Effect of Buses on Freeway Capacity

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•QUESTIONS frequently asked are, "How many buses can an exclusive bus lane on a freeway carry?" and "What is the effect of buses on mixed traffic flows on freeways?" Little published material has been released aimed toward providing an answer to these questions. Therefore, this study was initiated in the spring of 1962 in an effort to make a first step toward providing answers regarding bus equivalency in connection with mass transit operation on highways. It was limited to a study of buses on freeways and limited-access facilities.

In particular, the purpose of this study was to measure the speeds and the spacing between buses on freeways or other high-type facilities where several buses form a continuous group at relatively frequent intervals during the peak periods, to determine the passenger car equivalent of buses on such roads, thus permitting determination of the theoretical capacity of the separate all-bus lane on a freeway. It was felt that by studying a combination of speed-volume data and "cluster" data, it would be possible to develop capacity values as well as to determine the effect of buses on the traffic stream.

The study was designed to determine theoretical maximum volumes within a specified speed range. These volumes have been computed for level, tangent sections of freeway with 12-ft lane widths and no lateral restrictions. The effects of freeway interchanges, grades, ramps and ramp spacing have not been considered. The highest volume recorded of the several "maximum volumes within a specified speed range" for traffic streams consisting of 100 percent autos should, according to this criterion, approximate possible capacity under ideal conditions as defined in the Highway Capacity Manual (1). "Possible capacity," as determined by the study data and methods of analysis of this report, was calculated to be an average lane volume of 2,050 ± 50 autos/hr in both the 23- to 27-mph and the 28- to 32-mph speed ranges. This volume and these speed ranges agree quite closely with the possible capacity of 2,000 autos/hr per lane at approximately 30 mph presented in the Manual (1). The possible capacity of an exclusive bus lane, calculated by the same method, was determined to be 1,300 ± 100 buses/hr within the 28- to 32-mph speed range.

Locations Studied

Inquiries were sent to several agencies in an effort to find locations where there were a large number of buses in the traffic stream and/or where a separate lane was reserved for transit use. After studying the descriptions submitted of various locations the following areas were selected for study:

1. The Route 3 approaches to the Lincoln Tunnel in New Jersey;
2. The center tube of the Lincoln Tunnel;
3. Shoreway West in Cleveland, Ohio;
4. Lakeshore Drive in Chicago, Illinois;
5. The Mark Twain Expressway in St. Louis, Missouri;
6. The Bayshore Freeway in San Francisco, California; and
7. The lower deck of the San Francisco-Oakland Bay Bridge, including studies at three different locations on the exclusive bus lane in use at that time.

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Method of Field Observation

To examine the factors on which the determination of the capacity of a separate bus lane and the effect of buses on a typical freeway must depend, it was necessary to find a field method that would permit measurement of the following traffic characteristics: (a) lane volumes; (b) time headway in increments of hours (i. e., the spacing between vehicles measured in units of time); (c) vehicle classification (herein vehicles are classified as autos, buses, and trucks); and (d) vehicle speed.

The listed requirements suggested use of some kind of apparatus that would make a continuous record. Two relatively simple kinds of apparatus to do this are a motion picture camera and a graphic time recorder in which one or more pens record on a moving chart. The graphic time recorder was used in this study because of greater flexibility of the equipment in choosing site locations. For example, in using a motion picture camera it is necessary to have good light and a good view of the roadway at all times, whereas in using the graphic time recorder it was possible to study at any time, from the side of the road, on bridges, and in tunnels where lighting is marginal.

The graphic time recorder used in this study was a standard twenty-pen recorder, in which each pen, when actuated by its particular push button, makes a characteristic mark on moving paper. All observations were visual and recorded manually through the use of these push buttons.

In this study, only nine of the twenty pens were utilized. Chart paper moved through the recorder at the rate of 10 in./min. The paper was marked with 100 spaces/6 in. At the rate of 10 in./min, the time spacings could be read to the nearest 0.00005 hr (i.e., to the nearest 0.18 sec).

Pens 1, 2, and 3 were used to record automobiles, trucks, and buses, respectively, in lane 1. Similarly, pens 11, 12, and 13 were used to record automobiles, trucks and buses, respectively, in lane 2. Pens 4 and 14 were used to measure the time required for a vehicle to traverse a speed trap of predetermined length in lanes 1 and 2, respectively. The vehicle speeds were later calculated in the office. Pen 20 was actuated at 1-min intervals several times throughout the hour to check chart speed and at 5-min intervals to record the time. On multilane freeways only two lanes were studied at one time.

PRELIMINARY ANALYSIS

The preliminary analysis consisted of calculating and recording the time spacings, volumes, classifications, and speeds observed. These data were recorded on punch cards for use in computer analysis. It was found necessary to apply a paper speed factor to correct for day-to-day variation in chart speed on the spring-wound recorder.

Two breakdowns of these data were then made. The first breakdown was simply a calculation of the hourly volumes observed, the 15-min volumes observed, and the 5-min volumes observed for each lane at each study site. The volumes for the 5-min periods were further broken down into the different vehicle classifications and the average speed and speed ranges were calculated for the 5-min periods.

CLUSTER ANALYSIS

The basic method of analysis for this report is the cluster analysis. The theory behind the cluster analysis is that capacity flows are being approached on any actual highway when the driver of a vehicle begins to feel restricted by the vehicles around him.

The second breakdown of the field data, therefore, consisted of picking "clusters" from these data and calculating the cluster value. A cluster was defined as a group of three or more vehicles of the same type with a time headway between individual vehicles of 0.0020 hr (approximately 7 sec) or less. An average speed was calculated for each cluster and a location code was recorded so that the study site, lane number, date, and 5-min interval in which the cluster appeared could be readily determined. The cluster values were sorted into various speed ranges.

The cluster value is simply the expansion of a cluster volume to an hourly volume rate. This is calculated by

$$V_k = \frac{(N-1)\ (10{,}000)}{ft} \quad (1)$$

in which

V_k = cluster value in vehicles per hour;
N = number of vehicles per cluster;
f = factor to correct for variations in chart speed on the spring-wound recorder;
t = time spacing in 0.0001's hour (i.e., the time spacing from the front axle of the first vehicle in the cluster to the front axle of the last vehicle in the cluster); and
10,000 = factor to convert to a full hour.

For example, if a cluster consisted of three automobiles and the distance from the front axle of the first to the front axle of the second measured in units of time was 0.0011 hr; and if the time spacing between front axles of the second and third vehicles was 0.0009 hr; and if the chart paper was moving at exactly 10 in./min, the f-factor is 1.0.

In this example, then

N = 3
f = 1.0
t = 9 + 11 = 20 (i.e., a cumulative time spacing of 20 measured in units of ten-thousandths of an hour)

$$V_k = \frac{2\ (10{,}000)}{1.0\ (20)} = \frac{20{,}000}{20}$$

V_k = 1,000 vehicles per hour

The cut-off point of 0.0020 hr is that time headway frequently used in driver behavior studies as the point where the speed of a vehicle is affected by the speed of the vehicle preceding it. The Manual (1, p. 39) shows the critical spacing to be 9 sec or 0.0025 hr. For purposes of the cluster analysis, the use of 0.0020 hr instead of 0.0025 hr produced no significant differences in the results, and also was more conservative, establishing more certain clusters. Therefore, it was used throughout for greater ease in the manual calculations and checks.

It was assumed that the factors in Table 8 of the Manual (1, p. 54) could be applied to all types of vehicles. This table gives the means to correct for the effect of lateral restrictions and lane width; thus, the cluster data are adjusted to represent traffic on a 12-ft lane with no lateral restrictions. Once this adjustment is made, the main factors that are left to affect the driver of a vehicle are the vehicle ahead and the vehicle behind. The effect of these vehicles can be measured in terms of time headway.

It was previously mentioned that the cluster values were sorted into speed ranges. Within any particular speed range there was a distribution of cluster values. Therefore, if cluster values were averaged within any speed range (speed grouping), the average cluster value for that speed grouping would represent the maximum volume that could be expected to pass a point in one hour's time at the average speed represented by that speed grouping.

