Variations in Flow at Intersections as Related to Size of City, Type of Facility and Capacity Utilization

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•BEFORE publication of the Highway Capacity Manual by the Department of Commerce in 1950, the Highway Capacity Committee of the Highway Research Board in cooperation with the State, county, and city highway departments, and the Bureau of Public Roads made the first comprehensive analysis of intersection capacities based on data gathered at about 250 locations scattered throughout the United States. The results of this study as published in the Manual have been the principal basis of capacity for intersection design. Certain factors developed through specific studies in various metropolitan areas have been made from time to time to modify the capacities as determined from the Manual. These so-called "city factors" generally increased the values for intersection capacities above those shown by the Manual, usually about 10 percent but sometimes as much as 20 percent. Design capacities as shown by the AASHO policies were being modified as much as 40 percent.

In 1956 the Bureau of Public Roads began gathering new information on traffic volumes through intersections in order to update the Manual. Far more comprehensive information was obtained during these studies than was obtained for the original intersection capacity analysis. Data for a total of 1,600 intersection approaches were recorded during periods of peak traffic flow. The data included a total of 43 variables at each location and permitted a far more comprehensive analysis than had previously been possible. A few of the more important variables not previously obtained included the degree to which the intersection was loaded, pedestrian volumes, and coordination with adjacent intersections. Also, studies at each location were continued for a period of at least 1½ hr and usually 2 hr so that the conditions immediately preceding the succeeding the peak-hour period would be known.

TERMINOLOGY

The following are the definitions of a few of the more important variables that were obtained and analyzed in this study, some for the first time:

Load Factor

The ratio between the total number of green phases that were fully utilized by traffic during the peak hour divided by the total number of green phases for that approach during the same period. This factor is a relative measure of the degree to which the capacity of the intersection approach under the prevailing conditions was utilized during the peak hour. A green phase was considered loaded if there were vehicles entering the intersection during the entire phase with no unused time or exceedingly long spacings between vehicles at the end of the phase due to a lack of traffic.

Peak-Hour Factor

The ratio between the number of vehicles entering the intersection during the peak hour divided by four times the number of vehicles entering the intersection during the peak 15-min period. The peak 15-min period was used because it is considered the shortest time interval on which an index of the variation in traffic flow during the peak hour may be based. Traffic flow through an intersection, from a capacity viewpoint, during a 15-min period is influenced to some extent by the flow during a preceding period but not to the extent that the flow during any shorter period is influenced by the flow during a preceding period. For example, traffic entering an intersection during a specific green phase can be influenced to a large degree by the traffic conditions during the preceding green phase. This is especially true if the preceding green phase included one or more right- or left-turning movements. Likewise, the flow during a 5-min period will be influenced to a large extent by traffic conditions during the preceding 5-min period. Over a 15-min period, however, these effects are diluted sufficiently so that it is possible for an intersection to accommodate four times as much traffic during an entire 1-hr period as it accommodates during the peak 15-min period, provided of course that there is sufficient traffic approaching the intersection to utilize fully the green phases during the entire hour. It can be shown that this is not true for individual cycles or for peak periods shorter than 15 min because many of the significant variables that periodically influence the flow of traffic are not likely to occur during the shorter periods.

Vehicles per Hour of Green

The rate of traffic flow during green signal phases for a specific intersection approach. The rate includes vehicles entering the intersection or completing their movements through the intersection during the amber periods. No study made to date indicates that a more accurate capacity analysis can be obtained by including all or a portion of the amber phase with the green phase. At locations where vehicles are permitted to enter during the entire amber period, an appropriate modification may be made in the application of the results of this analysis.

Figures 1 through 5 are examples of the type of information recorded at each of the 1,600 intersection approaches. They further clarify the definitions for the load factor, the peak-hour factor, and the vehicles per hour of green as a measure of traffic flow. In these figures, each cycle during the peak hour is represented by a vertical bar showing the number of vehicles that entered the intersection from that approach during the specific cycle. The vertical bars with the close crosshatching represent green phases of the traffic signal that were loaded or fully utilized by traffic entering the intersection. The white bars that do not have the close crosshatching represent green phases that were not fully utilized by traffic. For example, in Figure 1 there were 50 green phases that were fully utilized by traffic and 16 green phases that were not fully utilized. The load factor at this location during the peak hour was therefore 0.76 (50/66).

During the peak 15-min period (or in this case, during 14.4 min which represents 16 complete cycles of 54 sec each) a total of 367 vehicles entered the intersection from this one approach (Fig. 1). This is a rate of flow of 1,529 vehicles per hour or 2,759 vehicles per hour of green for the 30-sec green periods.

During the entire peak hour 1,427 vehicles entered the intersection from this approach. This is a rate of flow of 2,569 vehicles per hour of green. The peak-hour factor was therefore 0.93 (1,427 divided by 1,529 or 2,569 divided by 2,759). This approach handled 93 percent as much traffic during the peak hour as it would have handled if the flow for the entire hour was the same as it was during the peak 15-min period. During many of the green phases that were not fully loaded, more traffic entered the intersection than during some of the pahses that were fully loaded. Also, both the loaded and unloaded phases were well distributed throughout the hour. In fact, during the peak 15-min period (14.4 min) relatively fewer green phases were loaded than during the hour. It is believed, therefore, that the load factor and the peak-hour factor are two extremely important variables to consider in a study of intersection capacities as related to design. They provide a means for accounting for a large share of the difference in traffic flow at intersections with similar geometric design characteristics. The peak-hour factor is as important in studying short-time fluctuations in traffic flow as the 30th hour factor is in a study of seasonal and daily flucuations of traffic.

Figure 2 shows the same type of information as Figure 1, but for another approach. This approach also had two traffic lanes. In addition, Figure 2 shows whether both of the traffic lanes were loaded during each green phase. If both lanes were loaded during the green phase, the entire vertical bar is crosshatched. If only the right-hand lane

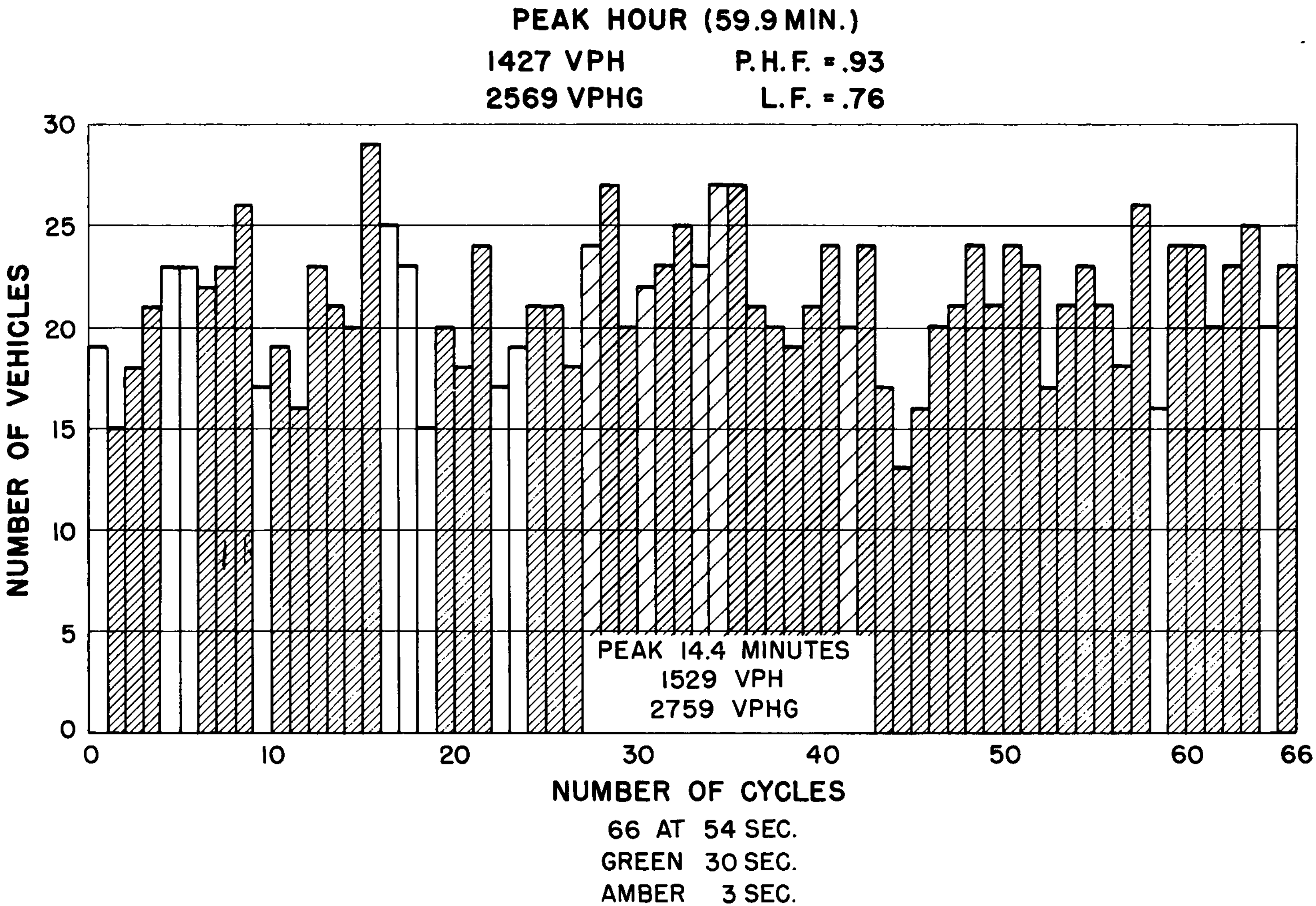

Figure 1. Two-way street, no parking, 20-ft approach.

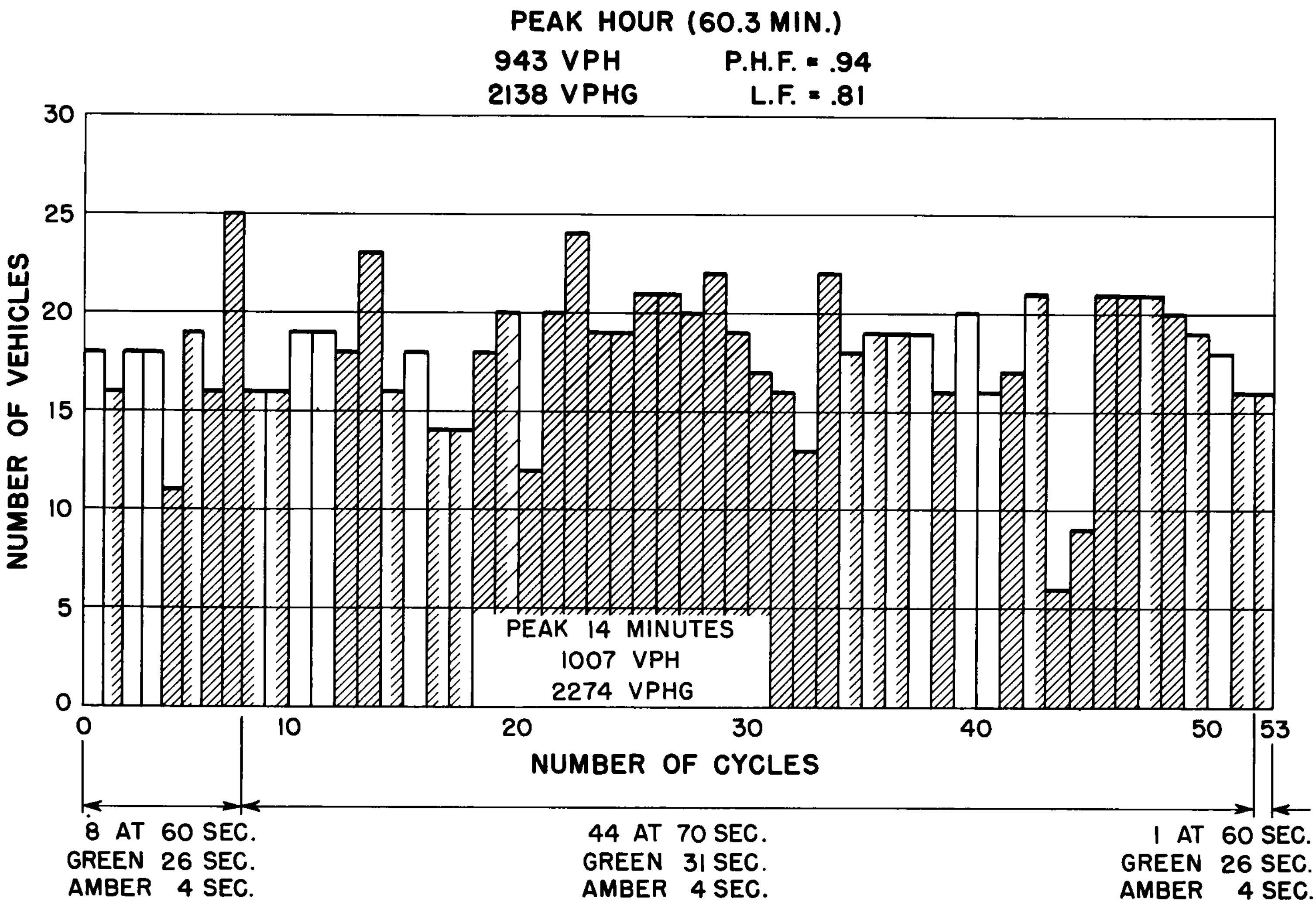

Figure 2. Two-way street, no parking, 22-ft approach.

was loaded during the green period, the right side of the bar is crosshatched, and if only the left-hand lane was loaded for the entire period the left side of the bar is crosshatched. In calculating the load factor, all the green phases with either one or both lanes loaded were divided by the total number of green phases during the peak hour. It might have been desirable to make some distinction between the green phases in which all lanes were loaded and those in which only a single lane was loaded, but inasmuch as this information was not available for all locations included in the study, such a refinement was not possible.

Figures 3, 4, and 5 show information similar to that in Figures 1 and 2 except the data are for other intersection approaches. In Figure 4, the 13th, 16th, and 17th cycles accommodated an exceedingly large number of vehicles during the green phase. Although this probably represents the most unusual condition that was recorded during any of the intersection studies, it was very commonly found that the first cycles during the initial period when an intersection was fully loaded accommodated a much larger number of vehicles than the succeeding cycles. Apparently as a loaded condition continues over a period of time it is less likely that the high initial volumes can be maintained. This is directly related to the finding discussed in a subsequent section of this report which indicates that an intersection will carry higher rates of flow for short periods if the flow on the facility builds up very suddenly than if the rate of flow increases gradually.

Figure 5 illustrates a condition that occurred on one intersection approach when the cycle length and the length of green phase were changed during the peak hour. In this case the cycle length was changed from 50 to 90 sec and the green phase from 22 to 55 sec. The large increase in the number of vehicles entering the approach after the cycle was changed from 50 to 90 sec was due to the length of the green phase rather than due to the fact that the cycle length was increased. Had this change taken place a little earlier during the peak hour, no congestion or backlog of vehicles would have occurred on this approach. Data similar to those shown in Figures 1 through 5 were available for most of the 1,600 locations at which data were obtained for this research project.

RELATION BETWEEN INTERSECTION CAPACITY, DELAY AND LOAD FACTORS

The principal objective of studying traffic flow at intersections is to improve the efficiency of traffic movement, particularly with respect to reducing delays and traffic accidents. Many studies made in the past have been concerned principally with a measurement of delay. In some specific instances this approach is justified but generally for a study of intersection capacities from data based on actual observations of existing facilities, a study of delays, no matter how accurately recorded, can result in some very erroneous conclusions. Figure 6 was prepared to illustrate this point and to define further the significance of the load factor.

Figure 6 shows the increase in the average delay per vehicle with an increase in traffic volume approaching an isolated signalized location. Referring to Curve A, when the traffic volume is very low, there is a certain amount of delay because some of the vehicles reach the signal while it is amber or red. As the traffic volume increases, there is at first a very slight but constant increase in the average delay due to some interference between vehicles. As the traffic volume continues to increase, a point will be reached where any further increase will result in the green time during one cycle in the peak hour being fully utilized. Up to this point, the load factor as defined for this study has been 0.00. As the traffic volume continues to increase more and more of the green phases will become loaded and the delay will increase at a more rapid rate with each increase in the number of loaded phases during the peak hour. As the approach volume continues to increase, all of the cycles during the peak hour will eventually become loaded. At this point the possible capacity of the intersection under the prevailing traffic conditions has been reached and the load factor is 1.00.

The delay will continue to increase even though there is no further increase in the approach volume but there can be no further increase in the capacity of the approach as indicated by the vertical portion of Curve A. There is, however, no limit to the amount of delay that might occur after the possible capacity has been reached. The

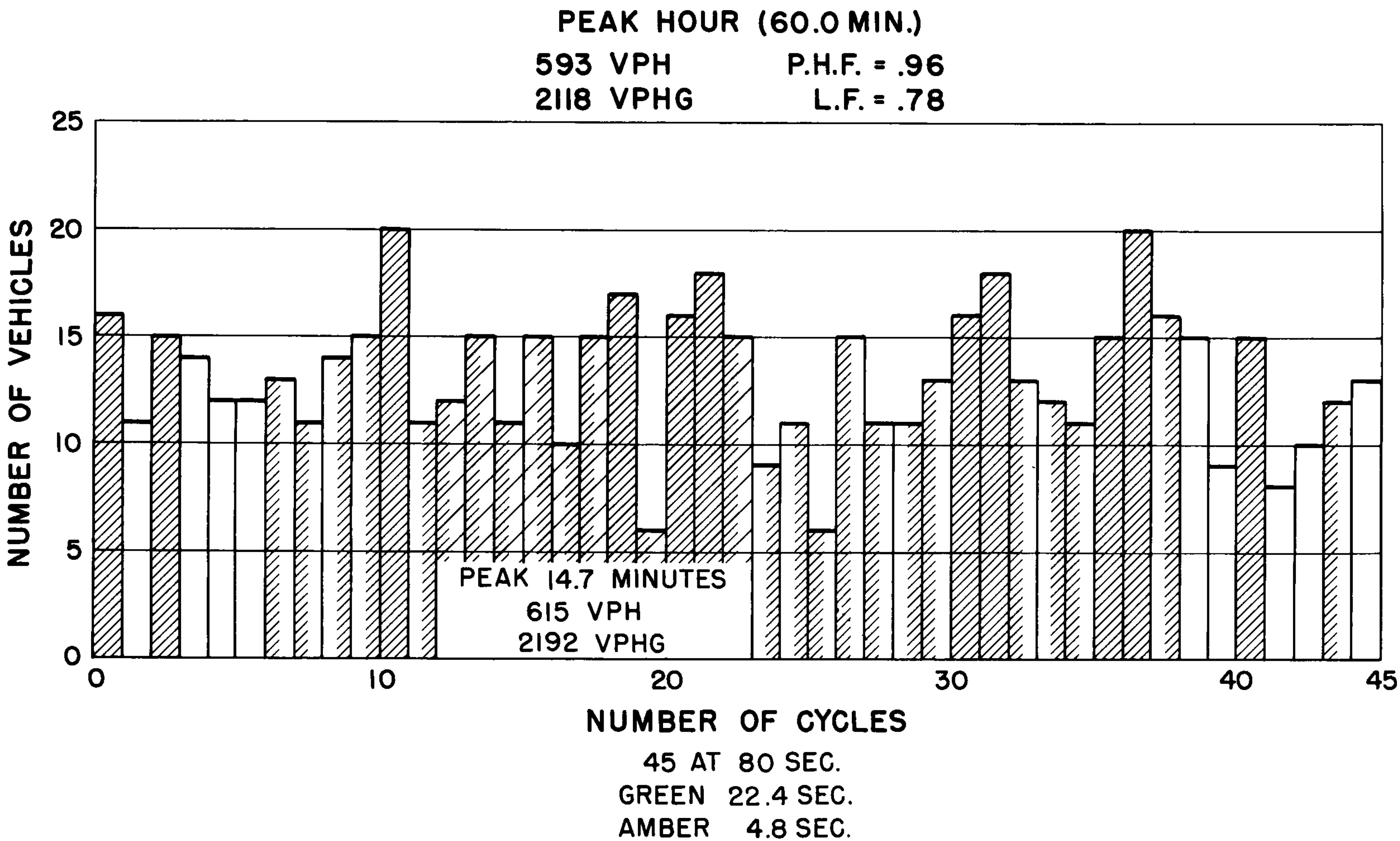

Figure 3. Two-way street, no parking, 22.5-ft approach.

