lane facility, but it is not capable of carrying the volume of a 12-lane freeway. Lane volumes on the collector roads are consistently lower than lane volumes on the freeway, which shows that full utilization of the capacity of the collector roads is not being accomplished. The separation of lanes between the freeway and collector road causes inflexibility in handling traffic fluctuations because even distribution of traffic in all lanes is prevented. The capacity of the collector road is also reduced because of design standards lower than those of the freeway; i.e., merging lengths are shorter.
6. On any design where a continuous collector-distributor road is proposed, it can be assumed that speeds will at times be high. Design standards including weaving and merging distances, acceleration and deceleration lane lengths, and sight distances should be consistent with these conditions. Generally speaking, the same design

criteria should be applied to a continuous collector-distributor road as are applied to the main line freeway.

7. Collector systems create high-volume slip-ramps. These ramps usually cause a capacity problem on the freeway during peak periods. Auxiliary lanes should be added to give these ramps a free entrance to or exit from the freeway. The auxiliary lanes should extend to the next interchange or at least 2,500 ft. This principle should apply to all high-volume ramps.

8. The use of auxiliary lanes between closely spaced interchanges increases the capacity of both the freeway and the ramps. This is considered the major benefit of auxiliary lanes. Auxiliary lanes also reduce weaving problems. Weaving occurs away from the mainstream of flow, therefore causing a minimum of disturbance to the freeway. Congestion upstream of an off-ramp with an auxiliary lane is minimized.

9. Auxiliary lanes should have special delineation to differentiate them from the through lanes of the freeway. Contact treatment is not necessarily the answer, but possibly use of special lane striping or dots may be.

10. The highest flow rates recorded in this study occurred downstream from bottleneck sections during periods when operational "breakdown" existed at or upstream of the bottleneck. Bottlenecks usually occur downstream of on-ramps or lane drops.

11. Operational "breakdowns" are manifested at lane densities between 40 and 50 vehicles per mile. In every case when the density was 50 vehicles per lane-mile or greater the operation was poor. During periods of operational breakdown, volume levels are near capacity.

Most of the findings of this report can be summed up by the following statement: Freeway designs that offer greater flexibility (freedom of choice to the drivers) will result in smoother and more efficient operation. For example, a freeway with auxiliary lanes has greater flexibility than a freeway with a collector road system with the same total number of lanes. It also has greater capacity and more efficient operation.

APPENDIX

SPACE-MEAN SPEED CALCULATED FROM LOW DENSITIES

In this report, the reader will note some incredibly high calculated space-mean speeds at fairly high volumes. These result from measured densities in the range of 20 to 40 vehicles per mile. At densitites greater than 40, the calculated speeds are more realistic. Extensive rechecking or "auditing" of the original data transcription failed to reveal any systematic error that would account for this phenomenon. Further analysis was made in an attempt to show that at least a portion of the anomaly can be attributed to the skewed distribution of small samples, even when a large number of samples is used for each data point. This attempt was unsuccessful, but it is still felt that there is something mystic about the effect of small numbers.

Density was determined by counting cars in a 400-ft trap every 5 sec and taking the mean of 60 such counts for the 5-min data point. A density of 33 vehicles per mile represents a mean count of 2.5 vehicles in the 400-ft trap. This means that a lot of zeros and ones are included in the 60. At first we suspected that, because zero could represent any intervehicle space from 400.1 ft to infinity, and knowing that the true value was a lot closer to 400 than infinity, some value higher than zero should be assigned to the zero readings. This would have had the effect of increasing the density, which in turn would result in more realistic space-mean speeds. However, it was soon discovered that this "suspicion" was founded on false reasoning; if the true mean space between vehicles is, say, 800.2 ft, there will be twice as many zeroes among the 60 samples as there would be if it is 400.1 ft.

Because of the anomaly (incredible speeds at low densities), this report was shelved for several years. However, in 1970 System Development Corporation (SDC) performed a study for NCHRP in which space-mean speeds were measured in a short (but much

longer than 400 ft) trap, using 1-sec time-lapse aerial photography. Aerial photography eliminates the principal source of potential error in reading the raw data; i.e., the number of cars in the trap is not subject to doubt because of foreshortening effects or difficulty of determining whether a car is in or out of the trap.

The SDC study also showed very high space-mean speeds at low densities (75 mph in lane 4, average of 70 mph for all lanes). The authors of that report have no explanation either, except that Los Angeles area drivers drive very fast. We do not accept that exaplanation, but at least we are not the only ones who had trouble with the process.

In any event, whether the anomaly is owing to reading errors, mystic "end-effects" of averaging small numbers, or any other reason (space-mean speed is always less than time-mean speed, so that cannot be the reason), a change in the absolute magnitude of the speeds will not affect the conclusions that were drawn from the graphs and tables in this report. The main thing the reader can be sure of is that, when densities were low enough to result in very high computed speeds, quality of flow was very good.