For example, if there were 49 bus clusters recorded traveling in the speed range of 28-32 mph; and if the average of the 49 cluster values was calculated to be 1,300 buses/hr it was assumed that a lane carrying 100 percent buses would have a maximum volume of 1,300 buses/hr when the average speed was approximately 30 mph.

It was felt that the average cluster values should be limited to an accuracy of ±150 vph within any speed range. To effect this the 95 percent confidence interval was calculated using the standard "t" distribution for each average cluster value and, if the confidence interval was >±150 vph, that average cluster value was considered to be "not statistically significant" and discarded. In other words, under capacity conditions on a 12-ft lane with no lateral restrictions, the volume rates presented in this paper ±150 vph should be actually observed at least 95 times out of 100.

Speed Range Volumes

The same correction factors (i.e., for lateral restrictions and lane widths) were applied to the speed volume groupings. There were three stages of these groupings: (a) all 5-min periods without commercial vehicles, except for buses (thereby eliminating the effect of trucks as a variable), were sorted into speed groups, and 5-min volumes were expanded to an hourly volume rate which was plotted according to speed grouping, the plots presenting bus vs auto volumes; and (b and c) similar graphs of the peak 5-min periods and the peak hour values were plotted except that trucks were included and converted to equivalent auto volumes by truck equivalency factors (1).

Results of Analysis

As previously mentioned, the cluster analysis was the basic method of analysis. It was assumed that the highest average cluster value at any given location would represent the values approaching possible capacity of the facility being studied. When these values are adjusted to compensate for the reduction in capacity due to lane width and lateral restrictions, the highest adjusted average cluster values represent possible capacity of an "ideal" roadway.

Possible capacity, as defined (1), represents the highest volume reached on a given facility, regardless of the speed at which this volume occurs. In this report separate capacity values are reported for each of the several speed ranges analyzed; each refers to the maximum hourly volume that can be expected within that speed range. Possible capacity would be the highest of these several maximums.

Although each study site initially was analyzed separately, only the analysis of all sites combined is discussed in this report.

Table 1 gives the unadjusted average cluster values for automobiles which were calculated for the seven locations studied, the 95 percent confidence limits, and whether or not these values were considered statistically significant. The values given in Table 1 are not adjusted to correct for lane width and lateral restrictions. The unadjusted average cluster values for automobiles are not significant above the 48- to 52-mph speed range.

Table 2 gives the unadjusted data calculated for bus clusters. There were no bus clusters recorded at speeds in excess of 52 mph. The unadjusted average cluster values for buses were not considered statistically significant above the 38- to 42-mph speed range. Tables 3 and 4 give the values presented in Tables 1 and 2, respectively, adjusted to 12-ft lane widths with no lateral restrictions.

The primary product of this study, the bus equivalent (or ratio of automobile capacities to bus capacities in terms of vehicles per hour) is given in Table 5. This ratio ranges from 1.52 to 1.64 and it indicates that a bus uses the same amount of space on one

TABLE 1

UNADJUSTED AVERAGE CLUSTER VALUES (AUTOS)

Speed Range (mph)	Unadjusted Average Cluster Value, Autos (vph)	95% Confidence Limits (vph)	Statistically Significant
13-17	1,448	± 38	Yes
18-22	1,690	± 36	Yes
23-27	1,844	± 36	Yes
28-32	1,885	± 45	Yes
33-37	1,858	± 48	Yes
38-42	1,756	± 43	Yes
43-47	1,726	± 53	Yes
48-52	1,734	± 88	Yes
53-57	1,705	± 175	No
58-62	1,570	± 406	No
63-67	1,426	± 1,003	No

TABLE 2

UNADJUSTED AVERAGE CLUSTER VALUES (BUSES)

Speed Range (mph)	Unadjusted Average Cluster Values, Buses (vph)	95% Confidence Limits (vph)	Statistically Significant
13-17	936	± 65	Yes
18-22	1,043	± 68	Yes
23-27	1,011	± 70	Yes
28-32	1,122	± 98	Yes
33-37	1,116	± 113	Yes
38-42	1,071	± 122	Yes
43-47	1,198	± 311	No
48-52	1,343	± 293	No
53-57	—[a]	—	No
58-62	—[a]	—	No
63-67	—[a]	—	No

[a]Not recorded.

TABLE 3

AVERAGE ADJUSTED CLUSTER VALUES (AUTOS)

Speed Range (mph)	Average Adjusted Cluster Values, Autos (vph)	95% Confidence Limits (vph)	Statistically Significant
13-17	1,737	± 43	Yes
18-22	1,932	± 38	Yes
23-27	2,045	± 36	Yes
28-32	2,039	± 47	Yes
33-37	1,940	± 50	Yes
38-42	1,832	± 45	Yes
43-47	1,797	± 56	Yes
48-52	1,817	± 95	Yes
53-57	1,770	± 184	No
58-62	1,628	± 403	No
63-67	1,561	± 1,157	No

TABLE 4

AVERAGE ADJUSTED CLUSTER VALUES (BUSES)

Speed Range (mph)	Average Adjusted Cluster Values, Buses (vph)	95% Confidence Limits (vph)	Statistically Significant
13-17	1,146	± 69	Yes
18-22	1,245	± 76	Yes
23-27	1,227	± 77	Yes
28-32	1,280	± 104	Yes
33-37	1,238	± 123	Yes
38-42	1,177	± 131	Yes
43-47	1,311	± 317	No
48-52	1,463	± 333	No
53-57	_[a]	—	—
58-62	_[a]	—	—
63-67	_[a]	—	—

[a]Not recorded.

TABLE 5

SPEED RANGE CAPACITIES

Speed Range (mph)	Speed Range Capacity (vph/lane)		Bus Equiv. Factor
	Autos	Buses	
13-17	1,750	1,150	1.52
18-22	1,950	1,250	1.56
23-27	2,050	1,250	1.64
28-32	2,050	1,300	1.58
33-37	1,950	1,250	1.56
38-42	1,850	1,200	1.55
43-47	1,800	_[a]	—
48-52	1,800	_[a]	—

[a]Not statistically significant.

TABLE 6

ROUNDED SPEED RANGE CAPACITIES

Speed (mph)	Highest Hourly Volume Expected, by Lane	
	100% Autos	100% Buses
15	1,750	1,100
20	1,950	1,200
25	2,050	1,300
30	2,050	1,300
35	1,950	1,200
40	1,850	1,150
45	1,800	1,100
50	1,800	1,100

lane of a highway as 1.52 to 1.64 automobiles would use. From this range, a bus equivalency factor of 1.6 was selected as a reasonably conservative general value. Because the sample sizes of the automobile clusters were much larger than the sample sizes of the bus clusters, the 95 percent confidence intervals for the automobile clusters were less than the 95 percent confidence intervals for the bus clusters; therefore, the automobile cluster values were used as a base and the equivalency factor of 1.6 was applied to this base. Table 6 gives the result of these calculations. The bus equivalency factor of approximately 1.6 was found to be constant for all facilities and for breakdown by lanes.

In Table 6, the possible capacity of a 12-ft lane carrying buses only is found to be 1,300 buses/hr. Similarly, the capacity of a 12-ft lane carrying automobiles only is found to be 2,050 auto/hr.

Originally ± 150 vph was established as the maximum allowable confidence interval; examination of Tables 3 and 4 shows that the maximum 95 percent confidence interval used for automobiles was actually ± 95 vph and the maximum interval for buses was ± 131 vph.

Therefore, it is safe to assume that at capacity flow, on a 12-ft lane with no lateral restrictions, the volume rates presented in Table 6, ± 150 vph, should be observed at least 95 times out of 100. It is also valid to assume that the volumes given in Table 6 will be observed much more often than the outer limit volumes, and the average volumes of any random nationwide sampling of volumes will be very close to those given in Table 6.

Incidentally, the cluster analysis further verifies many previous studies which have reported that the true possible capacity of most highways is achieved somewhere between 25 and 30 mph. The highest volumes that can be expected to be found within each of the different speed ranges, as determined by the cluster analysis, are given in Table 5. These volumes have been rounded to the nearest 50 vph.