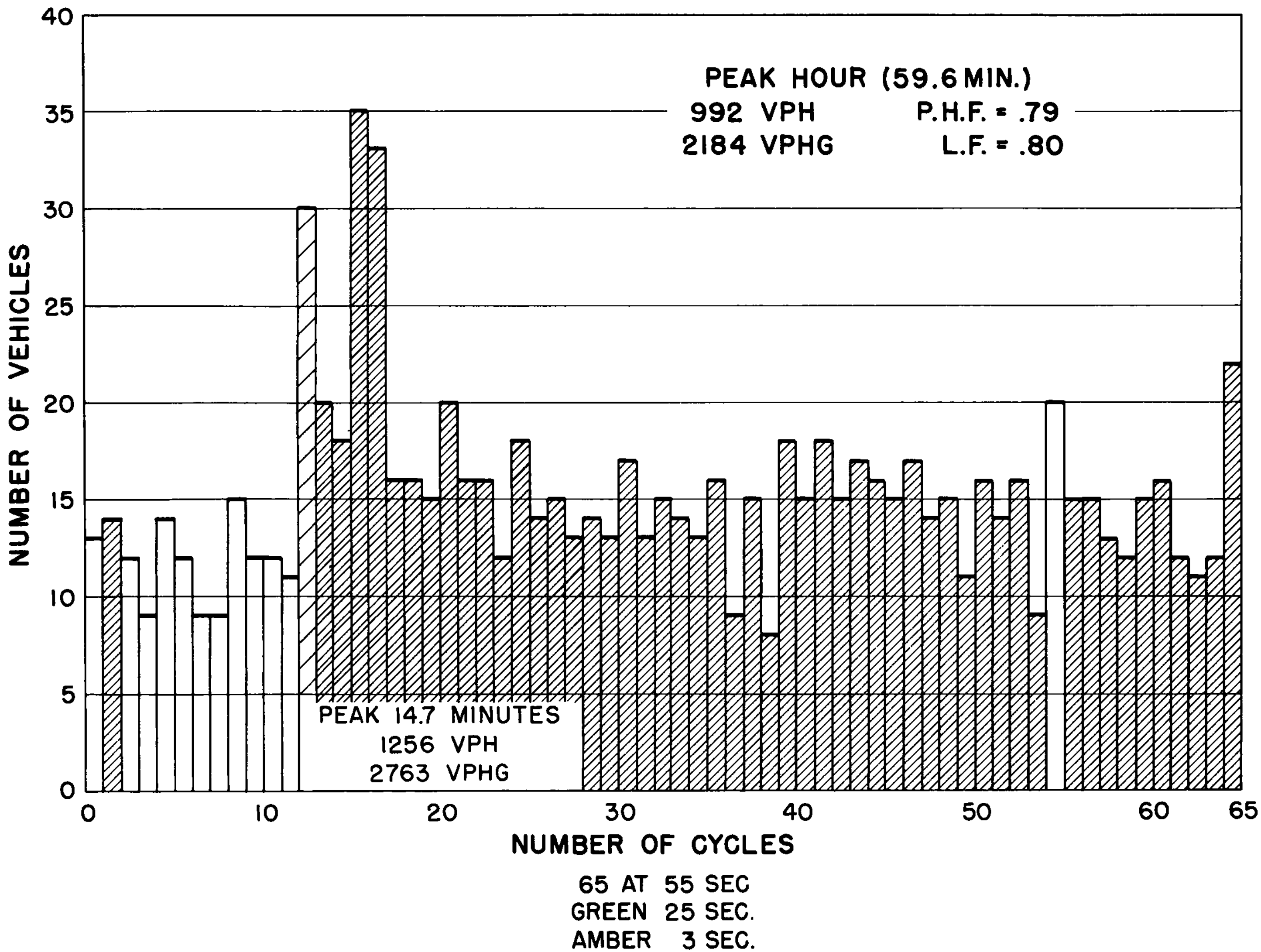

Figure 4. Two-way street, no parking, 21-ft approach.

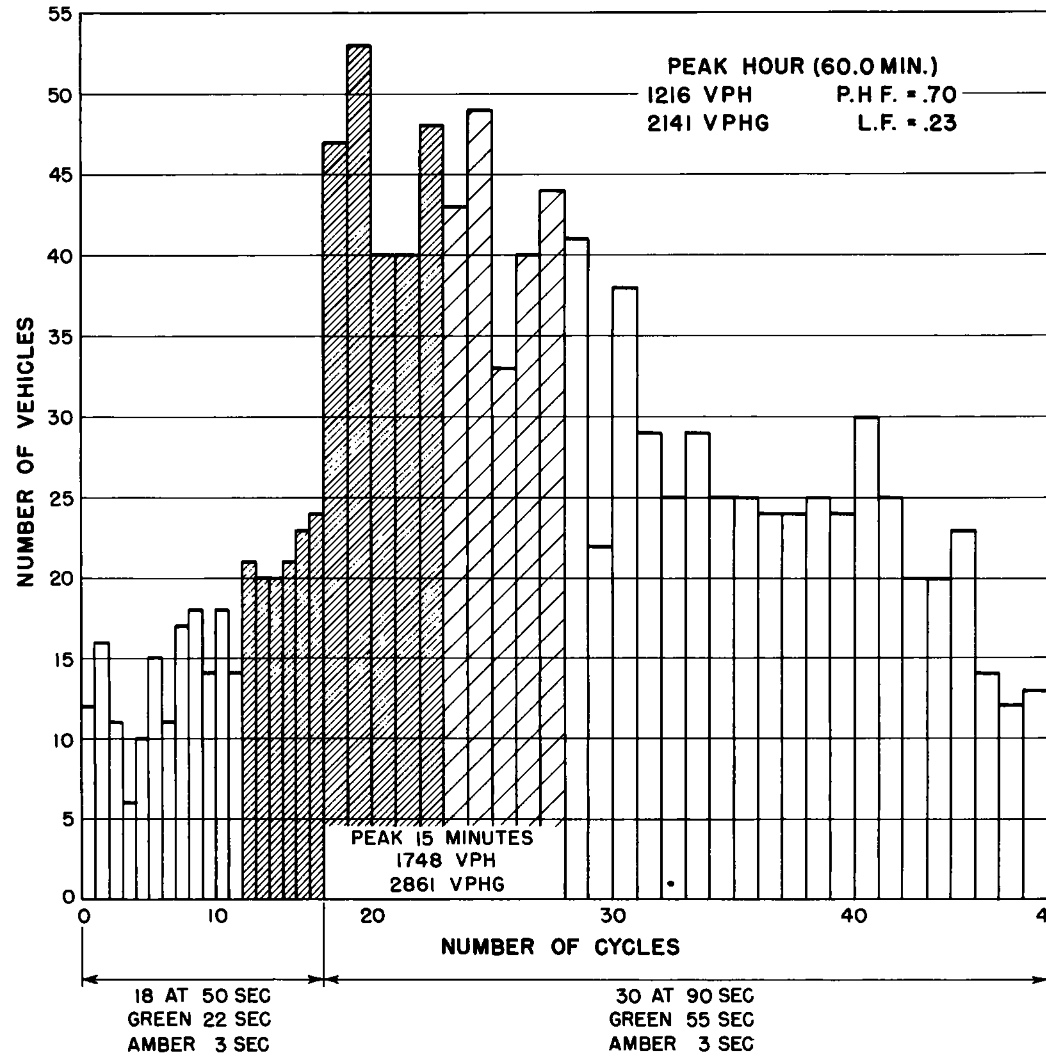

Figure 5. Two-way street, no parking, 22-ft approach.

average delay will depend entirely on the extent and length of time that the approach volume exceeds the intersection's capacity.

Curve B of Figure 6 represents the delay that might occur at the same intersection if it were located near another signalized intersection and the two signals were not properly coordinated. In this case the delay also increases very little with an increase in traffic volume until a point is reached where the delay starts to increase very rapidly. This delay curve would also become vertical at approximately the same number of vehicles per hour of green as for the condition represented by Curve A.

In the case of adjacent intersections, the magnitude of the delay at the second intersection is affected by the "offset" between the green phases at the two intersections. This is one reason that the load factor rather than vehicular delays is more appropriate for a study of intersection capacities. Admittedly, a further refinement in the load factor as recorded by the field parties would have been desirable, but delays, no matter how accurately recorded, would not have been as useful for a capacity deter-

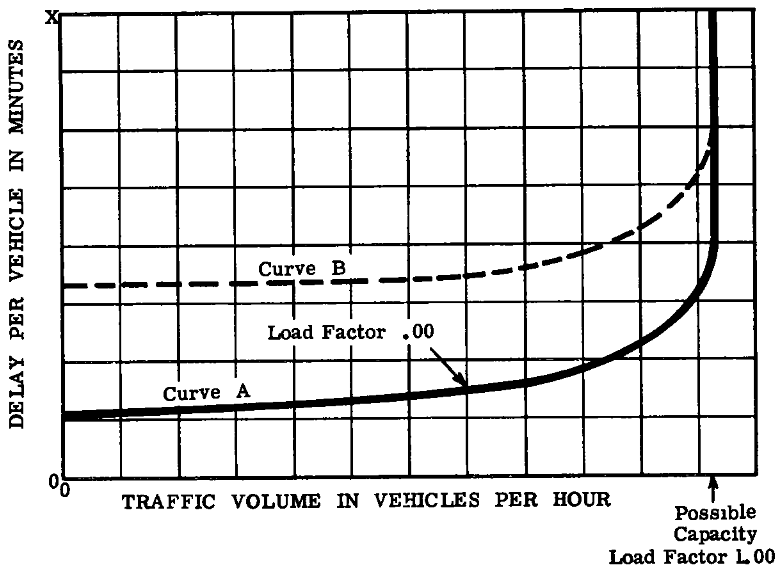

Figure 6. Relation between intersection capacity, delay, and load factors.

mination as the load factor unless for each of the intersections sufficient preliminary investigations had been made to be assured that the offsets to nearby intersections were properly adjusted so as to give a minimum over-all delay per vehicle.

For a study of intersection capacities, it is necessary to include only those approaches operating at or near capacity volumes. The load factor is a means whereby this determination can be made. An intersection approach where none of the green phases was loaded should obviously not be used. Furthermore, a number of conditions can occur at an intersection operating with relatively light traffic volumes that will cause an occasional green phase to become loaded. For this reason only those intersection approaches having about 10 percent or more of the green phases loaded were used for this analysis. This requirement, together with the requirement that the other data be complete and accurately recorded eliminated data for some locations from the analysis. Also, unusual layouts or intersections with more than four approaches were not included. This reduced the total number of approaches for analysis from 1,600 to 792 under fair-weather conditions. Approximately 200 additional studies made during inclement weather were suitable for analysis.

VARIATION IN PEAK-HOUR FACTOR

As defined, it is possible for the peak-hour factor to vary from 0.25 to 1.00. If the traffic flow is uniform during the entire peak hour so that each 15-min period carries the same amount of traffic as the other three 15-min periods during the hour, the peak-hour factor will be 1.00. At the other extreme, if all the traffic during the peak hour occurs during a single 15-min period with no traffic during the other three 15-min periods, the peak-hour factor will be 0.25. It is very unlikely, however, that such a condition will occur. In fact, the lowest peak-hour factor recorded during any of these studies was 0.47, with over one-half of the hourly flow during the peak 15-min period. At most locations, however, the peak-hour factor was in the neighborhood of 0.85 with 75 percent of the locations between 0.80 and 0.95.

Figures 7 through 11 show the distribution of the peak-hour factors for one-way and two-way streets with and without parking. There was some difference in this factor between the various types of streets that were included in this study, but apparently this was due to the method of sampling rather than due to any marked characteristic of the different types of streets as related to the peak-hour factor. The average peak-hour factor for all of the locations included in this analysis was 0.853.

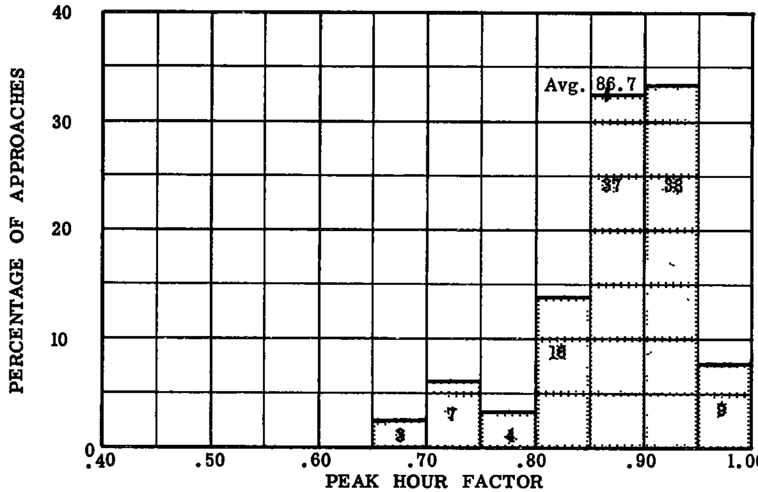

Figure 7. Distribution of peak-hour factors, one-way streets.

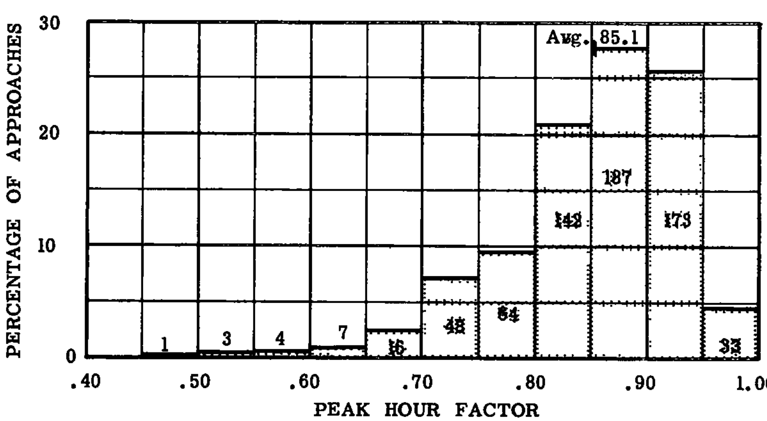

Figure 8. Distribution of peak-hour factors, two-way streets.

RELATION BETWEEN PEAK-HOUR FACTOR AND APPROACH CAPACITIES

Figure 12 shows, for the various peak-hour factors on two-way streets, the average traffic flow in terms of the vehicles per hour of green. As the peak-hour factor increases, the flow increases but at a very non-uniform rate.

Many other factors other than the peak-hour factor influenced the traffic flow. This is shown by Figures 13 through 17. For example, Figure 13 shows that the average street with a low peak-hour factor was narrower than the average street with a high peak-hour factor. Likewise, Figures 14 through 17 show that the average load factor, the average city size, the cycle length, and the length of the green phase all have a tendency to be higher at locations with high peak-hour factors than at locations with low peak-hour factors. Figure 12 does not therefore show the true relationship between the peak-hour factor and the traffic flow because all of these other variables also had a tendency to influence the relationship.

One would expect a direct relationship between the possible capacity in terms of the hourly flow and the peak-hour factor. For example, an intersection having a peak-hour factor of 1.00 should be expected to accommodate 25 percent more traffic during the peak hour than an identical intersection with a peak-hour factor of 0.80 without exper-

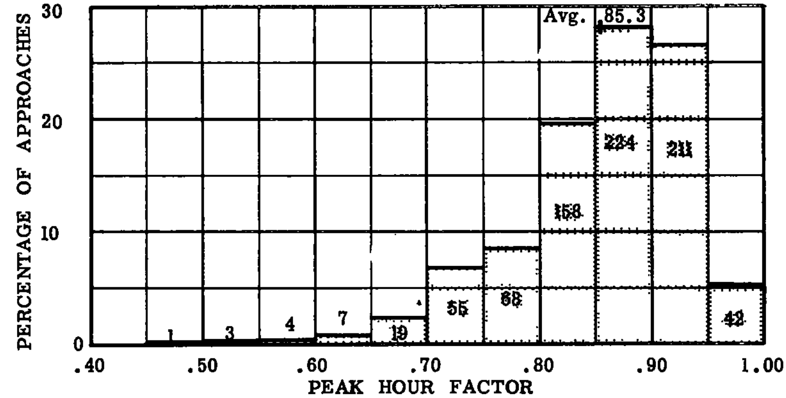

Figure 9. Distribution of peak-hour factors, all streets.

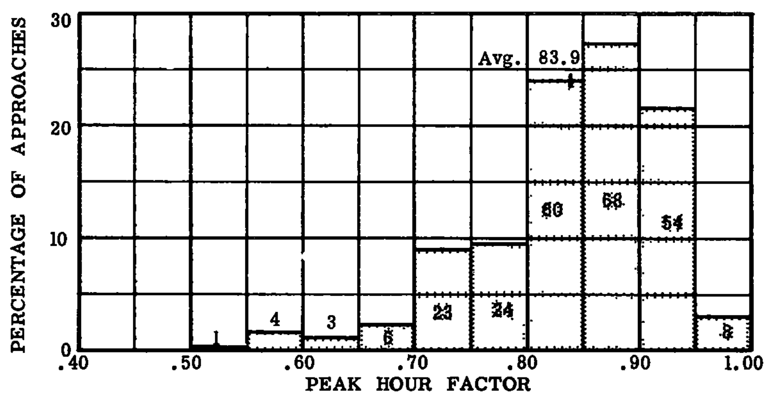

Figure 10. Distribution of peak-hour factors, two-way streets with parking.

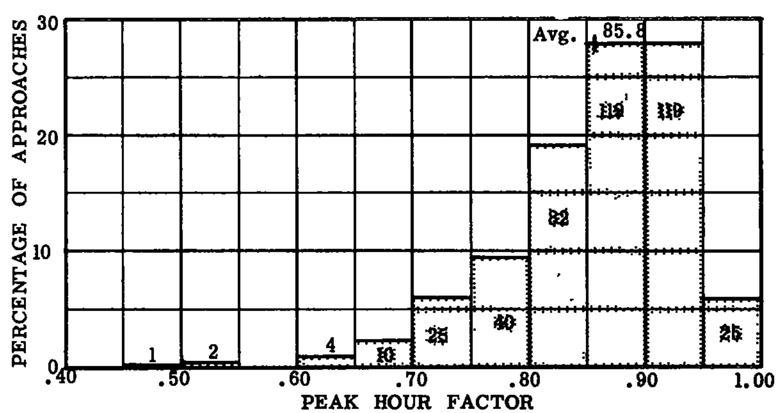

Figure 11. Distribution of peak-hour factors, two-way streets, no parking.

iencing any more congestion during the peak period. This would be true if both intersections accommodated the same number of vehicles during the peak 15-min period. A subsequent analysis shows, however, that the peak rate of flow for a 15-min period

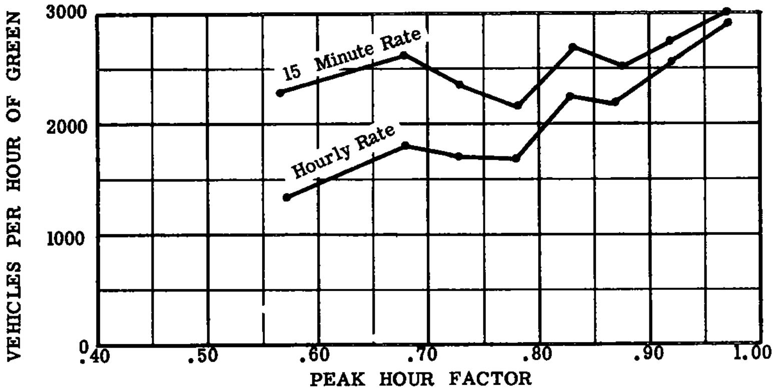

Figure 12. Traffic flow on two-way streets by peak-hour factors (no parking and uncorrected for street width and other factors).

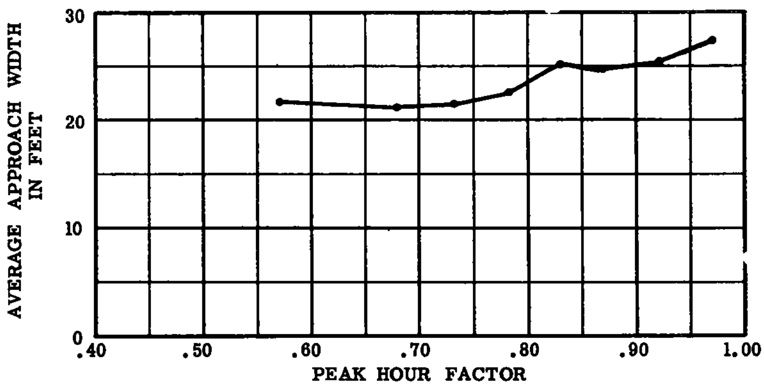

Figure 13. Average width of approaches on two-way streets by peak-hour factor.

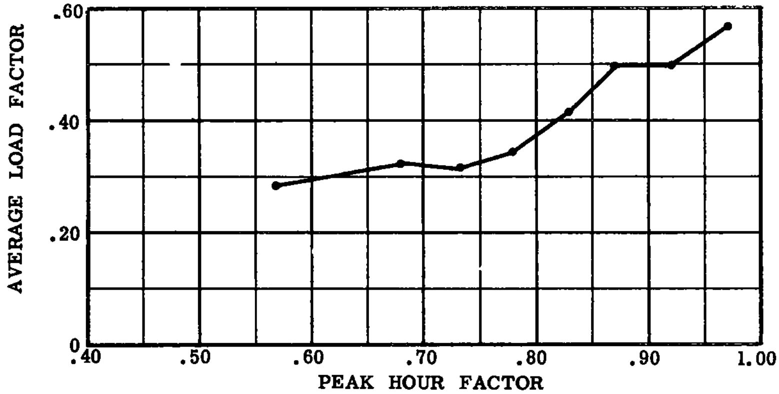

Figure 14. Average load factors for two-way streets by peak-hour factor.

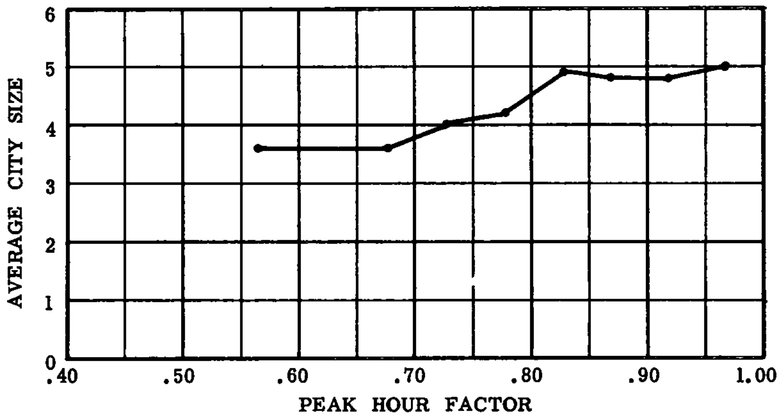

Figure 15. Average city size as related to approaches on two-way streets with no parking, by peak-hour factor.

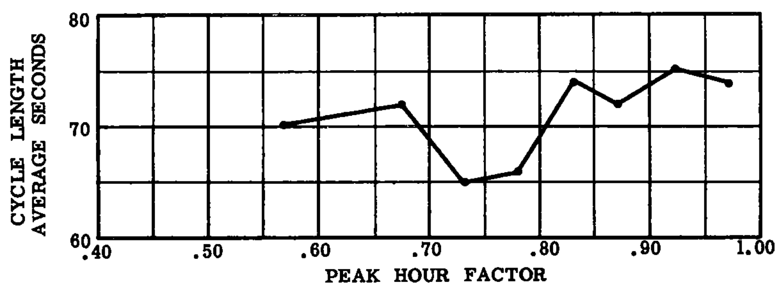

Figure 16. Average cycle length as related to approaches on two-way streets with no parking, by peak-hour factor.

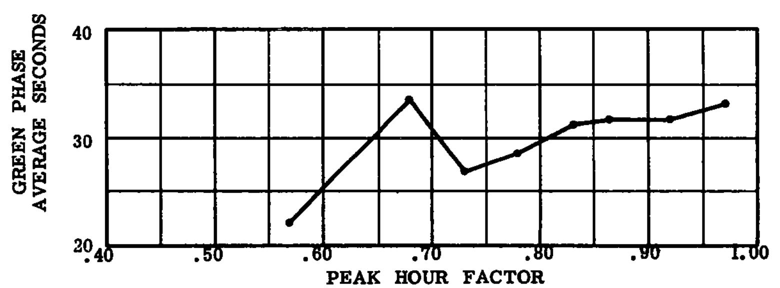

Figure 17. Average green phase as related to approaches on two-way streets with no parking, by peak-hour factor.

can be higher on a street with a low peak-hour factor than on an identical street with a high peak-hour factor. In other words, the same street will accommodate an extremely high rate of flow for a short period if the flow preceding the peak is low. Evidently the lower the flow preceding the peak, the less likelihood there is for the peak flow to be reduced as a result of the preceding flow.

METHOD OF ANALYSIS

Shortly after the field data were compiled and placed on punch cards, a contract was let to a contractor having the necessary equipment and personnel to perform a comprehensive analysis of the data. This firm worked on the analysis for a period of two years, using the most recent high-speed computer equipment available and employing the latest statistical methods and systems analysis procedures. The final result was a series of five equations, each with 14 different variables. Each equation represented intersection capacities for one of the following conditions:

1. Adverse weather conditions;
2. Locations in the central business districts;
3. Locations in the fringe business districts;
4. Noncentral locations with lane lines;
5. Noncentral locations with no lane lines.

The results were very disappointing, however, because the effect that the individual factors in the equation had on intersection capacities was not in line with the results as obtained from other research and from experience by professional engineers in traffic operations. For example, the effect of parking on intersection capacities as included in the equations was far from anything that could be considered reasonable. Furthermore, the application of the equations to the field data used for the analysis showed that the ability to predict the capacity of an intersection without considerable error was rather remote. For example, in 12 percent of the cases the predicted capacity was more than 50 percent higher or lower than the actual flow. Also in 48 percent of the cases the predicted capacity was more than 20 percent off and in 71 percent of the cases the predicted capacity was more than 10 percent off. To be useful for design purposes, it should be possible to obtain an accuracy of within 10 percent in most cases and within 20 percent except in rare cases involving unusual intersection layouts. It is believed that the following were the principal reasons that the results were so erratic:

1. Separate equations were not provided for one-way and two-way streets.
2. Separate equations were not provided for streets with and without parking.
3. Lane lines have an important effect on intersection capacities but there is a large variation in this effect depending on the specific width of the street.
4. The effect of certain variables, such as the length of the green phase, is not a straight-line relationship.

It is believed, however, that the principal reason for the erratic results and lack of correlation was the fact that each equation was derived from data including a mixture of one- and two-way streets some with and some without parking. The results of the current analysis definitely show that many of the variables have a different effect on one-way streets than on two-way streets and on streets with parking as compared with streets without parking. The analysis made by the contractor was, however, beneficial in that certain variables were found to affect intersection capacities to a much greater degree than other variables.

For the current study, the data were separated into five primary groups based on the type of street and parking conditions. A separate analysis was made for each. They include intersection approaches on the following:

1. One-way streets with no parking;
2. One-way streets with parking on one side;
3. One-way streets with parking on both sides;
4. Two-way streets with no parking;
5. Two-way streets with parking on both sides.

The effect of each of the more important variables was determined separately for intersection approaches involving these five types of streets. A separate analysis was also made for inclement weather conditions.

The following were four principal variables found to affect the hourly flow of traffic through intersections, other than one- and two-way operation and the presence of parked vehicles:

1. Peak-hour factor;
2. Load factor;
3. The approach width at the intersection;
4. Size of the city.

It was immediately apparent that the effect of these variables had to be accurately determined before the data could be used to obtain the effect of the many other variables such as right and left turning movements, commercial vehicles, cycle length, lane width, type of signal control, location of bus stops, and pavement markings. These variables for simplicity are referred to as secondary variables whereas the four previously listed are referred to as the primary variables for each of the five types of streets.

Many independent studies conducted over the past several years have produced information relating to the effects on capacity of several of the secondary variables. With the exception of the approach width, however, no comprehensive studies have been made to determine the effect of the primary variables on intersection capacities or hourly flows. It therefore seemed most appropriate first to analyze the primary factors as related to traffic flow at intersections because they are the principal measures or variables that indicate the patterns of mass traffic movement on the approaches whereas the secondary variables relate principally to traffic control measures, and the traffic movements within the intersection. Furthermore, when the intersections included in any one of the primary classifications (street type) are grouped according to the magnitude of any one of the variables, the average values for the secondary variables are generally about the same for all the groups when each contains in the neighborhood of 10 or more intersections. This is not true for the averages that involve the primary variables. Also, because an approximate value for the effect of each of the secondary variables on capacity is already known, reasonable adjustments can be made when plotting a curve whenever the average value of a secondary variable for one of the points is out of line. For example, the average value for each of the secondary variables was approximately the same for the points shown in Figure 18. The only significant exceptions were the following:

1. For the point representing 4 approaches, the average percentage of left-turning movements was double the percentage at the locations represented by the other points (14 percent against 7 percent).
2. For the point representing 3 locations, there were only one-half as many turning movements as at the other locations.
3. For the point representing 6 locations, there were only one-half as many local busses on a percentage basis as at the other locations.

Any reasonable adjustment made for these conditions would tend to make these three points fall closer to the average line, showing the effect of the peak-hour factor on the traffic flow, than they are now located.

One of the rather unusual features of this analysis was that no extensive statistical procedures were employed as the individual relation between one variable and the hourly capacity or traffic flow was developed. This would have been a waste of effort at this stage of the analysis and the statistical results would probably have been improperly interpreted to the same degree that they were in the initial analysis performed by contract. It is obvious that any one variable is not likely to have as great an effect on capacity as the combined effect of some 43 other variables. There is therefore bound to be a wide dispersion of the points when one of the independent variables is plotted against the traffic flow as the dependent variable. The resulting dispersion (or the coefficient of correlation) is only an indicator of how close the traffic flow can be predicted from that one variable. It is no measure whatever of the accuracy of the relation developed between the independent and dependent variables. This is the reason for leaving any statistical analysis until the combined effect of the accuracy of all variables in predicting the traffic flow can be determined. A comparison of the actual

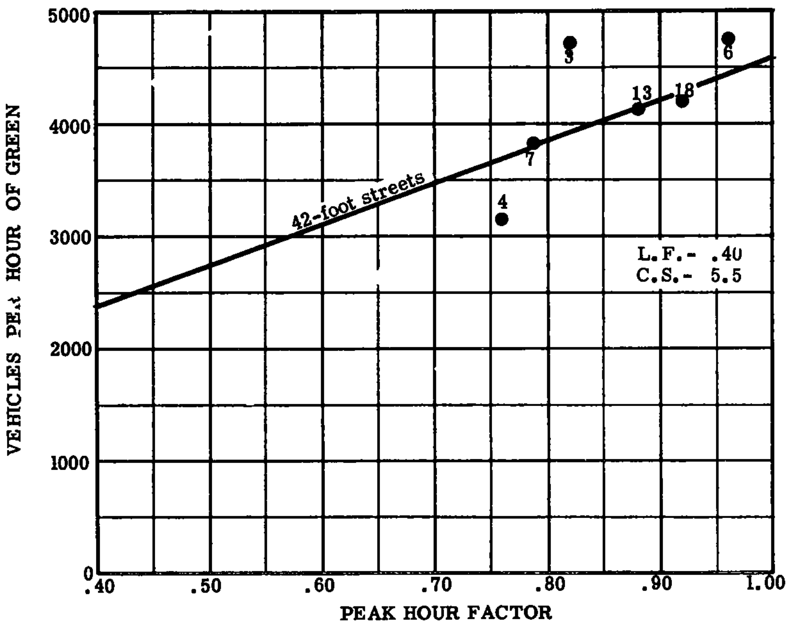

Figure 18. Effect of peak-hour factor on hourly intersection capacities, one-way streets with no parking.

traffic flow at individual intersections with the predicted flow calculated from the combined effect as determined for each independent variable will then be the "proof of the pudding."

Another consideration in plotting the curve to show the relation between an independent and a dependent variable from a series of points, other than the commonly used method of least squares, was the assumption that the curve for one set of points should have some relation to the curve for another set of points involving the same variables but of different magnitude. In other words, when more than two variables are involved, each curve for two of the variables should fit into a series forming a family of related curves in the same manner as would be the case by applying multiple correlation to three or more variables. This procedure was especially important in selecting the most appropriate curve when two or more curves would fit a series of plotted points equally well. Also, theoretical relationships and the results obtained by other studies in the same area influenced the selection in such instances.

Multiple correlation was not used for this analysis in view of the results previously obtained by the contract. Also, because new variables were being investigated, multiple correlation would not have disclosed whether the proper form of equation had been used or whether the data had been properly classified or segregated into appropriate groups.

The effect on capacity of the four primary variables was determined by a series of successive approximations because the method of multiple correlation had resulted in producing a relation that could not be considered reasonable. Each of three of the four variables was first assigned an assumed effect to determine a preliminary effect of the fourth variable. The results were then applied together with the previously assumed values for two variables to arrive at a more exact effect for the third variable which had previously been assumed. This procedure was then applied to determine more exact values for the other variables, then the entire series of calculations was repeated for all variables until there was no change in the resulting effect that any one of the variables had on the intersection capacities. This was a rather time-consuming process involving about 100 IBM tabulations and thousands of manual calculations. Before starting this procedure, however, special IBM tabulations were made listing all the variables for each intersection with two related variables shown in adjacent columns and in order by the magnitude of one of the variables. This was done to discover "odd balls" in the data and permit a thorough check in each such case with the original field sheets and in some cases with field conditions.

For example, when the intersection approach widths listed in order of magnitude were compared with the number of lanes as shown in the adjacent column, many cases such as a 24-ft approach with three lanes and parking, or a 12-ft approach with two lanes were discovered to be included in the data. In each such case, the data were corrected when the check produced reliable evidence that an error had been made while the field data were being recorded or in processing the data to IBM cards. In no case were data changed without complete information, and in no case were the data for any intersection discarded regardless of how unreasonable it appeared.

Some 300 substantial corrections were made in the data which involved over 40,000 items. There were undoubtedly many errors that were not detected, as evidenced by the "odd balls" that repeatedly appeared in successive tabulations. On the whole, however, the data were remarkably accurate and whatever errors remained could not have had a significant effect on the average values obtained by the analysis.

PEAK-HOUR FACTOR

Theoretically at least, the total flow that an intersection approach will accommodate during a peak hour should be directly related and proportional to the peak-hour factor. This can be true in practice, however, only if the approach can accommodate the same rate of flow for an hour as for a 15-min period. Furthermore, the peak 15 min for the hours with the higher peak-hour factors must be loaded to the same extent and carry the same rate of flow as the 15-min periods for the hours with the lower peak-hour factors. It was impossible to observe locations or analyze these data in such a manner as to control these two variables because, as shown later, the peak-hour factor does not change greatly from day to day at locations carrying capacity or near-capacity volumes for at least 15 min during the peak hours. (This statement may not and probably does not apply to changes in the peak-hour pattern that take place over a long period of time, such as those that occur with a large increase in the yearly flow.)