Using the bus equivalency factor of 1.6, it is possible to calculate the effect of buses on the capacity of a lane on a free-

TABLE 7

SPEED RANGE CAPACITIES – AVERAGE LANE VOLUMES
MIXED AUTO-BUS TRAFFIC

Percentage of Buses	Capacity Factor	Volume Rate of Auto-Bus Mixed Traffic (vph) at						
		15 Mph	20 Mph	25 Mph	30 Mph	35 Mph	40 Mph	45 Mph
0	1.000	1,750	1,950	2,050	2,050	1,950	1,850	1,800
5	0.971	1,700	1,890	1,990	1,990	1,890	1,800	1,750
10	0.943	1,650	1,840	1,930	1,930	1,840	1,750	1,700
15	0.917	1,600	1,790	1,880	1,880	1,790	1,700	1,650
20	0.893	1,560	1,740	1,830	1,830	1,740	1,650	1,600
25	0.870	1,520	1,700	1,780	1,780	1,700	1,610	1,570
30	0.847	1,480	1,650	1,740	1,740	1,650	1,570	1,530
35	0.826	1,460	1,610	1,690	1,690	1,610	1,530	1,490
40	0.806	1,410	1,570	1,650	1,650	1,570	1,490	1,450
45	0.787	1,380	1,540	1,610	1,610	1,540	1,460	1,420
50	0.769	1,350	1,500	1,580	1,580	1,500	1,420	1,380
55	0.752	1,320	1,470	1,540	1,540	1,470	1,390	1,350
60	0.735	1,290	1,430	1,510	1,510	1,430	1,350	1,320
65	0.719	1,260	1,400	1,470	1,470	1,400	1,330	1,290
70	0.704	1,230	1,370	1,440	1,440	1,370	1,300	1,270
75	0.690	1,210	1,340	1,420	1,420	1,340	1,280	1,240
80	0.676	1,180	1,320	1,390	1,390	1,320	1,250	1,220
85	0.662	1,160	1,290	1,360	1,360	1,290	1,230	1,190
90	0.649	1,140	1,270	1,330	1,330	1,270	1,200	1,170
95	0.637	1,120	1,240	1,310	1,310	1,240	1,180	1,150
100	0.625	1,100	1,200	1,300	1,300	1,200	1,150	1,100

way. This is given in two ways in Table 7: The first is the calculation of a capacity factor for any percentage of buses (this is shown in increments of five percent in the first two columns); the second is the calculation of volume rates of mixed traffic consisting of buses and autos.

The speed range capacity figures given in Tables 6 and 7 are average lane values. When the cluster analysis is made by lanes, different capacity values are found for each lane. Speed range capacities for individual lanes are given in Table 8. The volumes given are for a traffic flow consisting of 100 percent automobiles. These volumes can be divided by the bus equivalency factor of 1.6 to calculate the capacity of a lane carrying 100 percent buses. This can be done because the equivalency factor remained at approximately 1.6 when the cluster values for individual lanes were computed.

The four-lane-divided highway is represented by the two lanes of the center tube of the Lincoln Tunnel inasmuch as this is the only site studied with only two lanes in one direction; therefore, although these values have been adjusted to the standard 12-ft lane with no lateral restrictions, they may not be considered representative of the nation as a whole. However, the highest statistically significant adjusted cluster volume rate recorded in the tunnel is 2,000 equivalent passenger cars in lane 2 at 25 mph, which is the value given as possible capacity in the Manual (1).

From the available data, it appears that the addition of a third lane actually increases the capacity of the median lane. The possible capacity of lane 3 (the median lane) appears to be 2,350 vph at 35 mph, while the possible capacity of both lanes 1 and 2 is 2,100 vph at 25 mph. Although insufficient data were collected in this study to substantiate the fact, it seems reasonable to assume that on an eight-lane-divided highway, lanes 1 and 4 would carry volumes calculated for lanes 1 and 3 from Table 8, and volumes for lanes 2 and 3 would be the same as those calculated for lane 2 in the same table.

TABLE 8

SPEED RANGE CAPACITIES BY LANE
(ADJUSTED CLUSTER VALUES-VPH)

Speed (mph)	Divided Highway				
	Two Lanes One Direction		Three Lanes One Direction		
	Lane 1	Lane 2	Lane 1	Lane 2	Lane 3
15	1,900	1,650	1,650	1,700	1,800
20	1,950	1,850	1,900	1,900	2,050
25	1,900	2,000	2,100	2,100	2,050
30	–	–	1,950	2,000	2,200
35	–	–	1,900	1,850	2,350
40	–	–	1,600	1,850	2,150

OPERATIVE VOLUME

The preceding analysis has described the volume limits for the several speed ranges; these values have been defined as the speed range capacities. The speed range capacities may be considered as the maximum or "possible" free-flow capacity at a certain speed. Because the speed range capacity is the maximum hourly volume that can be obtained at a certain speed, it may be considered the volume rate of impending congestion.

It appeared desirable to investigate also operation under more clearly free-flow conditions. By definition and through use of ogive curves showing the distribution of volume rates within a speed range, it was possible to develop an "operative volume" for a speed range.

The operative volume is that cluster volume rate within a speed range which was exceeded by 50 percent of the observed clusters. The 50th percentile volume was arbitrarily chosen. It was assumed that if 50 percent of the drivers are willing to travel at a spacing closer than that required to attain the operative volume, then the operative volume is a volume rate at which a freeway lane should operate indefinitely without danger of congestion setting in. Operative volumes can be calculated for every speed range. However, it was assumed that operating speeds below 30 mph are not desirable on multilane highways; therefore, the operative volumes were calculated for speeds ranging from 30 to 45 mph at 5-mph increments. Figures 1 and 2 show the ogive curves for the various speed ranges. The fiftieth percentile of each curve is the operative volume for the speed range it represents. These values are shown in Table 9.

Table 9 gives the average cluster values divided by the 50th percentile volumes resulting in a ratio ranging from 1.1 to 1.3 for both buses and autos. The ratio of 1.25 was selected for calculating the operative volumes. The speed range volumes previously calculated were divided by 1.25 to arrive at the operative volumes given in Table 9.

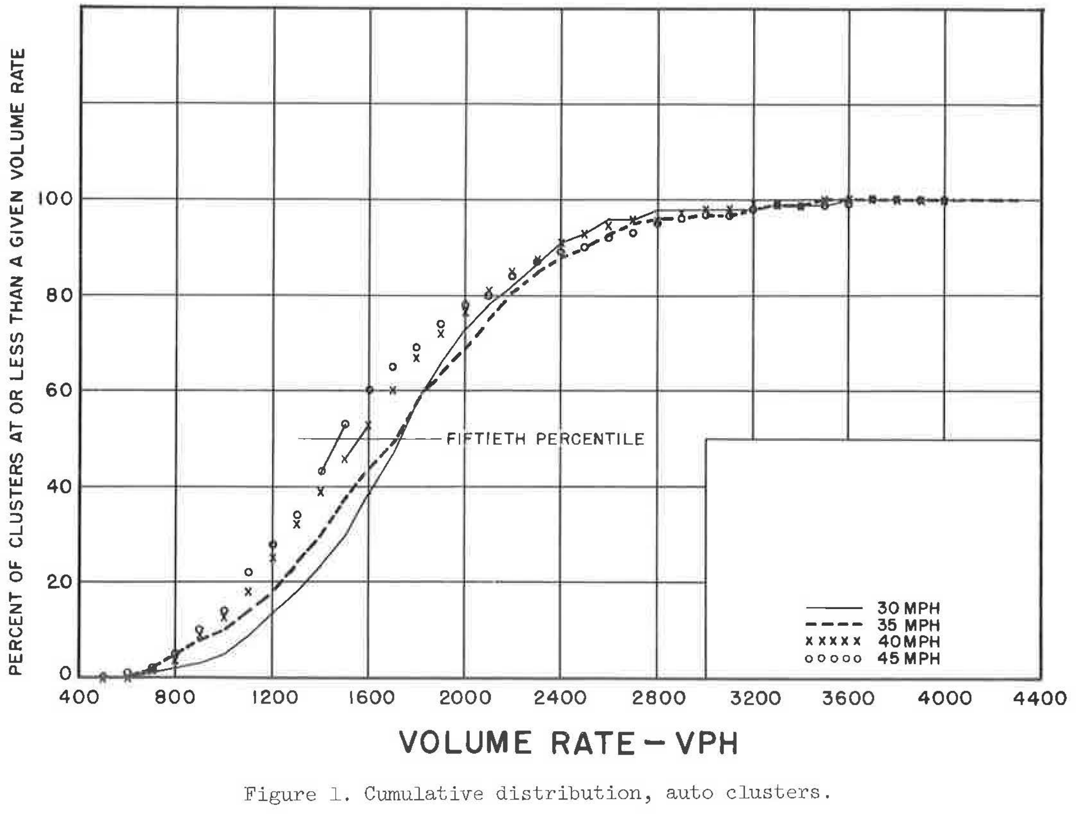

Figure 1. Cumulative distribution, auto clusters.