For this analysis of the effect of the peak-hour factor on intersection capacity, the other factors including the "load" factor during the peak hour were held constant. The conditions required for the theoretical relation between the peak-hour factor and the total traffic flow during the peak hour as set forth in the preceding paragraph could not be fulfilled. To illustrate this point, assume two intersection approaches of identical geometric design both having the same load factor of 0.40 and 60 traffic signal cycles per hour. The first has a peak-hour factor of 0.60 and the second a peak-hour factor of 0.90. In the first case, the 24 loaded cycles would necessarily be concentrated in and near the peak 15-min period, whereas in the second case, the 24 loaded cycles would most likely be reasonably well distributed throughout the hour. The flow during the peak 15-min period would therefore be somewhat greater in the first case than in the second, but the total hourly flow would be considerably lower and the total delays to traffic considerably greater in the first case. A series of successive green phases that are loaded indicates a backlog of vehicles on an approach, whereas a distribution of loaded phases throughout the hour separated by phases that are not fully loaded indicates a uniformly high flow during the hour with little or no backlog on the approach at any time.

Figures 18 through 22 show the effect of the peak-hour factor on hourly intersection capacities for the five types of streets. In each case, the load factor and city size are constant and both correspond with the average values represented by the data for the specific type of street. The load factor had approximately the same effect on the hourly

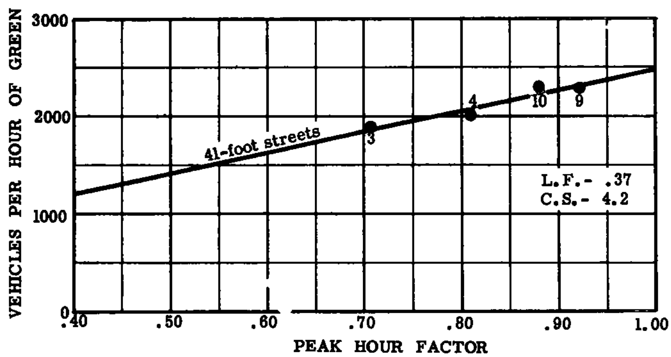

Figure 19. Effect of peak-hour factor on hourly intersection capacities, one-way streets with parking on one side.

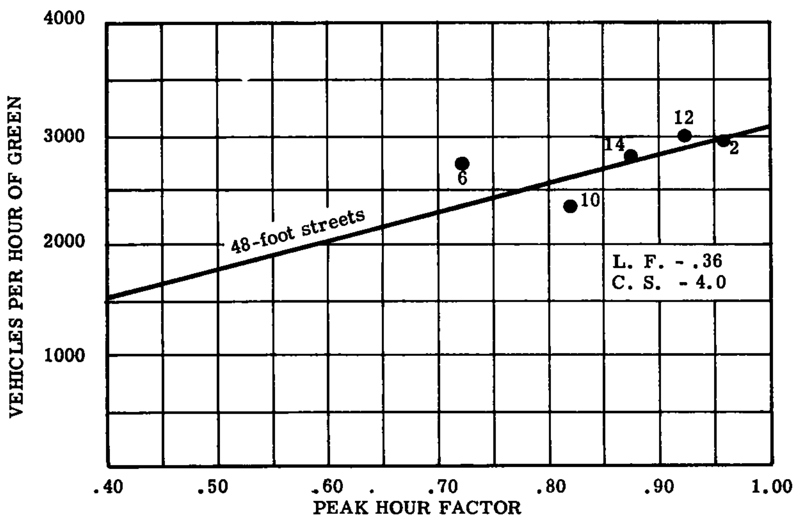

Figure 20. Effect of peak-hour factor on hourly intersection capacities, one-way streets with parking on both sides.

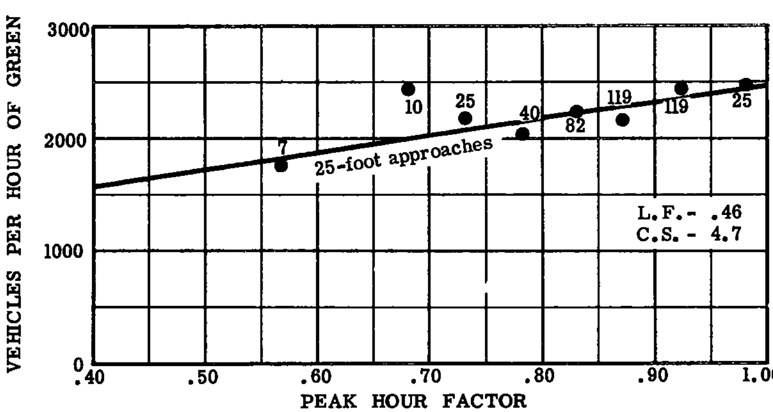

Figure 21. Effect of peak-hour factor on hourly intersection capacities, two-way streets, no parking.

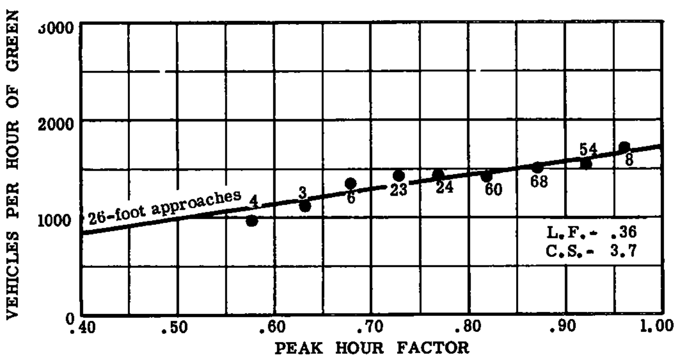

Figure 22. Effect of peak-hour factor on hourly intersection capacities, two-way streets with parking.

capacities for the three types of one-way streets as for the two-way streets with parking when the change in capacity is considered on a percentage basis. The effect for these four types of streets was, however, considerably different than for the two-way streets with no parking. This is illustrated by Table 1 which gives for each type of street the percentage increase in the peak-hour traffic with an increase in the peak-hour factor from 0.75 to 1.00.

On two-way streets with no parking, the effect of a change in the peak-hour factor on the peak-hour flow may be represented by the following equation:

$$\text{Change in peak-hour flow} = \left(\frac{\text{New PHF} + 0.653}{\text{Observed PHF} + 0.653} - 1\right) \text{observed flow}$$

The change and the observed flow may be either in terms of VPHG or VPH. For example, if 900 vehicles had been observed entering an intersection approach on a two-way street without parking during a peak hour while the peak-hour factor was 0.70 and 40 percent of the cycles were loaded, that same approach would accommodate 133 more vehicles or a total of 1,033 vehicles if the traffic pattern changed so that the peak-hour factor was 0.90, providing all other conditions including the number of loaded cycles during the hour remained the same. The effect of a change in the peak-hour factor is much greater for the other four types of streets, including all one-way streets and two-way streets with parking, than for two-way streets without parking. The change on these streets may be represented by the following equation:

$$\text{Change in peak-hour flow} = \left(\frac{\text{New PHF} + 0.20}{\text{Observed PHF} + 0.20} - 1\right) \text{observed flow}$$

If the effect of the peak-hour factor on traffic flow is to be of any value in intersection design, or to improve traffic conditions through better control methods, an understanding of the conditions that produce or cause changes to occur in this factor must be understood. This discussion is, however, deferred until after the analysis of the effect on capacity of other factors.

TABLE 1

INCREASE IN HOURLY FLOW

Type of Street	Fig. No.	Increase in Hourly Flow (%)
One-way:		
No parking	18	25
Parking one side	19	27
Parking both sides	20	27
Two-way:		
No parking	21	18
Parking both sides	22	26

EFFECT OF LOAD FACTOR

Figures 23 through 27 show the effect of the load factors on the traffic flows entering intersections from approaches on the five different types of streets when the

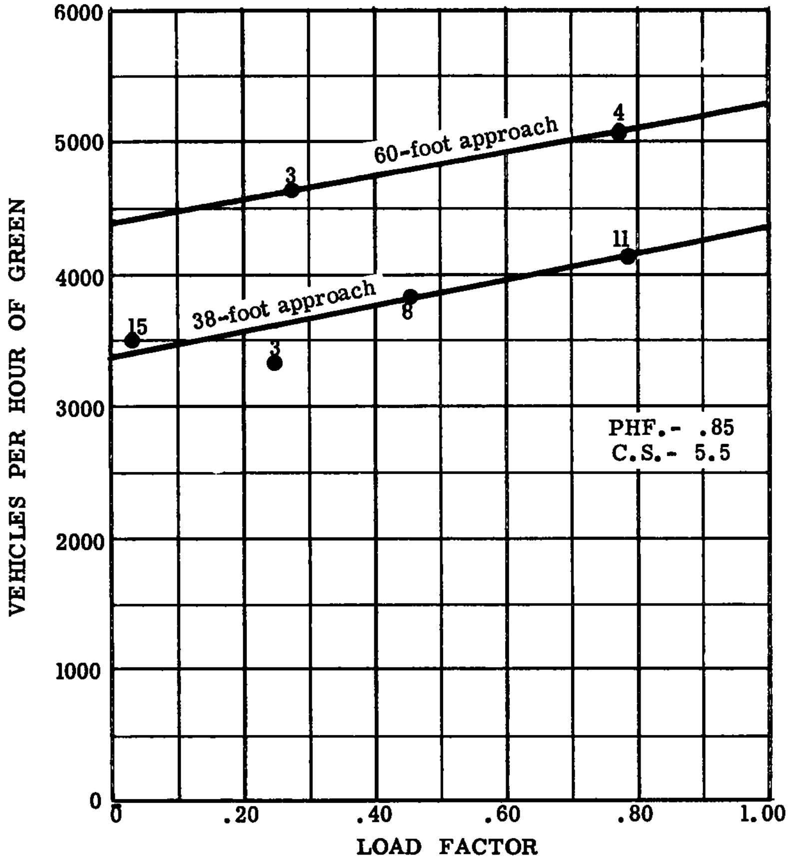

Figure 23. Effect of load factor on hourly intersection capacities, one-way streets with no parking.

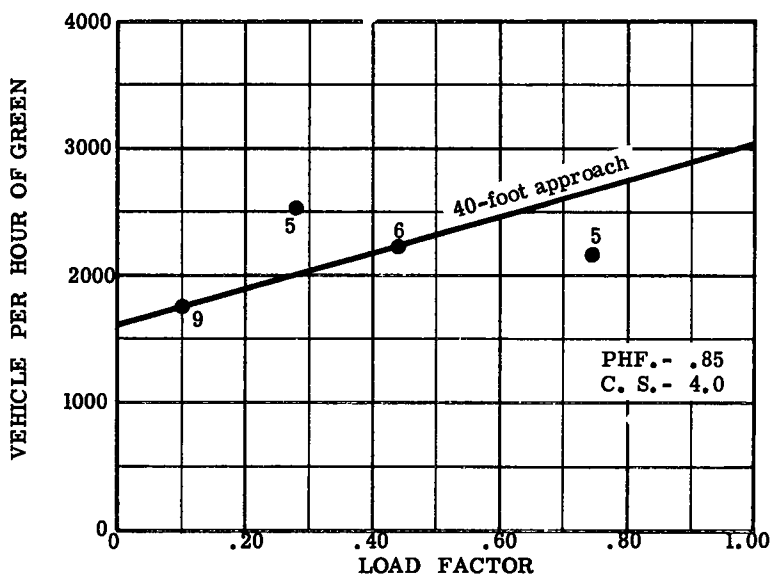

Figure 24. Effect of load factor on hourly intersection capacities, one-way streets with parking on one side.

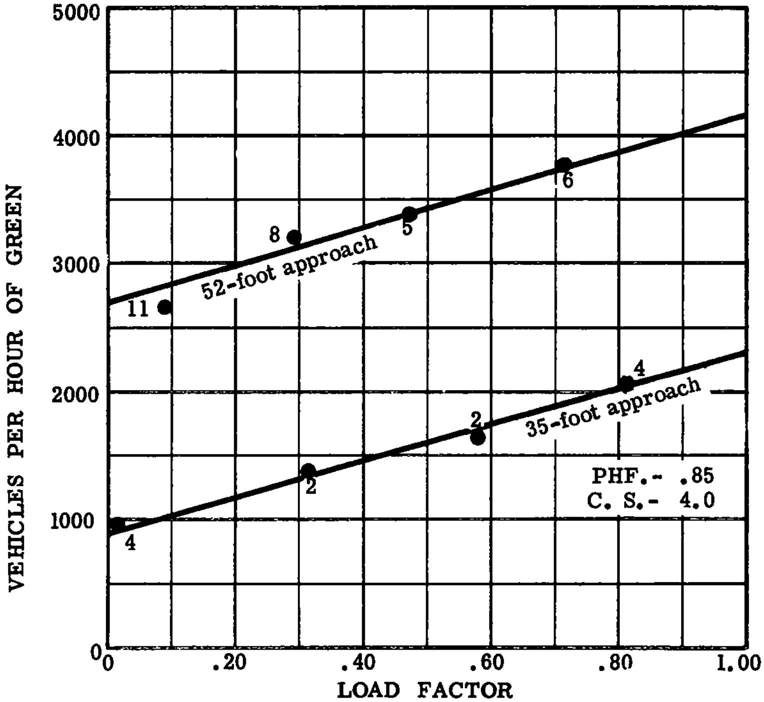

Figure 25. Effect of load factor on hourly intersection capacities, one-way streets with parking on both sides.

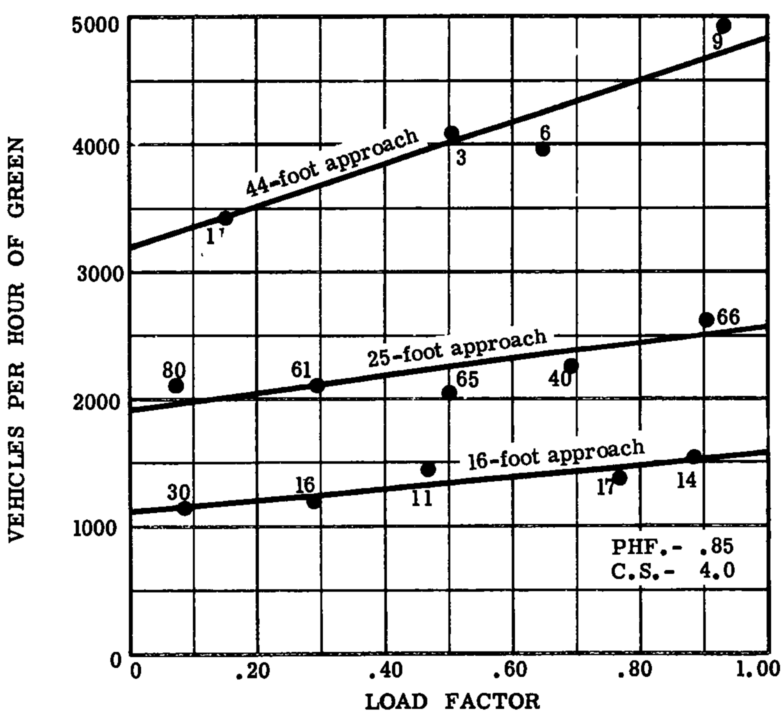

Figure 26. Effect of load factor on hourly intersection capacities, two-way streets, no parking.

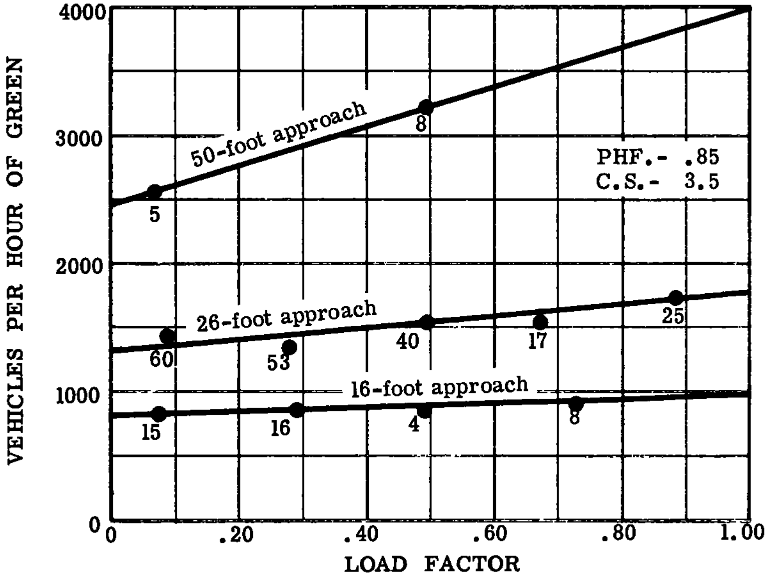

Figure 27. Effect of load factor on hourly intersection capacities, two-way streets with parking.

peak-hour factors and the city size are held constant. The outstanding characteristic of the results shown on these figures is that the lines representing the change in traffic flow with a change in load factor for the various widths of one-way streets are parallel (Figs. 23 and 25), whereas the lines tend to converge toward a common point for the two-way streets with the lines for the wider streets having a greater slope than the lines for the narrower streets (Figs. 26 and 27).

This means that for each type of one-way street, a specific change in the load factor will cause the same change in the traffic flow in terms of vehicles per hour regardless of the width of the street. For the two-way streets, a specific change in the load factor will cause a greater change in the flow on the wider streets than on the narrower ones.

In all cases, the load factor has a very marked effect on the traffic flow. The change in the volume of traffic on one-way streets, regardless of width, amounts to about 10 vehicles per hour of green period on the streets without parking for each change of 0.01 in the load factor. The corresponding figure for one-way streets with parking on one or both sides is 15 vehicles per hour of green. The effect of a change in the load factor on two-way streets where the change varies with the approach width is shown by Figures 28 and 29. The change is greater when there is no parking than with parking and much greater on the wider streets than on the narrower streets, neither of which was the case for one-way streets.

Figures 30 and 31 show the same information as Figures 26 and 27 plotted in a more usable form from which the effect of the load factor for any width of two-way street may be determined.

At this point it is well to refer to Figure 6 to obtain the complete significance of the curves shown in Figures 30 and 31. The curves of Figures 30 and 31 which represent load factors of zero show the highest hourly volumes than can be accommodated without traffic delays at signalized intersections being appreciably higher than at any lower volume. The volumes represented by the curves for a load factor of 0.00 are therefore certainly the minimum values that should be used for design or operation to obtain a very high level of traffic service. Any appreciable delays to traffic at these volumes must be charged to conditions other than the traffic load on the approaches to the intersections.

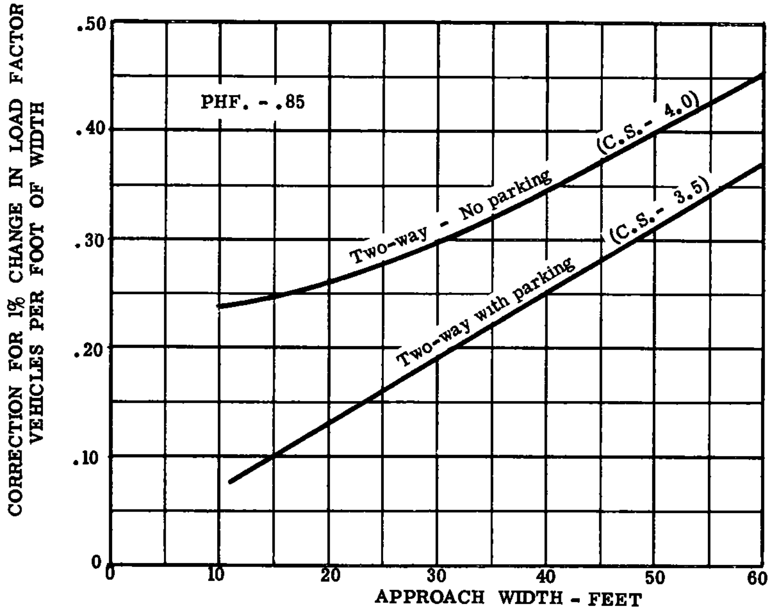

Figure 28. Chart for adjusting load factors to a common base.

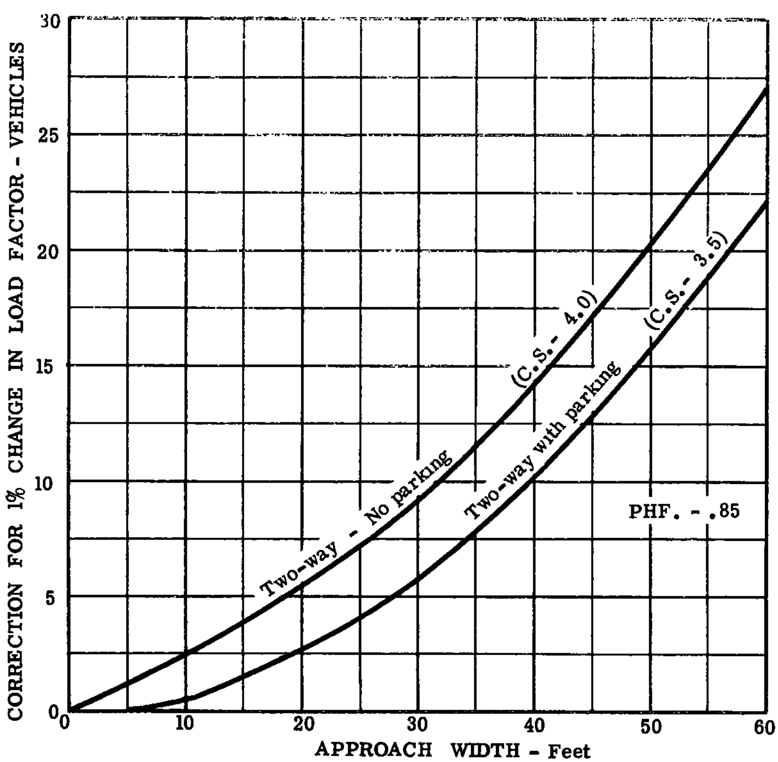

Figure 29. Total adjustment for a change in load factor.

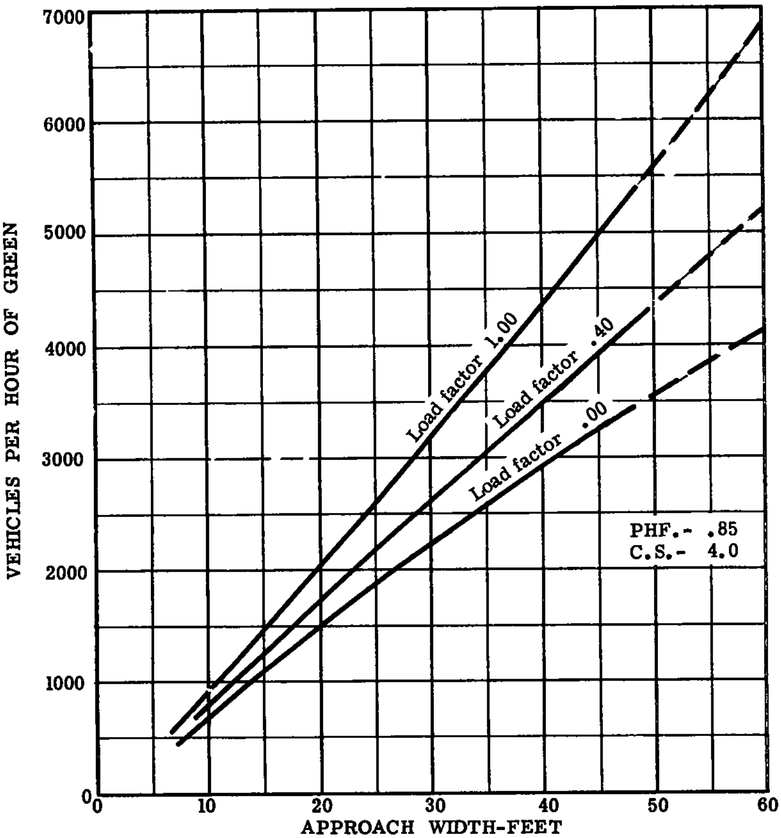

Figure 30. Effect of load factor on hourly intersection capacities, two-way streets, no parking.

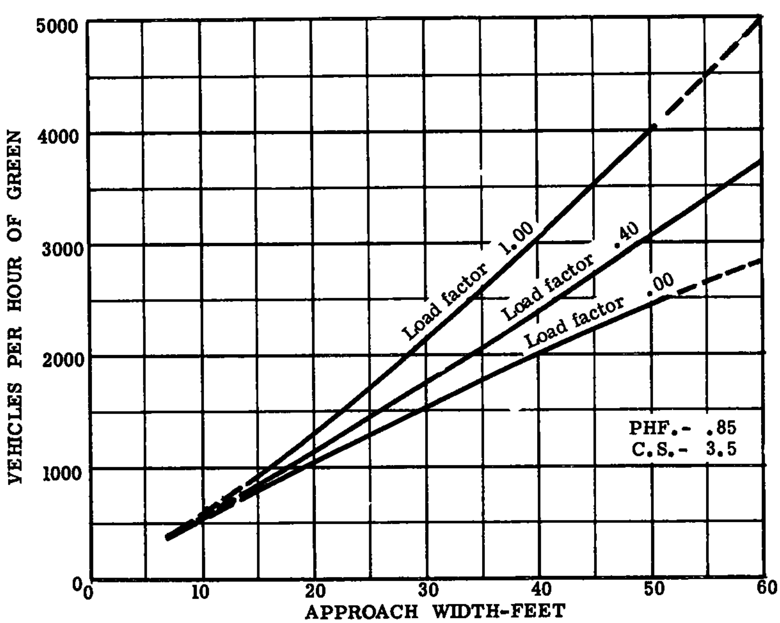

Figure 31. Effect of load factor on hourly intersection capacities, two-way streets with parking.

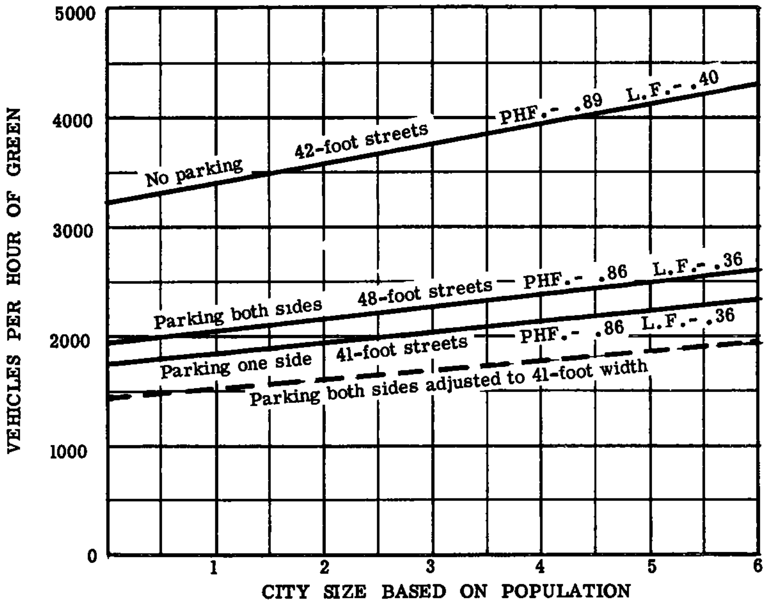

Figure 32. Effect of city size on hourly intersection capacities, one-way streets.

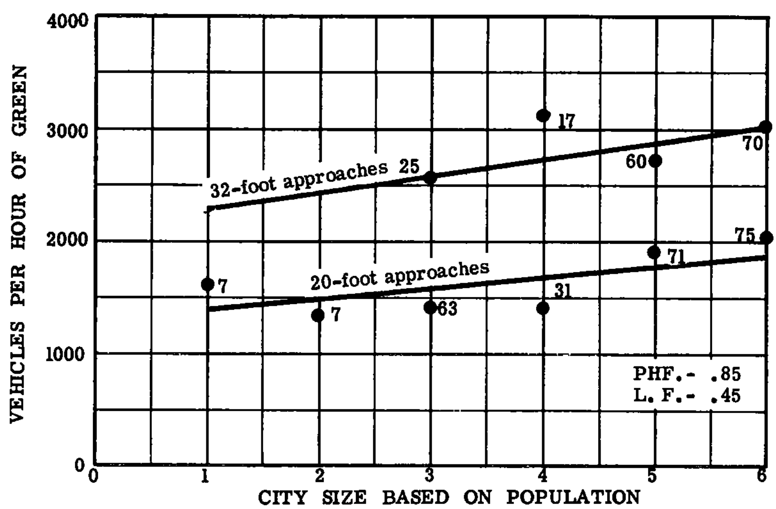

Figure 33. Effect of city size on hourly intersection capacities, two-way streets, no parking.

The curves representing a load factor of 1.00 (Fig. 30 and 31) also represent the maximum traffic flow that the various approach widths will accommodate regardless of the total traffic delay. In most cases, a load factor of 1.00 or approaching 1.00 can only be obtained with a continuous backlog of vehicles at the approach during the peak hour. With a properly coordinated signal system, fully responsive to the variations in traffic flow, load factors approaching 1.00 can be obtained without a continuous backlog of vehicles and with little more delay for the average vehicle than at lower traffic volumes. This is seldom accomplished at the present time. In fact, at the present time the most heavily loaded intersections selected for this study and scattered in cities

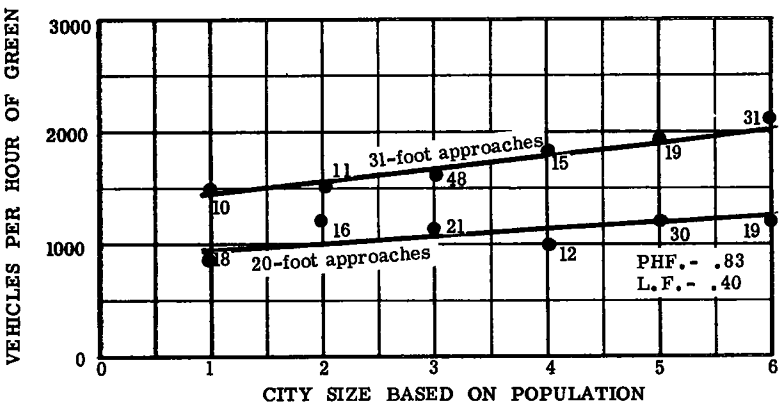

Figure 34. Effect of city size on hourly intersection capacities, two-way streets with parking.

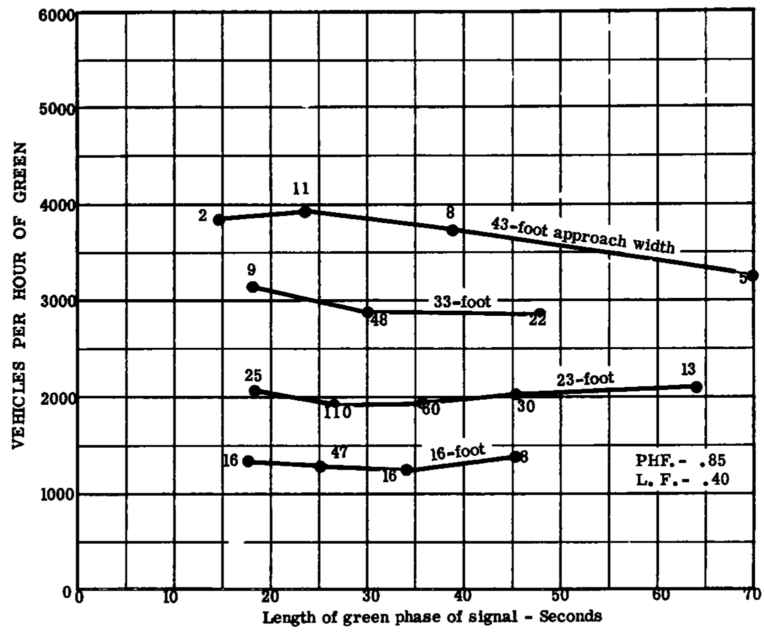

Figure 35. Effect of length of green phase on intersection capacity, two-way streets, no parking.

throughout the Nation were operating during the peak period at an average load factor of 0.40 which is the reason this specific curve was shown in Figures 30 and 31. Unless some major breakthrough occurs in traffic control, this curve certainly represents traffic volumes as high or higher than those that should be selected for design purposes if there is to be any improvement in traffic conditions in urban areas.

A whole series of curves similar to those in Figures 30 and 31 can be developed for different peak-hour factors and cities of different sizes with a knowledge of the effect of these factors on traffic flow at signalized intersections.

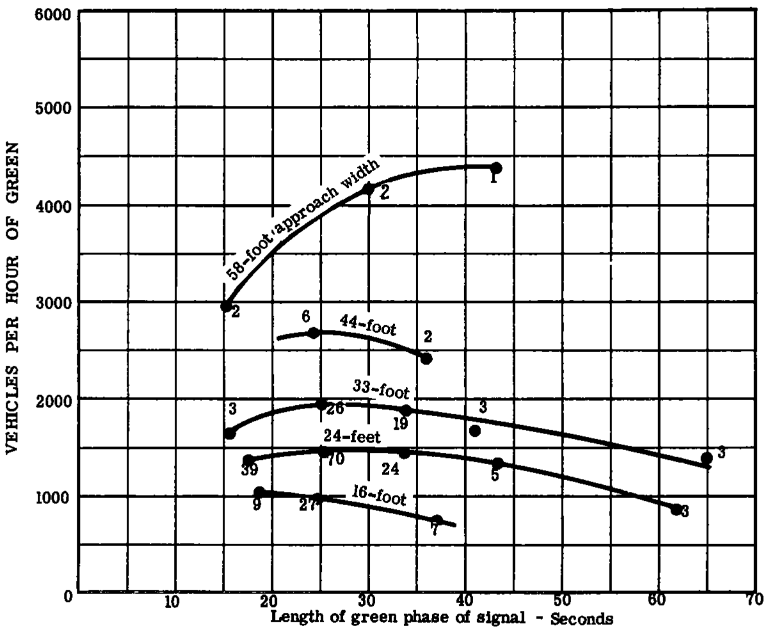

Figure 36. Effect of length of green phase on intersection capacity, two-way streets with parking.

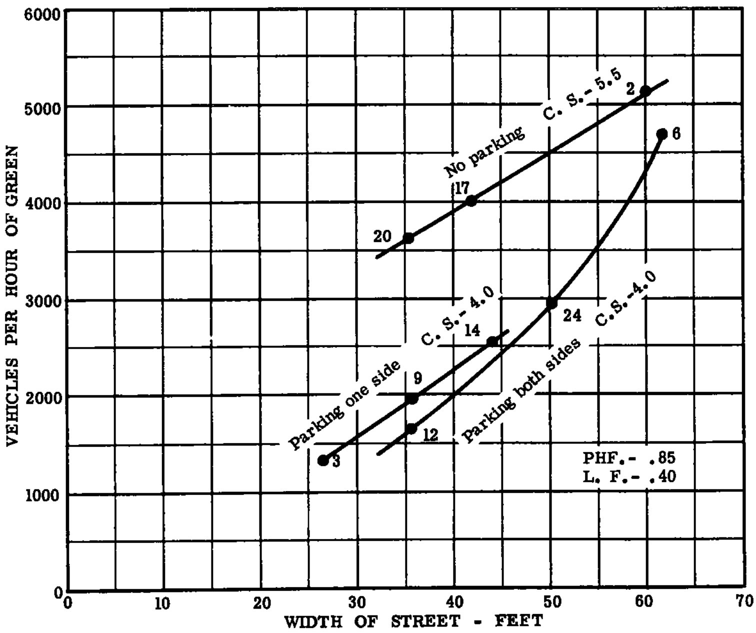

Figure 37. Capacity of intersection approaches on one-way streets.

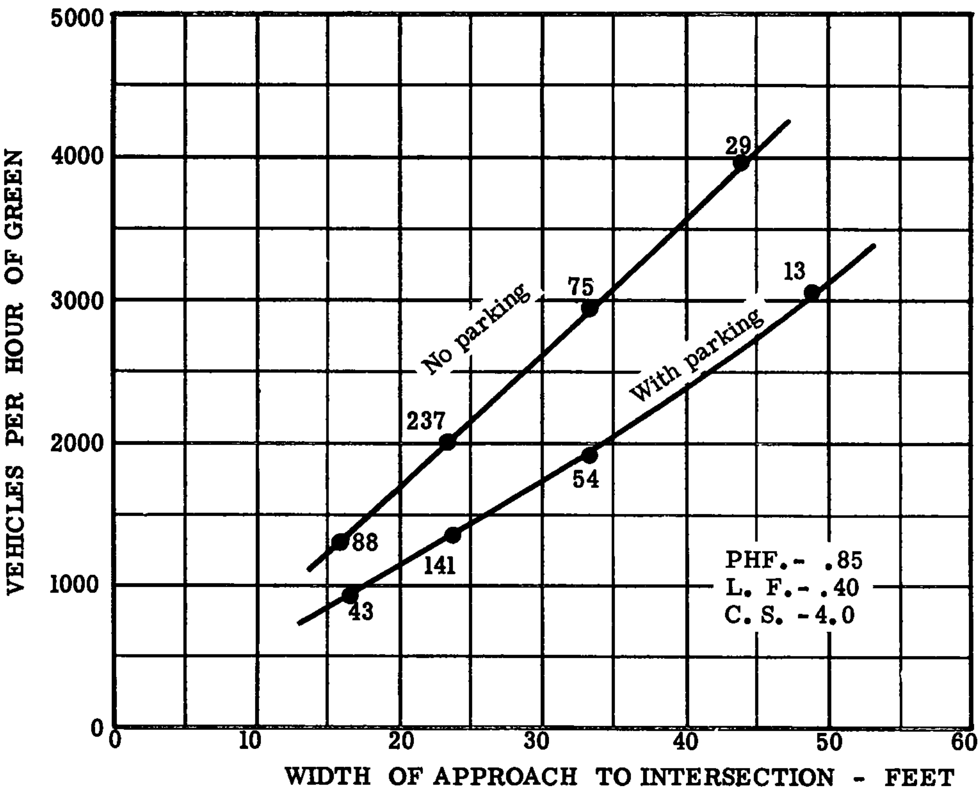

Figure 38. Capacity of intersection approaches on two-way streets.