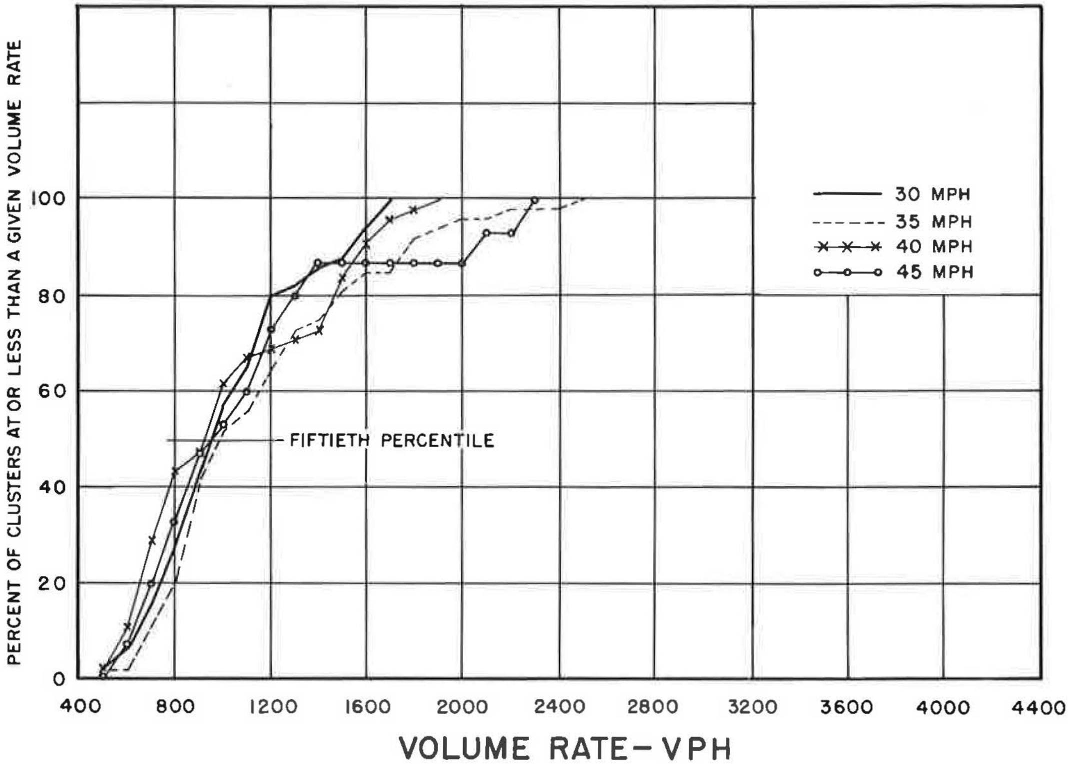

Figure 2. Cumulative distribution, bus clusters.

TABLE 9

COMPARISON OF OPERATIVE VOLUMES WITH SPEED RANGE VOLUMES

Speed Range (mph)	Volume from Ogive Curve, A (vph)	Average Cluster Value, B (vph)	Ratio B/A	Speed (mph)	Average Speed Range Capacity (vph)	Calculated Operative Volume (vph)
			(a) Autos			
28-32	1,720	2,050	1.2	30	2,050	1,640
33-37	1,710	1,950	1.1	35	1,950	1,560
38-42	1,560	1,850	1.2	40	1,850	1,480
43-47	1,470	1,800	1.2	45	1,800	1,440
			(b) Buses			
28-32	950	1,300	1.3	30	1,300	1,040
33-37	980	1,250	1.3	35	1,200	960
38-42	920	1,250	1.3	40	1,150	920
43-47	—	—	—	45	1,100	880

Additional calculations, somewhat incidental to the main purpose of this report, were made to determine the average densities, the standard deviations of the cluster volume rates, and the spacings in each of the speed ranges. Figures 3, 4 and 5 show the relationship of each of these values with speed. It should be noted that the spacings shown in Figure 5 include the length of the vehicle, thus the spacing shown is actually the average distance in feet from the front axle of a following vehicle to the front axle of the vehicle preceding it.

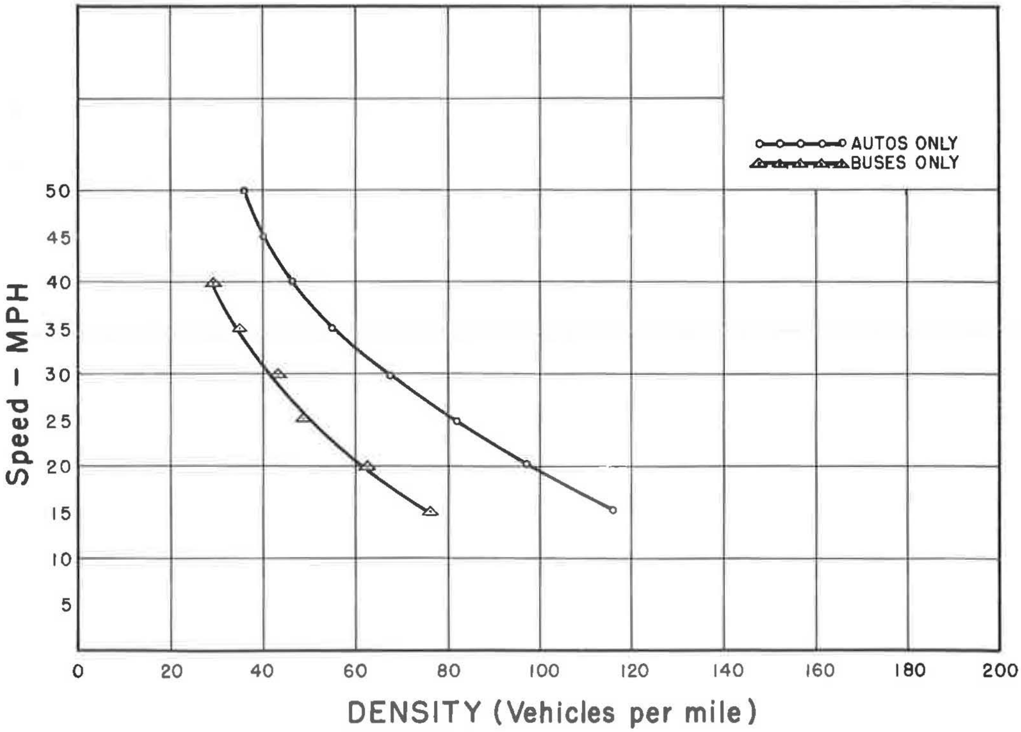

Figure 3. Speed-density relationships, cluster analysis.

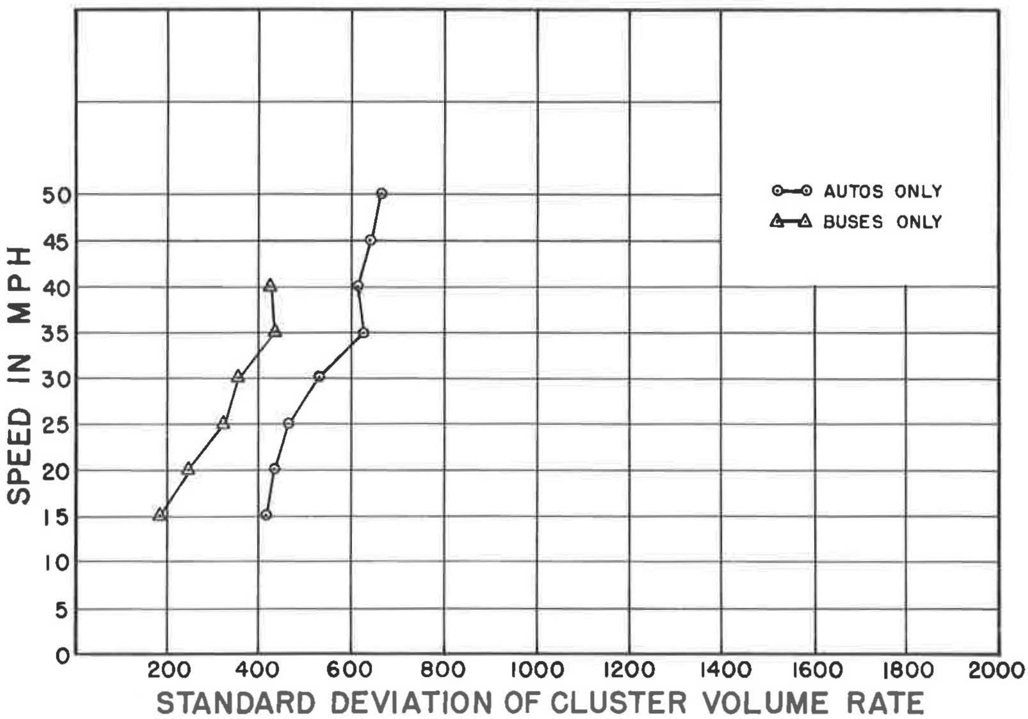

Figure 4. Speed-standard deviation relationship, cluster analysis.

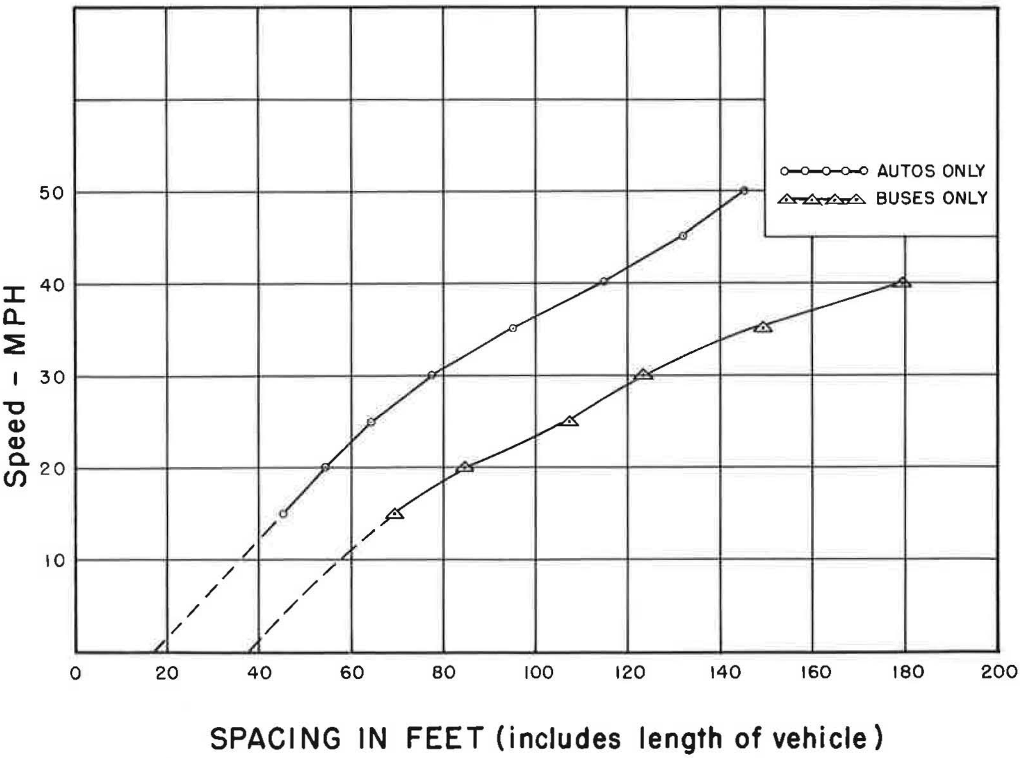

Figure 5. Speed-spacing relationships, cluster analysis.

SPEED RANGE VOLUME ANALYSIS

It was previously mentioned that the speed range volume analysis consisted of sorting the peak hour volumes, the peak 5-min period volumes, and the volumes for every 5-min period studied (omitting those 5-min periods which contained trucks) into speed ranges; each speed grouping was then plotted separately in a series of graphs in an effort to determine a bus equivalency factor independently from the cluster analysis and, in so doing, to check the validity of the cluster analysis.

The results of this analysis indicate that the bus equivalency factor may be taken as 1.6 and comparison of these results with those of the cluster analysis indicates that the cluster analysis is indeed a valid method of computing capacities.

The comparison of the results of the two different methods of computation has been made in two ways. The first method consists of converting the observed volumes to equivalent auto volumes using the bus equivalency factor of 1.6 which has been derived in this study and the truck equivalency factors which are given in the Highway Capacity Manual.

For example, if a lane in level terrain carried 1,000 autos, 250 buses, and 200 trucks, the equivalent auto volume would be 1,000, 400, and 400 autos/hr, respectively. The total equivalent auto volume carried is the sum of these volumes or 1,800 equivalent autos/hr.

The second method of comparison is the plotting of bus volume vs auto volume on graphs for each speed range as described earlier in this report.

The highest peak hour values, in terms of equivalent autos, are given in Table 10 and the average cluster values are given for purposes of comparison. If the limit of ± 150 vph is used as the 95 percent confidence interval, it can be seen (Table 10) that for the highest peak hour volumes recorded, only two exceeded these limits. These were the values for lane 2 at 25 mph and 40 mph on the 6-lane highway. The 2,300 vph

TABLE 10

HIGHEST PEAK HOUR VALUES PER SPEED RANGE COMPARED WITH AVERAGE CLUSTER VALUES

Speed (mph)	Equivalent Auto Volume			Volume as Computed by the Cluster Analysis		
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
	4-Lane-Divided Highway					
15	1,810	1,754	–	1,900	1,650	–
20	1,797	1,491	–	1,950	1,850	–
25	1,904	N. R.	–	1,900	2,000	–
	6-Lane-Divided Highway					
15	–[a]	–[a]	–[a]	1,650	1,700	1,800
20	1,311	–[a]	–[a]	1,900	1,900	2,050
25	1,768	2,300	1,954	2,100	2,100	2,050
30	1,469	1,508[b]	1,629	1,950	2,000	2,200
35	1,875	1,943	N. R.	1,900	1,850	2,350
40	1,408	2,278	2,124	1,600	1,850	2,150

[a]Not recorded.
[b]Accident occurred during this hour.