EFFECT OF CITY SIZE

The effect of city size on the traffic-carrying capacity of an intersection located in that city was the most difficult of the primary variables to determine because the other primary variables (including the street width, peak-hour factor, and load factor) are also related to some extent at least to size of city. The effect of size as shown by Figures 32 through 34 is, therefore, over and above the effect that these other variables have on intersection capacities.

Size has been designated by numbers ranging from 1 through 6. These numbers represent the following city sizes:

Number	Population
1	Under 50,000
2	50,000 to 99,999
3	100,000 to 249,999
4	250,000 to 499,999
5	500,000 to 999,999
6	1,000,000 or more

It would probably have been more appropriate to use semilog paper for Figures 32 through 34 if the actual size of the city had been entered on the punch cards. The

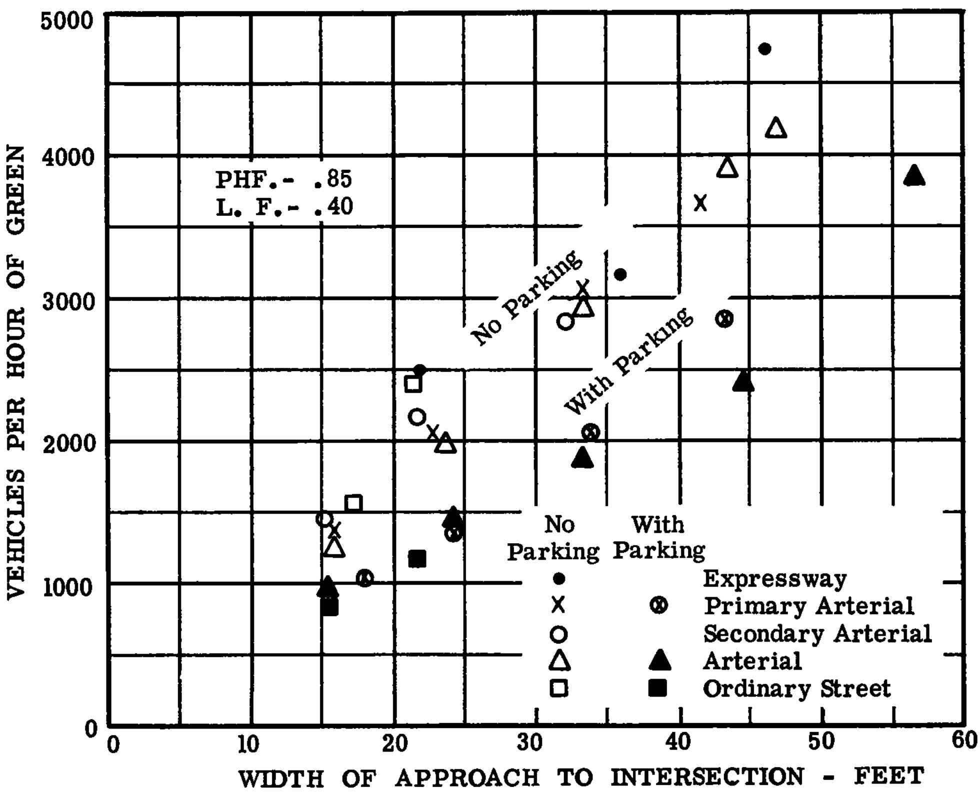

Figure 39. Capacity of intersection approaches, two-way streets by type of street.

average size of the cities as grouped, however, closely follows a logarithmic scale. In either case, the size of the city does have a very substantial effect on the traffic volumes that intersections on all types of streets will accommodate. The exact reason as to why the intersections in the larger cities accommodated more traffic than those in the smaller cities is not definitely known but the more common assumptions are (a) there are generally better traffic and pedestrian control measures in effect in the larger cities, and (b) drivers in the larger cities are more experienced in coping with high densities and congested traffic conditions than the drivers in the smaller cities.

The traffic volume that can be handled on an intersection in one city during the peak hour compared to that for an intersection in a larger or smaller city when all other conditions are the same, may be calculated by using the following equation:

$$VPH_2 = \left(\frac{14 + CS_2}{14 + CS_1}\right) VPH_1$$

in which

VPH_1 = known hourly volume for intersection in first city;
VPH_2 = hourly volume in second city;

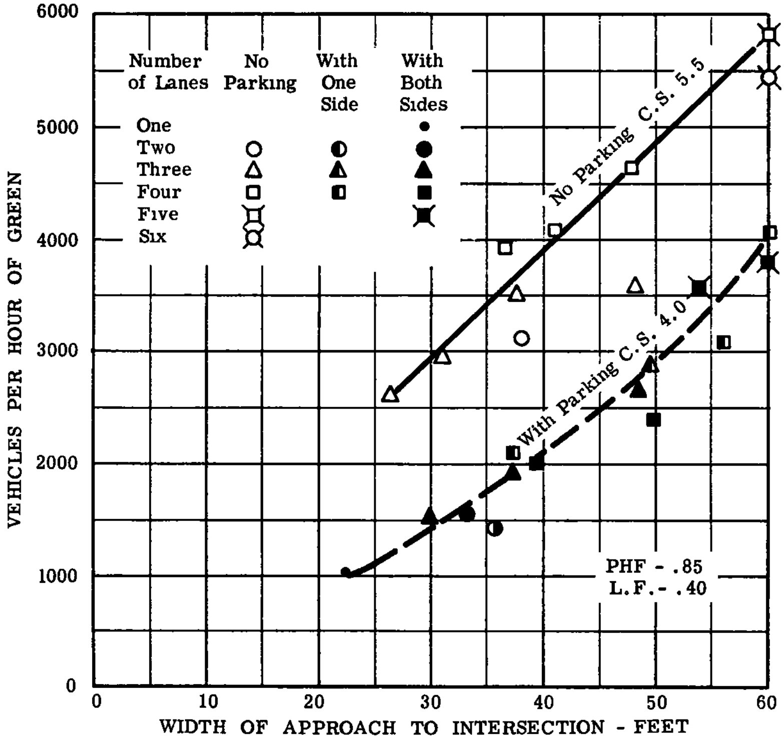

Figure 40. Effect of number of lanes, one-way streets.

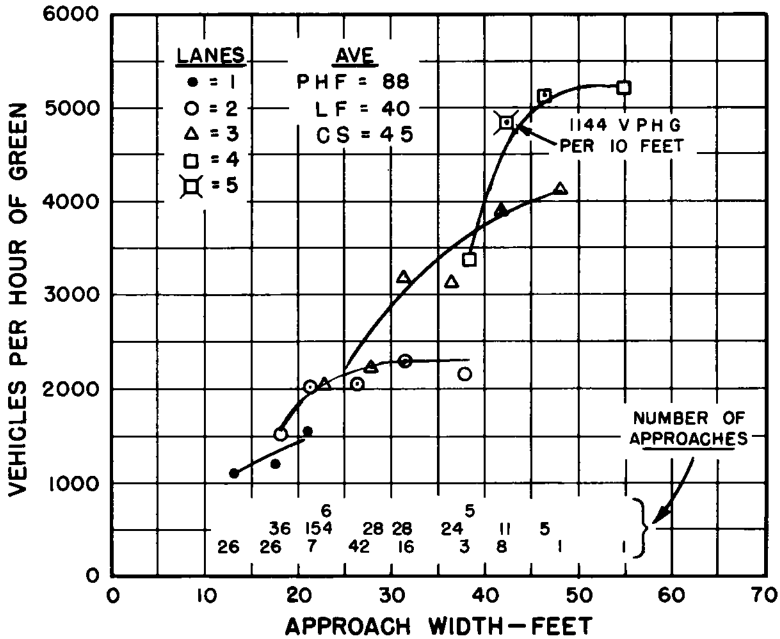

Figure 41. Effect of number of lanes, two-way streets, no parking.

CS_1 = size of first city;
CS_2 = size of second city (both city sizes being in terms of the code numbers used for this study).

For example, if an intersection approach in a city with a population of 162,000 can handle 500 vehicles per hour, an intersection with the same geometric features can be expected to accommodate about 560 vehicles per hour in a metropolitan area with 750,000 population $\left(\frac{14+5}{14+3} \times 500\right)$ providing traffic and other conditions are also the same.

EFFECT OF LENGTH OF GREEN PHASE

Figures 35 and 36 show for two-way streets the effect of the length of the green phases of the traffic signals on the traffic flows through intersection approaches in terms of the number of vehicles per hour of green time. The rate of flow per hour of green was obtained by expanding the flow as recorded during the green phases included in the peak 60 min to a full hour of green time.

On the two-way streets without parking (Fig. 36), there is little change in the rate of flow with green phases of different lengths. Any increase or decrease is not consistent between the different approach widths. On the two-way streets with parking, there is a general tendency for the rate of flow to increase as the length of the green phase is increased from 10 or 20 sec to 25 or 30 sec, depending on the street width, and then to decrease with any further increase in the length of the green phase. The exception is the curve for approaches 58 ft wide which continues to show an increase up to a green phase of 45 sec. This curve and also the curve for the 44-ft approach width are based on too few data to indicate a tendency that would be reliable enough to be applicable to other locations.

The results of this study are somewhat unexpected in view of the generally accepted practice of increasing the signal cycle to obtain higher capacities during peak traffic periods. These results do not necessarily condemn such a practice because some decrease in the flow during the green phases can be tolerated to reduce the percentage of amber time during the hour. For example, a peak of 1,450 vehicles per hour of green occurred on the 24-ft approach width (Fig. 36) when the green phase was 30 sec. With a green phase of 40 sec the vehicles per hour of green decreased to 1,400 VPHG. If a 60-sec cycle is assumed in the first case, a 77-sec cycle must be assumed in the second case to have two 4-sec amber periods and for the same ratio of green time in both cases between the intersecting roadways. With the 60-sec cycle, the total volume during a clock hour on the 24-ft approach would be 700 vehicles with 1,800 sec of green time, whereas with the 77-sec cycle the corresponding figure would be 727 vehicles with 1,867 sec of green time. The total delay to traffic at the intersection would depend on the peak-hour factor, the load factor, and the total traffic volume approaching the intersection during the peak hour. If the traffic volume approaching the intersection during the peak hour were under 700 vehicles, the total delays would be considerably greater with the 40-sec green period and 77-sec cycle than with the 30-sec green period and 60-sec cycle. At some approach volume considerably above 700 vehicles per hour, the total delay during the peak hour would under certain conditions become less for the 77-sec cycle than for the 60-sec cycle.

From the results of this study, it appears that the principal advantage of the use of green phases longer than 20 or 30 sec at individual locations results from the reduction in the percentage of the total time devoted to the amber phases and "all red" or "overlapping red" periods when they are necessary to clear the intersection of pedestrians or vehicles between the green phases. The longer green phases are also necessary at times to obtain the proper progression of traffic through a system of interconnected or coordinated signals. The disadvantages of the longer green phases as compared to the shorter green phases are (a) increased delays to traffic during periods when good progressive movement is not obtained and (b) fewer opportunities during the peak hour for vehicles that block the traffic movement in a lane to clear the intersection.

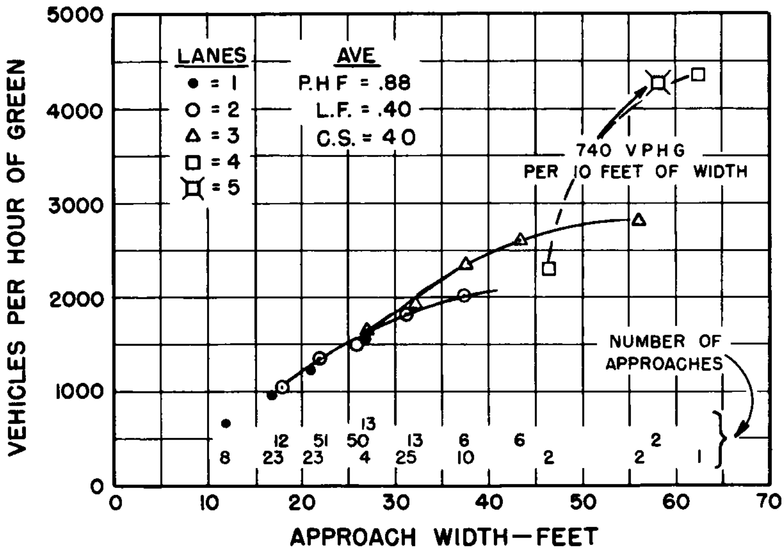

Figure 42. Effect of number of lanes, two-way streets with parking.

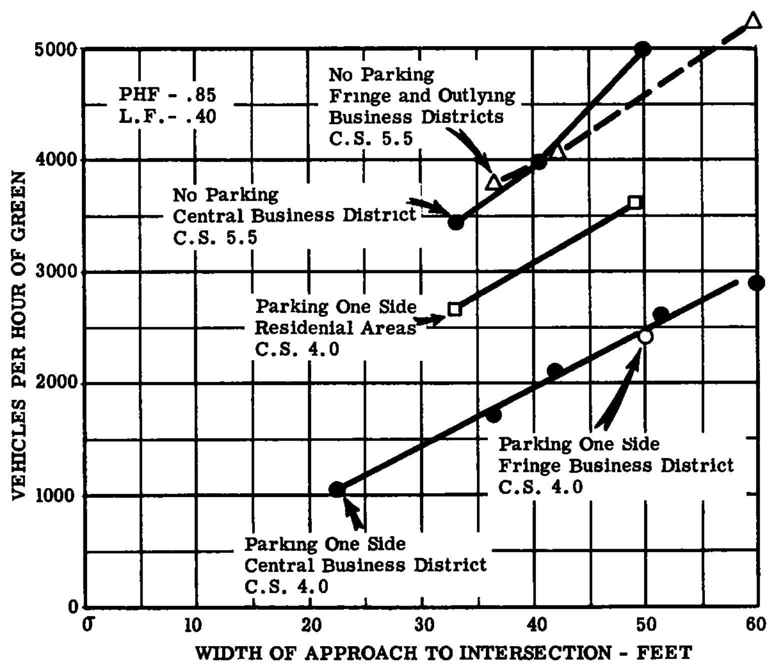

Figure 43. Capacity of intersections by area of city, one-way streets, no parking and parking one side.

EFFECT OF ON-STREET PARKING

The figures that have been presented thus far can be used to determine the effect of parking on one-way and two-way streets, but Figures 37 and 38 are more appropriate for this purpose. It is rather evident from Figure 37 that the sample of one-way streets

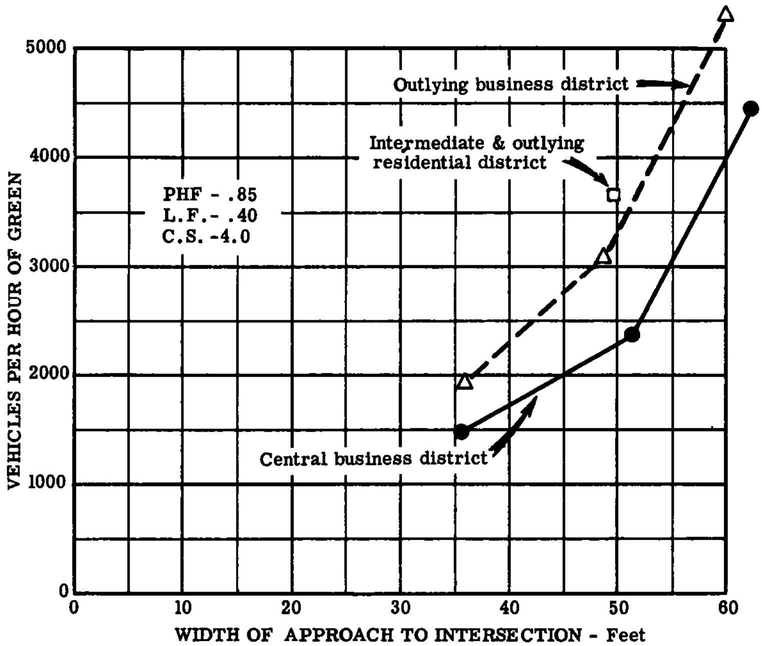

Figure 44. Capacity of intersections by area of city, one-way streets, parking both sides.

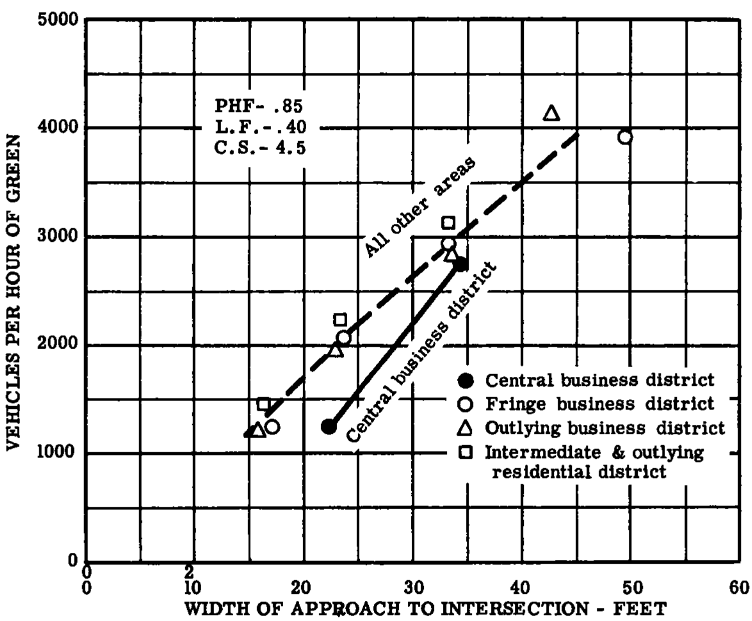

Figure 45. Capacity of intersections by area in city, two-way streets, no parking.

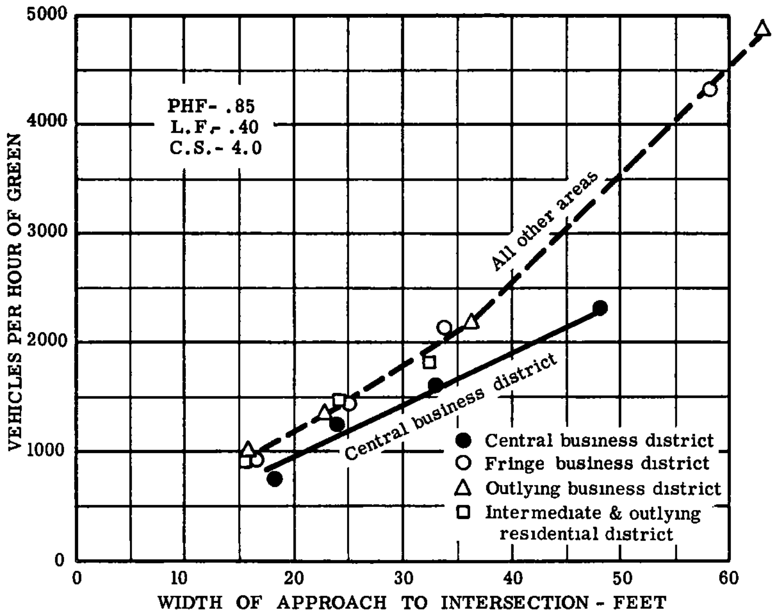

Figure 46. Capacity of intersections by area in city, two-way streets, parking both sides.

included in this study was too limited to obtain accurate values except for street widths within a range of 35 to 45 or 50 ft. The most accurate comparison can be made between the 40-ft widths which is as follows:

Parking	VPHG
None	3,550
One side	2,250
Both sides	2,000

Parked vehicles on one side of a one-way street 40 ft wide reduce its capacity 33.5 percent. The corresponding figure for parking on both sides is 43.6 percent. Fron another viewpoint, eliminating parking on one side of a one-way street 40 ft wide will increase its capacity only 12.5 percent whereas eliminating parking from both sides will increase its capacity 77.5 percent. Comparisons for other one-way street widths are not reliable because the data are not adequate to make such a comparison.

It is also evident that the one-way streets, especially those with parking on one side and the wider streets without parking, were not being operated in such a manner as to obtain anything like their potential capacities. Can it be true that the same effort is not being made through known traffic control procedures to obtain the potential capacities on these streets as on other types and widths of streets? Or is it too often assumed that one-way operation will solve a traffic problem and the street is then left to fare for itself? Two things are certain from the detailed studies that have been made of the data obtained for one-way streets: (a) there is a greater range in the traffic volumes carried by one-way streets with similar geometric and traffic characteristics when loaded to the same degree than for two-way streets, and (b) there is little or no advantage to one-way operation from a capacity viewpoint unless the one-way operation extends for a sufficient distance to obtain full utilization of the street's capacity. One-way operation for a few blocks may solve some of the problems at the intersections for the cross-streets but in such cases, the one-way streets cannot be expected to operate efficiently. There was an abnormal number of one-way streets included that were only a few blocks long that were connected at one end or the other with two-way streets of the same or a similar width.

The effect of parked vehicles on the capacity of two-way streets is shown by Figure 38. The results are considered reliable for approach widths of 15 to 45 ft. Parking reduced the capacity an average of about 30 percent regardless of the street width. It should be remembered, however, that parking is usually eliminated for some distance back from the crosswalk on most streets with parking and that more of the approaches of certain widths had the parking eliminated for a considerable distance to provide an additional usable lane than the approaches of other widths. The effect of this variable is covered later.

TYPE OF STREET BY SYSTEM

It was considered reasonable to assume that there might be some difference in the capacity of identical intersections on different types of streets. The type of street on which each intersection approach was located was therefore recorded during the field studies. Figure 39 indicates, however, that if the type of street or the street system made any difference, this fact was not apparent from the available data either for streets with or without parking, except possibly for the expressways at grade which show a slight tendency to be able to accommodate higher traffic volumes at the intersections than other facilities of the same width.

EFFECT OF NUMBER OF LANES

Traffic at intersection approaches of equal width sometimes operates in a different number of lanes at one location than at another. This is shown by Figures 40, 41, and 42.

One-Way Streets

Figure 40 shows that at the one-way streets with no parking the following obtained:

1. When traffic operated in four lanes on streets between 35 and 40 ft wide, the street accommodated, on an average, about 400 more VPHG than when the traffic was in three lanes, and about 800 more VPHG than when traffic was in two lanes.
2. Streets between 45 and 50 ft wide accommodated 1,050 more VPHG or nearly one-third more traffic when the vehicles were in four lanes at the intersection than when they were in three lanes.
3. For widths of 60 ft, five lanes accommodated somewhat more traffice than six lanes.

In considering the effect of the number of lanes for one-way streets with parking (Fig. 40), the elimination of parking ahead of the crosswalk must be considered. It is quite obvious that three lanes of traffic on a 30-ft street or four lanes of traffic on a 40-ft street could not have been accommodated at an intersection approach unless parking had been eliminated for a considerable distance ahead of the crosswalk. The data for the one-way streets were too meager to arrive at any extensive conclusions, but in general the streets where parking had been eliminated only near the intersection to permit traffic to operate in one additional lane did not, in most cases, accommodate substantially higher volumes than other streets of the same width but with traffic in one fewer lane on the approach. The curves in the figure represent, however, the minimum volumes that should be accommodated if the streets of specific width are divided into the most appropriate number of lanes.

Two-Way Streets

Sufficient data were recorded for the two-way streets to develop some interesting facts relative to effective street widths and their division into lanes. The results for two-way streets without parking (Fig. 41) show that streets of various widths accommodate more traffic when they operate with the following number of traffic lanes than with any other number of lanes:

Approach Width (ft)	Number of Traffic Lanes
Below 14	1
15 to 22	2
23 to 35	3
36 to 50	4

The traffic accommodated by the more efficient approach widths under average conditions with a peak-hour factor of 0.88 and a load factor of 0.40 on two-way streets without parking may be expressed by the following equation:

$$\text{VPHG} = (\text{Approach width in feet} - 5\text{ ft})\ 130$$

The average rate was considerably lower than this for approaches that were 15 ft, and 35 to 40 ft wide regardless of the number of lanes. There is some doubt, therefore, that these approach widths should be constructed or provided through line markings, except for unusual traffic conditions such as when there are either no commercial vehicles or an exceptionally large percentage of commercial vehicles during the peak hours. Approach widths of 35 to 40 ft, for example, might be very efficient when operating as four lanes with no commercial vehicles or as three lanes with an exceptionally large number of commercial vehicles. Lane lines must be well marked to obtain even reasonably efficient operation under the following conditions: (a) two lanes of traffic on widths under 20 ft; (b) three lanes of traffic on widths under 30 ft, and (c) four lanes of traffic on widths under 40 ft. A more detailed discussion of the effect of well-marked lane lines is presented later.

The intersection approaches on two-lane streets with parking that were of the more efficient widths accommodated average traffic volumes during the peak hours which may be expressed by the following equation when the peak-hour factor is 0.88 and the load factor 0.40 (Fig. 42):

$$\text{VPHG} = (\text{Approach width in feet} - 5\text{ ft})\ 78$$

This is 60 percent of the traffic accommodated by streets of equal width without parking. The number of lanes in which traffic was operating on the approach had a far less effect on the total peak-hour volume than for two-way streets without parking. This suggests that the midblock conditions have a very substantial effect on traffic flow, regardless of the number of lanes, on the intersection approach. For example, approach widths between 25 and 30 ft wide accommodated an average of about 1,500 vehicles per hour of green regardless of whether traffic entered the intersection from one, two, or three lanes. To obtain three-lane operation with widths of 25 to 30 ft, parking was prohibited on the approach for some distance ahead of the crosswalk, whereas this was not necessary for one- or two-lane operation. Likewise, parking had to be eliminated ahead of the crosswalk to obtain two-lane operation on widths under 25 ft. The data available also indicate that approaches between 40 and 48 ft wide on streets with parking are less efficient per foot of width than the wider or narrower approaches. Because approaches of this width generally occur only on two-way streets wider than 80 ft, the sample of such intersections included in this study was too small to be able to place any reliability in a general conclusion based on this statement.

LOCATION WITHIN A CITY

Each intersection included in this study was classified by the area of the city in which it was located. The five different location classifications were as follows:

1. Central business district;
2. Fringe of central business district;
3. Outlying business district;
4. Intermediate residential area; and
5. Outlying residential area.

Some intersections on two-way streets with and without parking were located in all of

TABLE 2

EFFECT OF RAIN ON INTERSECTION CAPACITIES (FROM DIRECT COMPARISONS)

Two-Way Streets								One-Way Streets with Parking			
No Parking				With Parking							
Approach Width (ft)	VPH of Green: Clear	VPH of Green: Rain	Percent Change	Approach Width (ft)	VPH of Green: Clear	VPH of Green: Rain	Percent Change	Approach Width (ft)	VPH of Green: Clear	VPH of Green: Rain	Percent Change
16	1,310	1,100	-16	17	1,070	810	-24	36	1,460	1,490	2
17	1,180	990	-16	18	1,260	1,240	- 2	36	1,190	1,230	3
20	2,380	2,200	- 8	24	950	900	- 5	36	1,050	1,040	- 1
20	3,460	2,750	-21	24	1,490	930	-38	36	1,700	1,530	-10
21	1,980	1,780	-10	24	1,910	1,580	-17	36	1,440	1,470	2
21	2,720	2,420	-11	38	3,790	2,410	-36	36	1,520	1,190	-22
24	1,060	1,130	8	38	1,560	1,370	-12	50	1,870	1,720	- 8
24	1,970	1,670	-15					50	1,630	1,590	- 3
24	2,750	2,010	-27					50	1,860	1,790	- 4
24	2,500	1,360	-46					50	2,300	1,990	-15
30	4,740	2,990	-37					50	2,480	2,040	-18
30	3,790	1,910	-50					50	1,740	1,730	- 1
Total	29,840	22,310	-249		12,030	9,240	-134	50	1,450	1,130	-22
Avg			-20 8				-19 1		21,690	19,940	-97
Weighted avg			-25 3				-23 2				- 7 5
											- 8 1

TABLE 3

AVERAGE VALUES FOR INTERSECTION APPROACHES WHERE EFFECT OF RAIN WAS STUDIED BY DIRECT COMPARISONS

Type of Average Value	Two-Way Streets								One-Way Streets with Parking			
	With 16- to 24-ft Approach Width				With 30- to 38-ft Approach Width				With 36-ft Approach Width		With 50-ft Approach Width	
	No Parking		With Parking		No Parking		With Parking					
	Clear	Rain	Clear	Rain	Clear	Rain	Clear	Rain	Clear	Rain	Clear	Rain
No of approaches	10	10	5	5	2	2	2	2	6	6	7	7
Width (ft)	21	22	21	21	30	30	38	38	36	36	50	50
Left turns (%)	7	6	12	7	21	0 5	2	0 5	11	8	8	15
Right turns (%)	13	11	2	8	20	9	36	0 5	11	15	12	4
Commercial (%)	6	8	5	10	10	8	10	7	11	7	5	7
Peak-hour factor	0 86	0 87	0 91	0 84	0 84	0 87	0 76	0 84	0 87	0 84	0 89	0 81
Load factor	0 32	0.40	0 57	0 41	0 74	0 22	0 41	0 18	0 14	0 12	0 17	0.17
VPH of green	2,131	1,741	1,340	1,090	4,270	2,450	2,680	1,890	1,390	1,330	1,900	1,710
Percent change	--	-18 3	--	-18 6	--	-42 6	--	-29 5	--	-4 3	--	-10 0

TABLE 4

EFFECT OF LOCAL BUSSES ON TWO-WAY STREETS

Type of Parking	Load Factor	Peak-Hour Factor	City Size	No of Lanes at Crosswalk	Avg Approach Width (ft)	Without Busses: No of Approaches	Without Busses: Avg per Hour Vol (VPHG)	With Busses: No of Approaches	With Busses: Avg. per Hour Vol (VPHG)	With Busses: Avg No Busses	Bus Equiv. in Passenger Cars
Without	0 40	0 85	5 0	1	16	29	1,300	29	1,180	24	6 0
				2	22	72	2,100	161	1,950	39	4 8
				3	32	29	3,007	65	2,957	47	2 1
				4	42	4	4,083	17	4,030	64	1 8
With[1]	0 40	0 85	3 5	1	20	22	1,250	36	1,200	24	3 1
				2	26	25	1,624	123	1,490	30	5 5
				3	32	8	2,170	30	1,845	31	11 5

[1] Parking eliminated only at bus stop

these areas but no data were available for one-way streets under the following conditions:

1. No parking in residential area;
2. Parking on one side in outlying business district; and
3. Parking on both sides at fringe of business district.

One-Way Streets

For the one-way streets without parking (Fig. 43), there was no definite indication that intersection capacities were significantly different in central, fringe, or outlying business districts. There were no data for these streets in residential areas.

For the one-way streets with parking on one side (Fig. 43), intersection capacities were about the same in the central and fringe business districts. In both of these areas, the capacities of such streets were much lower than in the residential areas. In the central and fringe business districts they handled 34 to 40 percent less traffic than in residential areas with the greater difference percentage-wise being on the narrower streets. No data were available for one-way streets with parking on one side in outlying business districts.

For one-way streets with parking on both sides (Fig. 44), intersection capacities, on an average, were about 10 percent lower in the outlying business districts than in the residential areas. In the central business districts, they were 25 to 30 percent lower than in the residential areas.

Two-Way Streets

Intersection capacities for two-way streets, both with and without parking (Figs. 45 and 46), were, on an average, about 20 percent lower in the central business districts than in other areas of the cities. There was also some tendency for the two-way streets without parking to accommodate more traffic in the residential areas than in fringe or outlying business districts, but the difference was too small to make a distinction between these areas in traffic capacity determinations for two-way streets.

There are several reasons for the lower capacities in the central business districts than in other areas of the city. Two of the more important ones are (a) a greater frequency of vehicles stopping to load or unload passengers and (b) more pedestrians causing interferences to vehicular traffic. The latter cause can be further investigated with the data available. This will be in conjunction with the use and effect on capacity of separate pedestrian signals, separate pedestrian phases, and the "scramble" system in a subsequent report.

The fact that intersections with like geometric features are able to accommodate considerably higher peak-hour volumes when located in certain sections of a city than when located in the central business district makes it especially important that the curves thus far presented be modified in an effort to obtain a more accurate comparison of the relative capacities of one-way and two-way streets. This can be accomplished only after the effect of most of the other variables has been investigated.

EFFECT OF RAIN ON INTERSECTION CAPACITIES

Some 200 intersection approaches were studied during inclement weather conditions including periods while it was raining or snowing or while the streets were wet or covered with snow. None of these data has thus far been used in this analysis.

A detailed review of data for inclement weather conditions revealed that for 32 of the locations where rain occurred during the peak hour, repeat studies were conducted during fair weather conditions. The results obtained by comparing the hourly volumes through each of the 30 intersections during the rainy periods with the fair weather conditions are given in Table 2. Two-way streets with and without parking, and one-way streets with parking are included. No direct comparisons were obtained for one-way streets without parking.

The intersections on the two-way streets carried an average of 20 percent less traffic when rain occurred during the peak hour than for the fair weather condition. The reduction, on an average, was about the same for the two-way streets with parking as for those without parking. The corresponding figure for the one-way streets was 7.5 percent with only 5 of the 13 one-way streets being affected to any appreciable extent. There was also a tendency for the intersections on the wider streets, both one-way and two-way, to be affected more on a percentage basis than the narrow streets. The reduction due to the rain was therefore somewhat greater based on the weighted averages (by street width) than for the unweighted averages; 24 percent for the intersection approaches on two-way streets and 8 percent for those on the one-way streets.

There was a large variation in the effect of rain at the different locations but this variation was probably no greater than the difference in the rainy conditions that occurred. These varied from a light drizzle or wet pavement for a few minutes during the peak hour to a continuous light rain for the entire hour. Accurate information as to the exact conditions during the rainy periods is not available but there is no indication that a heavy downpour occurred for any extended period of time at any of the locations while the studies were in progress. A heavy downpour over an extended period of time would probably have caused a much greater reduction in the traffic flow. Also (Table 3), the lower volumes accommodated during the rainy periods as compared with the fair weather conditions were not the result of a lower traffic demand or a difference in other conditions (such as an increase in turning movements or in the percentage of commercial vehicles) which would also have had a tendency to reduce the traffic flow during the peak hours. A further analysis of the data for all the locations where inclement weather occurred might be desirable, but, if so, this can only be done on a basis of comparing average values for similar intersections, using the entire mass of data for each weather condition.

EFFECT OF LOCAL BUSSES

Local busses were operating on about 70 percent of the two-way streets on which the intersection approaches included in this study were located. The local bus volume at most of these locations was in the neighborhood of 2 percent of the total traffic during the peak hours. The number of local busses varied from an average of 24 per hour in the one direction on the narrower streets to 64 per hour on the wider streets with four traffic lanes for the one direction of travel. No attempt has been made to determine the effect of local busses on one-way streets or to relate the change in bus equivalents with a change in the number of busses on specific widths of streets in view of the limited data for this purpose.

Table 4 gives the results of the study to determine the effect of local busses in terms of the equivalent number of passenger cars. The bus equivalent varies for the two-way streets without parking from 6.0 when there is only only traffic lane to 1.8 when there are four traffic lanes. On the two-way streets with parking, the bus equivalent increased with an increase in the number of lanes; 3.1 on the streets with one lane to 11.5 for streets with three lanes for traffic in the one direction. Parking was always estimated at the bus stop on the streets with parking. This accounts in a large measure for the differences between the bus equivalents on the two-way streets with and without parking, especially when the following conditions are considered:

1. A bus while loading is usually out of the normal traffic lane on a street with parking and at least some of the right-turning vehicles can use the bus stop when no bus is present, thus providing an added street width part of the time. This is not true for streets without parking and only one lane for each direction of travel.
2. On the wider streets with parking, a bus in entering and leaving a bus stop interferes with traffic in lanes other than the one the bus occupies. This is not necessary on the streets without parking.