TABLE 11

TWENTY HIGHEST BUS PEAK HOURS COMPARED WITH CLUSTER VALUES

Bus Vol.	Auto Vol.	Truck Vol.	Truck Vol. in Equiv. Autos	Auto Vol. plus Equiv. Truck Vol.	Adjusted Bus Vol.	Adjusted Auto plus Equiv. Truck Vol.	Avg. of Avg. Speeds	Speed Group	Bus Vol. in Speed Group Equiv. Autos	Total Equiv. Autos	Vol. as Calculated by the Cluster Analysis
213	1,012	130	520	1,532	236	1,700	23.0	25	378	2,078	2,100
273	1,251	8	32	1,283	303	1,424	25.5	25	485	1,727	2,050
337	835	1	4	839	438	1,091	18.3	20	701	1,792	1,950
169	860	4	16	876	220	1,139	17.6	20	352	1,491	1,850
351	815	5	10	826	456	1,094	16.6	15	730	1,804	1,900
176	1,066	0	0	1,066	229	1,386	14.6	15	366	1,752	1,650
209	963	137	548	1,511	232	1,677	22.8	25	371	2,048	2,100
260	1,170	7	28	1,198	289	1,330	25.5	25	462	1,792	2,050
122	910	96	192	1,102	135	1,223	23.8	25	216	1,439[a]	2,100
224	917	20	40	957	249	1,062	20.6	20	398	1,460[a]	2,050
223	1,007	129	516	1,523	250	1,691	24.2	25	413	2,104	2,100
251	1,316	4	16	1,332	279	1,479	24.2	25	446	1,925	2,050
141	1,408	64	128	1,536	157	1,705	41.5	40	251	1,956	1,850
291	1,400	17	34	1,434	323	1,592	40.8	40	517	2,109	2,150
117	1,121	0	0	1,121	118	1,132	37.8	40	189	1,321	1,850
247	8	0	0	8	274	9	26.9	25	438	447	1,300[b]
226	12	0	0	12	251	13	39.0	40	402	415	1,150[b]
196	478	227	454	932	218	1,035	31.9	35	349	1,384	1,900
243	10	0	0	10	270	11	39.3	40	432	443	1,150[b]
163	580	170	340	920	181	1,021	19.0	20	290	1,311	1,900

[a]Major stoppage occurred during this hour.
[b]Values calculated for separate bus lane at speeds given.

recorded at 25 mph is 200 vph more than the average cluster value for that speed range and the 2,278 vph recorded at 40 mph is 428 vph more than the average cluster value for that range. The remainder of the volumes fall either reasonably close to the average cluster value (i.e., within the ± 150 vph confidence interval) or the values are so low that the roadway cannot be considered to have been handling close to possible capacity at the time of the study.

Peak hour volumes using buses per hour per lane as the controlling factor rather than vehicles per hour per lane were also calculated. The 20 highest bus peak hours are given in Table 11.

The highest observed hourly volume for buses per lane occurred in the center tube of the Lincoln Tunnel with volumes of 351 buses/hr, 816 autos/hr and 5 trucks/hr. When these values are adjusted to compensate for lane width and lateral restrictions, they amount to 456 buses/hr, 1,074 autos/hr, and 7 trucks/hr or an equivalent of 1,804 autos/hr. During the same hour, the adjoining lane carried 176 buses/hr, 1,066 autos/hr and no trucks. When these values are adjusted for lane width and lateral restrictions, the volumes become 229 buses/hr and 1,386 autos/hr or an equivalent automobile volume of 1,752 vph. The average speeds within this hour were in the 15-mph range. Thus the adjusted hourly volumes are 1,804 vph and 1,752 vph compared to 1,750 vph, the average cluster value calculated for the combined seven study locations by the cluster analysis, or to 1,900 vph and 1,650 vph calculated for the by-lane breakdown for the tunnel.

The value of 527 buses/hr is also the highest hourly bus volume that was observed on any roadway in the country in this study.

The separate bus lane on the San Francisco-Oakland Bay Bridge, which did not operate at close to capacity volumes, had peaks of 247 buses/hr at an average speed of 25 mph, and of 243 buses/hr at 40 mph. Three different locations on the exclusive bus lane were studied: one near the beginning of the lane, one near the middle, and one close to the end of the lane. The average speed of 25 mph was recorded at the site close to the beginning of the exclusive lane. At this site the buses had not yet accelerated to the 40-mph average speed observed at the other two locations.

It was difficult to get accurate hourly comparisons mainly because of the method of calculating the average speeds over a full hour. The average speeds used for purposes of comparison were simply the average of all speed samples taken during the hour. It was not possible to get a speed for each individual vehicle during the course of the study. Also, the average speeds do not reflect the effect of stoppages because speed samples were not taken when the cars were stopped; thus there are no 0-mph speeds included in the averages. Even with these built-in inaccuracies, most of the peak hour volumes compare favorably with the average cluster values that would be achieved if the speeds retained a fair degree of homogeneity throughout the hour.

The peak 5-min periods in terms of vehicles per hour were also calculated and compared with the cluster values. These peak 5-min periods were converted to equivalent auto volumes as the hourly volumes were. All 5-min values were expanded to hourly rates, as previously mentioned. Table 12 gives the highest peak 5-min periods for each speed range.

In Table 12 the 21 peak periods shown are the highest peak 5-min period shown in each speed range. Six of the values are higher than the upper limit of the 95 percent confidence intervals. Because 1,022 different 5-min periods were included in this analysis, it can be expected that many of them should fall outside of the 95 percent confidence intervals.

All 5-min periods which did not contain any trucks were plotted with auto volume vs bus volume and these values were compared with the limiting volumes calculated with the bus equivalency factor derived from the cluster analysis. Figures 6 through 10 show samples of these graphs. Separate graphs have been plotted for each lane in every speed range for both 4-lane and 6-lane-divided highways and are fairly good examples of how the observed volumes compared with the calculated cluster values. The solid line in each graph represents the speed range capacity in terms of mixed bus and auto traffic as calculated from the cluster analysis. The

TABLE 12

HIGHEST PEAK 5-MIN PERIOD IN A SPEED RANGE

Speed (mph)	Equivalent Auto Vol.			Vol. as Computed by Cluster Analysis		
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
(a) 4-Lane-Divided Highway						
15	_a	1,875	–	1,900	1,650	–
20	1,901	_a	–	1,950	1,850	–
25	1,856	1,938	–	1,900	2,000	–
(b) 6-Lane-Divided Highway						
15	_a	1,899	_a	1,650	1,700	1,800
20	1,676	2,510	2,097	1,900	1,900	2,050
25	1,958	2,105	2,105	2,100	2,100	2,050
30	2,031	1,869	_a	1,950	2,000	2,200
35	2,013	2,421	2,323	1,900	1,850	2,350
40	1,444	1,977	2,321	1,600	1,850	2,150
45	1,549	2,229	_a	1,600	1,850	2,100

[a]Not recorded.

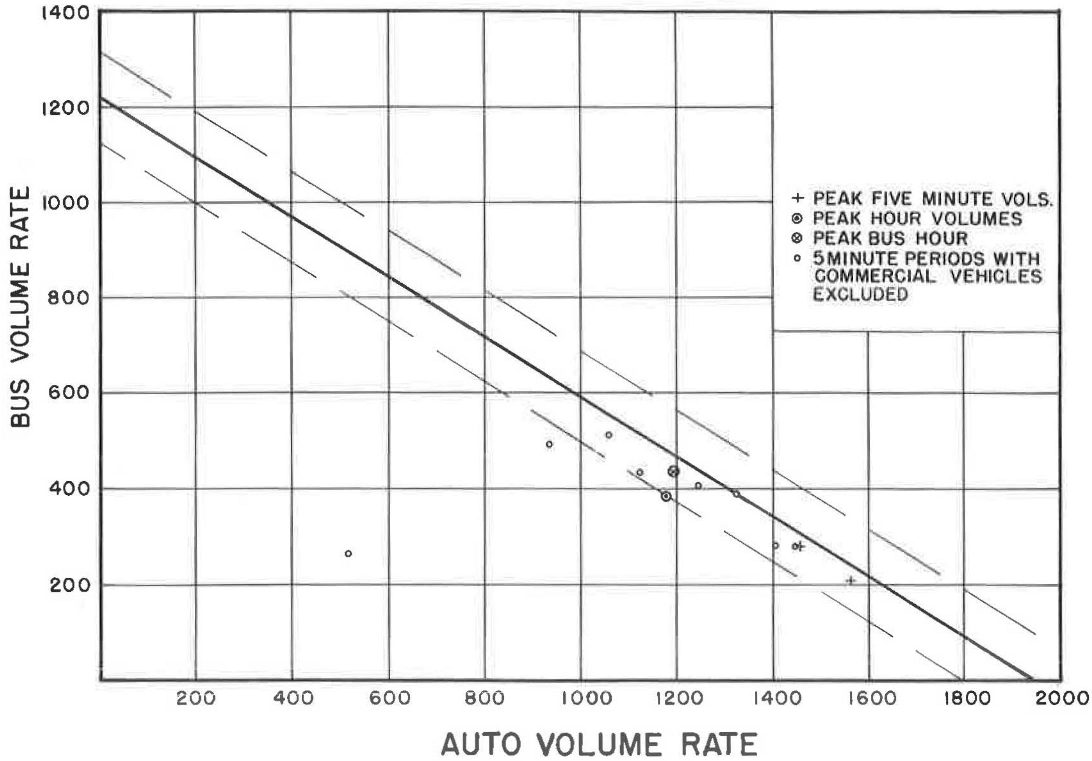

Figure 6. Auto vs bus volume, 4-lane divided, lane 1—20 mph.

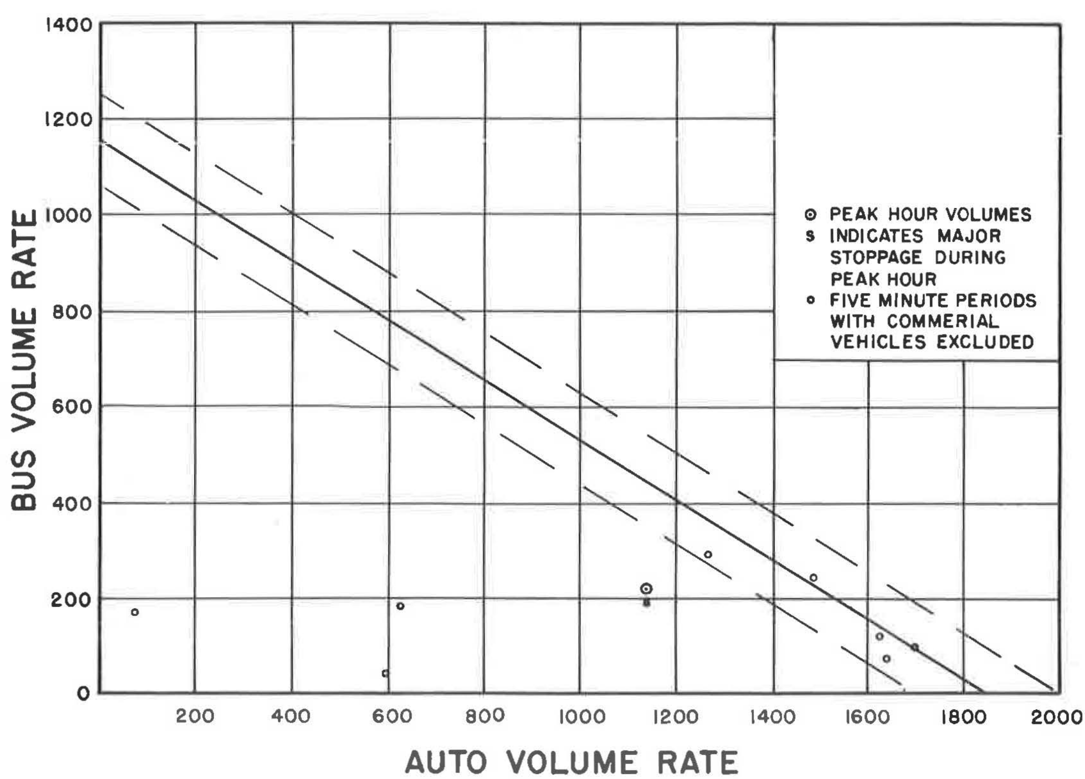

Figure 7. Auto vs bus volume, 4-lane divided, lane 2—20 mph.

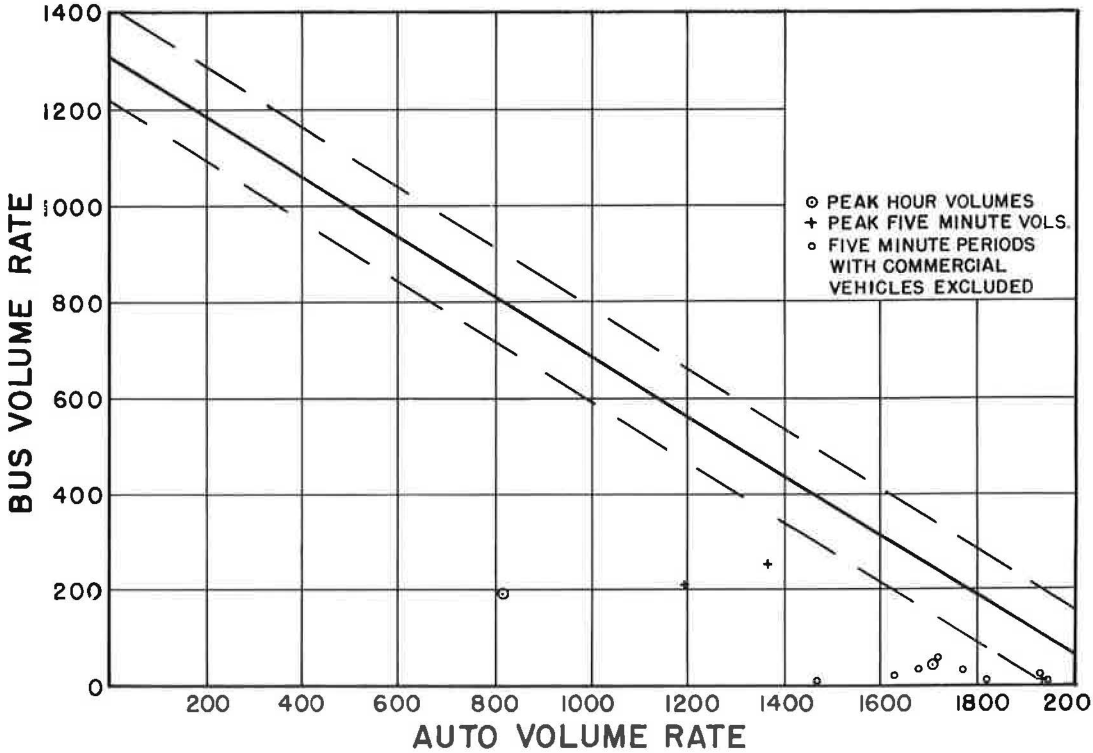

Figure 8. Auto vs bus volume, 6-lane divided, lane 1—25 mph.

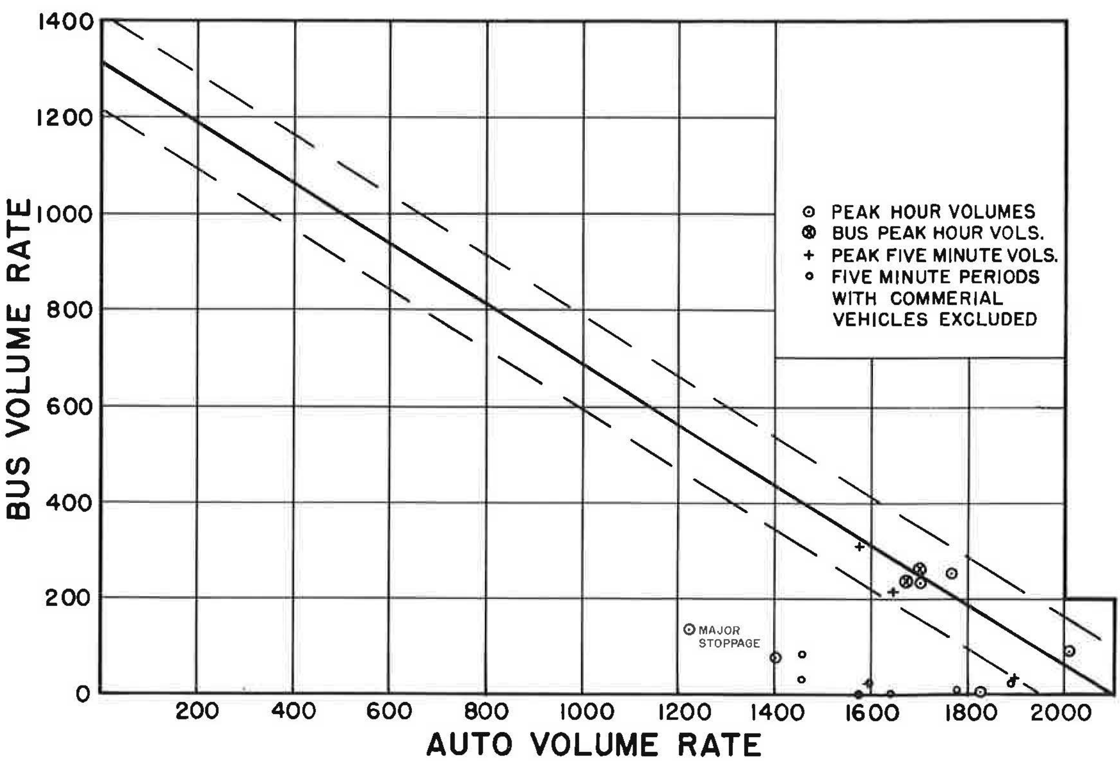

Figure 9. Auto vs bus volume, 6-lane divided, lane 2—25 mph.