Locations where no local busses stopped during the peak hour to load or unload passengers, as well as near- and far-side bus stops and intersection approaches with both near- and far-side bus stops, were included in the preceding analysis. The number and percentage of locations for each each of these conditions are given in Table 5.

The data for the two-way street intersections that had two traffic lanes for the one direction of travel contained the largest sample and were therefore used to determine the relative advantage of near- and far-side bus stops. The results are given in Table 6 for the two-way streets. These results show that the busses cause less interference to other traffic if the stop is located at the far side on the streets without parking and at the near side on streets with parking.

TABLE 5

DISTRIBUTION OF LOCATION OF LOCAL BUS STOPS

Bus Stop	Intersection Approaches for Two-way Streets			
	With No Parking		With Parking	
	Number	Percent	Number	Percent
None [a]	75	27.5	52	27.5
On near side	142	52.3	109	57.7
On far side	44	16.2	22	11.6
On both sides	11	4.0	6	3.2
Total	272	100.0	189	100.0

[a] No passenger stop made by local busses during peak hour.

OTHER FACTORS AFFECTING CAPACITY

There still remain for analysis several variables that have an extremely important effect on intersection capacities. These include right turns, left turns, commercial vehicles, type of signal control; effect of separate pedestrian signals and pedestrian intervals; and the use of three- and four-phase control together with scheduling the movements during each phase and the sequence of the different phases. Some exploratory work has been done in all these areas using the extensive data obtained during this study, but the preliminary results in some cases contradict established traffic engineering practices to such a degree that further analyses are needed or desirable before their publication. As a few examples of the less controversial items, the preliminary analyses show that under certain conditions the following obtain:

1. An increase in the right-turning movements will improve the traffic flow through an intersection, especially when there are three traffic lanes on the approach.
2. At many intersections where three phases are being used, the third phase is not only unnecessary but hinders rather than improves the smooth and safe flow of traffic.
3. Traffic lane lines in good condition are far more necessary at certain locations than at other locations. In fact, in certain instances, even when applied in the most correct manner, they reduce capacities without improving safety.
4. The "scramble system" for pedestrians not only reduces the time available for vehicular movement but also increases pedestrian delays and pedestrian inter-

TABLE 6

EFFECT OF BUS STOP LOCATION ON BUS EQUIVALENTS

Item	No Parking		With Parking	
	Near-Side Stop	Far-Side Stop	Near-Side Stop	Far-Side Stop
No. of traffic lanes at crosswalk	2	2	2	2
Approach width (ft)	22	22	26	26
No. of locations	85	24	78	16
Traffic volume during PH (VPHG)	1,854	2,119	1,499	1,406
Avg. no. of busses during PH	41	34	40	37
Bus equivalent in passenger cars	7.0	1.0	4.1	7.0

ferences to traffic so that less traffic capacity is available during the shorter available periods for traffic movement.

There is such a wealth of information available in the data that have been compiled for this project that every effort should be made to analyze it to the maximum extent possible in an effort to obtain reliable information on which to base scientific traffic engineering practices for improving transportation in urban areas. There must also be developed a new basic family of curves for use in the design of intersections and for capacity determinations. These apparently will not invalidate any previous work that has been based on the Highway Capacity Manual published in 1950 but will place the entire procedure on a more scientific basis.

USE OF LOAD FACTOR RATIOS IN DETERMINING EFFICIENCY OF SIGNAL OPERATION

The most efficient movement of traffic and the least total delay occurs at an intersection when the two approaches carrying the major cross-movements are loaded to their same relative capacities. An excessive delay should not be encountered by traffic on one approach while there is little or no delay to traffic on the intersecting approach or approaches. The load factors obtained for the various approaches for the capacity analysis offer a means of determining the efficiency of a traffic signal in allocating time between the intersecting flows. By dividing the highest load factor for any of the approaches at an intersection into the highest load factor for the intersecting street, a ratio may be obtained which is called the peak-hour "load factor ratio" between the approaches. This ratio cannot exceed 1.00 but increases in magnitude with an increase in the efficiency of the signal in allocating the time between the two approaches. This may not be true at locations where a major street intersects a minor street because in such a case the least delay occurs if the signal is set to favor the major facility. Nearly all (95 percent) of the locations included in this study were, however, at the intersection of two major arterials.

TABLE 7

DISTRIBUTION OF LOAD FACTOR RATIOS FOR ALL TYPES OF INTERSECTING STREETS

Load Factor Ratio Between Approaches		Intersection with Data Available		Peak-Hour Factor	
Group	Avg	No	Percent	Avg Highest at Intersection	Avg Ratio Between Approaches
0 01 - 0 09	0 02	43	16 0	0 87	0 92
0 12 - 0 18	0 15	16	6 0	0 90	0 93
0 20 - 0 29	0 24	17	6 3	0 87	0 91
0 30 - 0 39	0 34	27	10 1	0 87	0 92
0 40 - 0 49	0 45	30	11.2	0 88	0 93
0 50 - 0 59	0 54	24	9 0	0 86	0 93
0 60 - 0 69	0 65	31	11 6	0 86	0 94
0 70 - 0 79	0 75	21	7 8	0 88	0 93
0 80 - 0 89	0 85	26	9 7	0 91	0 92
0 90 - 0 99	0 95	33	12 3	0 90	0 94
Total		268	100 0		

There were 268 intersections included for which complete data regarding the intersecting movements are available. At the other intersections, both streets did not carry traffic volumes of sufficient magnitude to load at least one approach on each street so as to produce a load factor of about 0.10 or higher. In such cases only the data for the one approach with a load factor of 0.10 or above were included and therefore the "load factor ratio" for the intersection cannot be calculated. In certain instances, the signal cycle was also changed from its normal setting for this study in order to obtain a high load factor on one of the approaches. The traffic volumes on the approaches carrying the cross-traffic were in such instances too low to be used for the capacity analysis so these intersections are also not included in the 268 for which complete data for the cross-movements are available.

Table 7 shows that the load-factor ratios for the 268 intersections were almost uniformly distributed over the widest possible range. There were just as many intersections with a poor adjustment of the signals for peak-hour traffic, resulting in a load-factor ratio under 0.09, as there were intersections with the best adjustment of the signals. A load-factor ratio of 0.09, for example, means that eleven times as many of the signal cycles on one approach were loaded as on another approach carrying cross-traffic. A further condensation of this table shows that at 37 percent of the intersections the load-factor ratio was 0.4 or less, at another 37 percent it was between

TABLE 8

DISTRIBUTION OF LOAD FACTOR RATIOS BY TYPE OF INTERSECTING STREETS

Load Factor Ratio Between Approaches		Intersection with Data Available		Avg. Highest Load Factor at Intersection	Peak-Hour Factor	
Group	Avg.	No.	Percent		Avg. Highest at Intersection	Avg. Ratio Between Approaches
Intersection of One-Way Streets						
0.00 - 0.07	0.01	18	41.9	0.16	0.88	0.94
0.10 - 0.15	0.15	1	2.3	0.13	0.88	0.90
0.20 - 0.28	0.25	4	9.3	0.35	0.90	0.89
0.32 - 0.34	0.34	3	7.0	0.27	0.84	0.96
0.41 - 0.49	0.44	3	7.0	0.34	0.86	0.92
0.50 - 0.56	0.53	3	7.0	0.32	0.92	0.93
0.66 - 0.69	0.67	3	7.0	0.68	0.94	0.94
0.71 - 0.77	0.74	2	4.6	0.46	0.88	0.94
0.81 - 0.89	0.85	4	9.3	0.59	0.91	0.91
0.92 - 0.99	0.92	2	4.6	0.30	0.93	0.94
Total	0.32	43	100.0			
Intersection of Two-Way Streets						
0.00 - 0.09	0.02	22	11.6	0.32	0.85	0.90
0.12 - 0.18	0.14	12	6.3	0.60	0.91	0.94
0.20 - 0.29	0.23	11	5.8	0.52	0.87	0.90
0.30 - 0.39	0.34	17	9.0	0.51	0.87	0.93
0.40 - 0.49	0.45	24	12.6	0.56	0.88	0.92
0.50 - 0.59	0.54	15	7.9	0.68	0.85	0.94
0.60 - 0.69	0.64	26	13.7	0.65	0.84	0.94
0.71 - 0.79	0.75	17	8.9	0.61	0.88	0.92
0.80 - 0.89	0.85	18	9.5	0.71	0.91	0.92
0.90 - 0.99	0.96	28	14.7	0.74	0.89	0.94
Total	0.53	190	100.0			
Intersections of a One-Way and a Two-Way Street						
0.00 - 0.09	0.02	3	8.6	0.50	0.92	0.89
0.10 - 0.15	0.15	3	8.6	0.50	0.88	0.93
0.26 - 0.29	0.26	2	5.7	0.61	0.81	0.97
0.30 - 0.38	0.34	7	20.0	0.45	0.88	0.90
0.42 - 0.49	0.46	3	8.6	0.51	0.90	0.98
0.50 - 0.58	0.52	6	17.1	0.39	0.84	0.90
0.67 - 0.69	0.68	2	5.7	0.73	0.93	0.93
0.72 - 0.77	0.74	2	5.7	0.70	0.89	0.94
0.81 - 0.85	0.83	4	11.4	0.62	0.92	0.94
0.91 - 0.96	0.93	3	8.6	0.71	0.91	0.93
Total	0.48	35	100.0			

0.4 and 0.8, and at only 26 percent of the locations was the load-factor ratio 0.8 or higher during the peak hours.

These figures illustrate the tremendous possibility of improving traffic flow or reducing delays at intersections within urban areas through methods and equipment which will give a better allocation of the green signal time between traffic on intersecting streets. The results would have been even more astonishing had not most of the intersection approaches where load factors under 0.10 were recorded been excluded from this capacity analysis. There is general agreement that it is easier to achieve the proper allocation of the green signal time at the intersection of one-way than two-way streets. Table 8 (cols 1 and 4), however, shows that such a possible achievement was not accomplished in actual practice. The fifth column does show, however, that there was some tendency to obtain a better allocation of the green time between approaches at the most heavily loaded intersections. All intersections selected were heavily loaded.

Columns 6 and 7 in Table 8 also show that the "peak-hour factors" and the "ratio" between the peak-hour factors on intersecting approaches at the same intersection did not have a tendency to change with a change in the load factor ratio. This means that an improvement in the allocation of green time between intersecting approaches may have changed the magnitude of the two traffic flows through the intersection but did not change the patterns of the flows during the peak hour.

It is of interest to investigate the peak-hour load factor ratios by the type of traffic signal system inasmuch as the data for this study included the most heavily loaded intersections in all areas of the United States. It is believed that the sample was fairly representative for the various areas because each selected intersection was generally at the location of the worst congestion on a street or highway, or system of streets or highways. It is not purported, of course, that the sample includes the most heavily loaded intersections in the United States as a whole.

Tables 9 and 10 give the distribution of signal types and the average load-factor ratio for each of the signal types separated by isolated signal locations in coordinated systems. The figures in these tables indicate that during periods of peak flow, at least on an average, fully actuated signals are either not being operated properly or do not have the type of performance that they are normally expected to have. The results, however, confirm the advantage obtained by the increased use that is being made of flexible progressive systems. The analysis to determine the effect of the type of signal system on the capacity of various types of streets has not, as yet, been completed. It is expected that the results of the study will be extremely useful in further improving the efficiency of traffic flow in the United States. There is still plenty of room for improvement.

STABILITY OF PEAK-HOUR FACTORS

The results of published studies on the 30th highest hourly volume during a year is an extremely reliable index for use in the design of highway facilities. It does change with time and with increases in traffic volume but these changes can be fairly accurately predicted. If the peak-hour factor is likewise to be a useful index for the design of intersections or for predicting future traffic volumes that they can accommodate, it is necessary to know more about the variables that tend to cause changes in the magnitude of the peak-hour factor. Although this study was not designed for this specific purpose,

TABLE 9

DISTRIBUTION OF TRAFFIC SIGNAL TYPES AND LOAD FACTOR RATIOS AT ISOLATED SIGNAL LOCATIONS

Type of Operation	Distribution (percent)	Average Load Factor Ratio
Fixed time	80	0 54
Pre-timed program	3	0 64
Semi-actuated	6	0 66
Fully actuated	11	0 36

TABLE 10

DISTRIBUTION OF SIGNAL TYPES AND LOAD FACTOR RATIOS FOR COORDINATED SYSTEMS

Type of System	Distribution (percent)	Average Load Factor Ratio
Simultaneous	7	0 43
Alternate	10	0 34
Simple progressive	63	0 42
Flexible progressive	20	0 61

TABLE 11

DISTRIBUTION OF RATIOS BETWEEN PEAK-HOUR FACTORS FOR THE TWO HEAVIER CROSS-MOVEMENTS AT EACH INTERSECTION

Peak-Hour Factor Ratio		Intersection with Data Available		Avg. Highest Peak-Hour Factor	Avg. Highest Load Factor	Avg. Load Factor Ratio
Group	Avg.	No	Percent			
0.54 - 0.74	0 64	4	1.5	0 85	0.59	0 45
0.75 - 0.79	0 77	8	3.0	0.87	0 42	0 36
0.80 - 0.84	0.82	12	4.5	0.86	0.33	0.40
0 85 - 0.89	0.87	33	12.3	0.85	0 49	0 42
0 90 - 0.94	0.92	79	29.5	0.89	0.54	0.53
0.95 - 0 99	0.97	132	49.2	0.88	0.57	0.50
Total		268	100.0			

the data do lend themselves to a few preliminary results that will help to guide future studies.

Table 11 shows, for example, that at about 50 percent of the intersections the peak-hour factors for the two heaviest cross-movements were within 5 percent of one another, and at nearly 80 percent the difference was less than 10 percent (cols 1 and 4). Also, the magnitude of the highest peak-hour factor at an intersection did not have a tendency to be greater where the difference between the two peak-hour factors was large than where the difference was small (col 5). Furthermore, there is only a slight, if any, tendency for the highest load factor at an intersection, or the load-factor ratios, to be greater at locations where the difference in the peak-hour factors for the two heavier cross-movements are large than where they are small (col 6 and 7). These are rather important findings if verified by more extensive studies under a larger variety of conditions.

There were only 48 intersection approaches that were studied twice during peak hours on clear days where the traffic volume during one study was appreciably higher than during the other study. The peak-hour factors and peak-hour factor ratios have been summarized in various forms in relation to the traffic flow rates and load factors for these 48 locations in Tables 12, 13, and 14.

TABLE 12

VARIATION IN PEAK-HOUR FACTOR AT SAME APPROACH

Peak-Hour Factor Ratio			Approach Studied Twice		Highest Peak-Hour Factor		Highest Flow Rate (VPHG)		Ratio of Traffic Flow Rates	
Group	Total	Avg.	No.	Percent	Total	Avg.	Total	Avg.	Total	Avg.
0.76 - 0.84	736	0.82	9	18.8	7,952	0.88	17,070	1,895	5.65	0.63
0.85 - 0.89	1,051	0.88	12	25.0	10,760	0.90	24,940	2,078	9.08	0.76
0.90 - 0.94	1,109	0.92	12	25.0	10,936	0.91	30,260	2,522	7.57	0.63
0.95 - 0.99	1,455	0.97	15	31.2	13,140	0.88	35,480	2,365	10.64	0.71
Total or avg.	4,351	0.906	48	100.0	42,788	0.891	107,750	2,245	32.94	0.686

TABLE 13

VARIATION IN PEAK-HOUR FACTOR BY MAGNITUDE OF PEAK-HOUR FACTOR

Highest Peak-Hour Factor		Approach Studied Twice		Avg Ratio Between Peak-Hour Factors	Highest Flow Rate at Approach (VPHG)	Avg Ratio Between Flow Rates
Group	Avg.	No	(%)			
0 75 - 0 79	0 77	4	8 3	0 88	2,420	0 62
0 80 - 0 84	0 82	5	10 4	0 91	2,046	0 68
0 85 - 0 89	0 87	13	27 1	0 94	1,983	0 70
0 90 - 0 94	0 927	22	45 9	0 90	2,447	0 68
0 95 - 0 99	0 964	4	8 3	0.88	2,056	0 75
Total		48	100 0			

TABLE 14

VARIATION IN PEAK-HOUR FACTOR AT SAME APPROACH COMPARED TO VOLUME CHANGE

Ratio Between Traffic Flow Rates		Approach Studied Twice		Avg Highest Traffic Flow Rate (VPHG)	Avg Highest Peak-Hour Factor	Avg Peak-Hour Factor Ratio
Group	Avg	No	(%)			
0 26 - 0 39	0 33	7	14 6	3,410	0 89	0 93
0 43 - 0 48	0 45	5	10 4	3,030	0 92	0 85
0 51 - 0 69	0 62	9	18 8	1,940	0 86	0 90
0 72 - 0 78	0 76	12	25 0	1,960	0 89	0 88
0 84 - 0 89	0 86	4	8 3	1,530	0 89	0 92
0 90 - 0 99	0 94	11	22.9	1,980	0 90	0 94
Total		48	100 0			

Table 12, which gives items by the magnitude of the ratios between the two peak-hour factors, shows that the average difference between the two traffic flows at the same locations were no greater, nor the peak-hour factors higher, where the larger changes in the peak-hour factors occurred than where the smaller changes occurred. Likewise, Table 14, which gives locations by the magnitude of the difference in traffic volume during the two studies, shows that the higher of the two peak-hour factors (col 5) and the ratio of the two peak-hour factors (col 6) do not increase or decrease with an increase in the difference between the traffic flow rates (col 1).

The two peak-hour factors for the same location determined during two different days will, on an average, be within 10 percent of one another even though the traffic volume on one day is triple the traffic volume on another day. The peak-hour factor at a given location apparently does not change with a change in the total flow during the peak hour. This is an extremely important traffic characteristic in relation to intersection design and capacity determinations.

CONCLUSIONS

There is little doubt but that the improvement of the efficiency of traffic movement at intersections is one of the more important, if not the most important, urban transportation problems. This study indicates that there is a lot of room for improvement. The study also develops new criteria in use for improving traffic flow through increased efficiency at intersections regardless of whether this improvement will come about through the use of present traffic control equipment, additional electronic equipment on the car or in the roadway; or the use of new equipment employing radar, infrared, or sonic detection with centralized control employing extensive high-speed computer systems to handle predetermined as well as feed back information.

Much remains to be done in translating the results of this study to a coordinated set of usable charts and tables and in completing the analysis of factors for which only preliminary results are available. What needs to be done, however, is clearly evident and not too involved. The terms "making better use of city streets," "coordinating street and expressway systems," and "the application of more scientific technology to urban transportation problems" are time-worn phrases that no one has completely understood or been able to put in practice to the extent desired. A continuation of this investigation is certain to produce new criteria and information that will go a long way toward the realization of these goals.