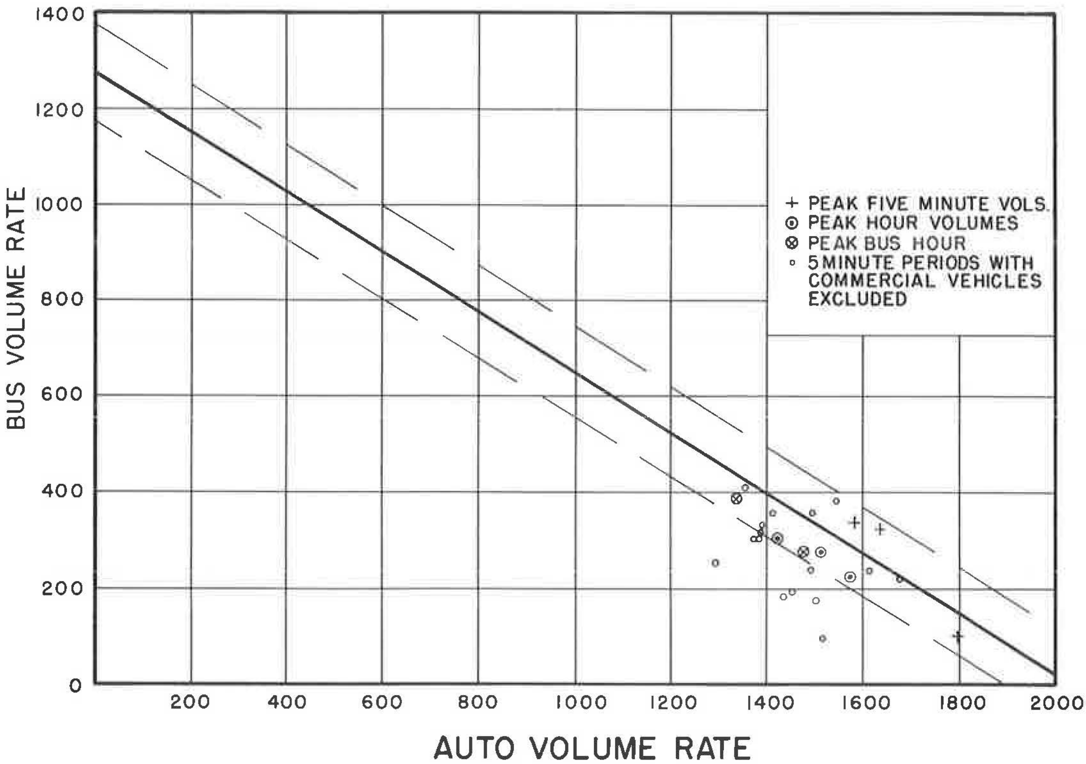

Figure 10. Auto vs bus volume, 6-lane divided, lane 3—25 mph.

dotted lines represent the ±150-vph limit set for the 95 percent confidence interval. The peak period values have also been added to these graphs for purposes of comparison.

For example, in Figure 10, the graph for lane 3 of a 6-lane-divided highway in the 25-mph average speed category (i.e., the 23- to 27-mph speed range), the solid line indicates that when the lane is operating at capacity it can carry 1,200 autos/hr plus about 530 buses/hr for a total of 1,730 vph. This can be calculated using the average cluster value previously derived for autos (2,050 autos/hr) and the bus equivalency factor of 1.6 for a traffic flow consisting of 30.7 percent buses and 69.3 percent automobiles. Similarly, every auto volume shown on the abscissa has a complementary bus volume shown on the ordinate axis. The two volumes added together give the total vehicles per hour (autos and buses) that can be carried by lane 3 of a 6-lane-divided highway at 25 mph. The points plotted on Figure 10 include two observed bus peak hour volumes, 3 peak hour volumes (where the peak was determined by the total number of vehicles—i.e., buses, autos, and trucks—and not by the bus peak hour), and several 5-min expanded volumes. It will be noted that all of the observed peak period volumes fall within the 95 percent confidence limits; none of the observed volumes exceeds the upper confidence limit; a scattering of 5-min periods fall below the lower confidence limit indicating that these particular 5-min periods were not carrying volumes approaching possible capacity. It should be noted that the slope of the theoretical capacity line appears to be correct, although for this graph the observed peak hour periods seem to indicate that possible capacity of this lane should be reduced from 2,050 autos/hr to 2,000 autos/hr at 25 mph. All observed volumes have been adjusted to 12-ft lanes with no lateral restrictions; the observed peak period volumes include some trucks which have been converted to equivalent autos as described previously.

Figures 6 through 10 are fairly representative of the speed range volume graphs which were plotted. However, in the higher speed ranges a large number of the random non-peak 5-min volumes which were plotted were below the lower limit of the confidence interval. In almost all of the cases the volumes were so low that it was obvious the roadway was not carrying close to possible capacity at that particular time. The number of observed volumes higher than the upper limit of the 95 percent confidence interval was no more than could be reasonably expected.

SUMMARY AND CONCLUSIONS

The following results have been derived from this study:

1. The bus equivalency factor for a bus on a reasonably level freeway may be taken as 1.6 regardless of which lane it is in or the speed at which it is traveling.
2. It is possible to determine the capacity of a lane through use of cluster analysis. The term capacity is used here as the maximum volume within a speed range.
3. The possible capacity of an exclusive bus lane is 1,300 buses/hr per lane at 25 and 30 mph. Actually, on a multilane highway, if lane 1 (the right shoulder lane) is designated as the separate bus lane, the possible capacity would be 1,300 buses/hr at 25 mph, if lane 2 is chosen, possible capacity is 1,300 buses/hr at 25 mph, and, if lane 3 is selected, possible capacity is 1,450 buses/hr at 35 mph.
4. Operative volumes may be taken as approximately 80 percent of the speed range capacities as derived from the cluster analysis.
5. The maximum number of buses actually observed on any of the roadways studied in a 1-hr period was 527 buses/hr in the center, two-lane, tube of the Lincoln Tunnel. At the same time, the same roadway carried 1,882 automobiles and 5 tractor-semi-trailer trucks.

This study indicated that, in some instances, it may prove desirable to designate exclusive bus lanes on freeways. However, even if the maximum number of buses observed in this study on any roadway in the country (i.e., 527 buses/hr in the center tube of the Lincoln Tunnel) were put on a single lane, that lane would still appear capable of carrying at least 800 more automobiles with relatively little speed reduction in level terrain. In the author's opinion, it would seem, therefore, that an exclusive, continuous bus lane on a freeway would not prove practical unless:

1. The freeway was already operating beyond its practical capacity to the point of congestion.
2. There were at least 200 buses/hr using the lane during peak periods.

Where adverse grades exist, of course, bus climbing lanes might be desirable under other conditions.

This volume of 200 buses/hr appears to be a reasonable, lower-volume limit because on the typical 6-lane-divided freeway 200 buses/hr can carry at least 10,000 people/hr, more than equal to the capabilities of automobiles in two adjacent lanes, which would in all likelihood carry less than 8,000 people/hr. Such criteria, which would apply only to peak periods, would insure that a majority of the people using the freeway would not be affected by the congestion. (Vehicle occupancy counts were not made during this study, but it was noted that most of the buses observed carried a large percentage of standing passengers; with such loading, the percentage of commuters avoiding congestion would be even greater.) Strict enforcement, or physical separation to keep autos from traveling in the bus lane, would be required.

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