on the main street speed distribution;

2. A continuously flashing beacon encourages lower vehicle speeds along the stopped approach, but not if the beacon is actuated; and

3. The use of the actuated WHEN FLASHING—VEHICLE CROSSING signs and beacons along the main street approaches causes a reduction in speed dispersion along the approach, which is more pronounced on the approach with poor sight distance.

The use of advance warning beacons in conjunction with a STOP AHEAD sign was found to reduce speed variance. In addition, vehicles begin the braking maneuver farther from the intersection. However, these results become less significant when any beacon is used at the downstream intersection, probably because the intersection beacon flashes red while the STOP AHEAD beacon flashes yellow. This presents the driver with conflicting indications and negates any positive benefits. There does not seem to be any operational advantage to actuating an advance warning beacon.

ACKNOWLEDGMENT

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Effects of Signal Phasing and Length of Left-Turn Bay on Capacity

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A periodic scan computer simulation program was developed to investigate the effects of signal phasing and length of left-turn bay on capacity. After the simulation program was tested, inputs (phase sequence, volume, cycle length, and length of left-turn lane) were varied to evaluate their interrelationships under a range of conditions. Additional analysis was conducted by using a modified Poisson approach. The results show that, for a left-turn bay, traffic delay increases and signal capacity decreases when traffic interactions and flow blockages occur between left-turning and through vehicles. High left-turn volumes and short bay storage lengths experience the most severe reduction in capacity. We developed mathematical relationships between reductions in left-turn capacity and geometric and traffic conditions and provide design guidelines to minimize capacity reductions. Judicious selection of signal phasing reduces the loss in capacity to some extent, although all phasings can experience large losses under some geometric conditions.

Field observations of rush-hour traffic flow at signalized intersections having a protected left-turn bay suggest that the capacity of left-turn phases can be reduced by vehicles that block the entry of other vehicles into the left-turn bay. The left-turn bay may be blocked during the red phase of the signal so that the bay cannot fill, or vehicles may even be blocked from entering on a portion of the left-turn green phase. As traffic blockages begin to occur, the left turners may also begin to impede through vehicles, and capacity problems and intersection congestion are compounded.

Reductions in left-turn capacity generally occur as average traffic demands increase beyond the storage length of the left-turn bay and the cycle length of the signal. Shorter left-turn bays and longer cycles are more susceptible to such reductions. A shorter left-turn bay means that fewer vehicles can be stored before a blockage occurs; a longer cycle requires more vehicles to be stored for a given volume level before a green.

Some signal phasing sequences that improve traffic flow and left-turn capacity have been implemented, but primarily by trial and error methods. Little information that describes improvements made by increasing the left-turn bay length or by changing phasing sequence is readily available.

Basic design criteria for the length of the left-turn bay have been previously related to the Poisson approach (1, pp. 688-690), but design trade-off relationships are not provided. Operational corrective treatments for an existing situation are also limited and not emphasized.

The mathematical analysis of the movement of through and left-turning vehicles at an intersection under various traffic conditions, design configurations, and signal phasing sequences is extremely complicated, which is probably the reason for the lack of pertinent design and operations information.

SIMULATION APPROACH

The periodic scan computer simulation approach was selected to investigate the left-turn capacity problem. The many variables and project time and budget constraints meant that this study could not be completely exhaustive and that some questions would undoubtedly remain unanswered. Answers were sought, however, to basic cause-and-effect relationships and trends among (a) capacity, (b) demand volume, (c) signal phasing, and (d) length of left-turn bay.

Traffic operations were simulated on only one intersection approach, which included a protected left-turn lane and an adjacent through lane. A schematic of the approach model is depicted in Figure 1. The junction of the left-turn and through lanes is the first single storage position upstream of the left-turn bay and can be varied in the simulation program. Arriving automobiles (trucks and buses each equal two automobiles) progress through the left-turn and adjacent through approaches by moving from one storage position to the next in discrete movements according to a defined strategy. These queue positions were defined to represent an average storage length of an automobile stopped on red.

QUEUE CHARACTERISTICS

Field studies were conducted in College Station, Texas, to determine average automobile storage spacing characteristics. Stations every 7.6 m (25 ft) were marked along the median of the divided approaches, and distances to the end of each queue and the number of automobiles in the queue to the recorded point were manually estimated for each cycle. Queue lengths up to 131 m (429 ft) long were measured. There were no significant grades on the approaches to the intersection and few trucks. These average storage lengths are presented in the following table (1 m = 3.3 ft).

Study Location	Left-Turn Lane (m/automobile)	Through Lane (m/automobile)
University Avenue at South College Avenue	7.3	7.7
Texas Avenue at University Drive	7.1	7.3

We used a slightly conservative value of 7.6 m/automobile (25 ft) in the simulation program (2, p. 432). Left-turn and through storage lengths were assumed to be the same.

Queue movement characteristics were also important inputs to the simulation model. An automobile approaching the end of a queue was assumed to stop instantaneously when it reached the last unoccupied storage position. The stopped automobile remained at that position until a specific time after the signal turned green. At this time, the automobile began to move immediately at a speed that would result in crossing the effective stop line at the front of the queue at the correct clearance time for the given automobile position in the queue.

Studies of queue movement and clearance characteristics were conducted at three busy intersections in College Station. The results are summarized in Figure 2. Also shown are the two following representative equations for describing the data:

$$T_f = 2.0 + 1.0N_p \tag{1}$$

and

$$T_c = 2.0 + 2.0N_p \tag{2}$$

where

- T_f = time after start of green for the automobile in queue storage position number N_p to begin moving forward (s);
- T_c = time after start of green for the automobile in queue storage position number N_p to clear the stop line on the approach (s); and
- N_p = queue storage position number (Figure 1) for either left-turning or through automobile.

These equations were selected specifically to expedite the simulation process. They are obviously descriptive of the measured characteristics but were not determined by a formal optimization process such as linear regression. The simulation process was greatly simplified by assuming that all the coefficients of the previous two equations had integer values.

SIMULATION INPUTS

The following variables are inputs to the intersection approach simulation program:

1. Total lane approach volume (automobile/h),
2. Percentage of total approach volume turning left,
3. Cycle length of signal (s),
4. Length of left-turn bay storage (automobiles),
5. Green time of left-turn signal (s),
6. Green time of through movement signal (s), and
7. Leading or lagging left turns (single or dual) shown in Figure 3.

SIMULATION MODEL

The following is a brief outline of the simulation model in statement format.

1. The left-turn and adjacent through lanes are divisible into discrete automobile length storage positions, as illustrated in Figure 1.
2. The length of the left-turn lane is defined by the first upstream single storage position or the junction.
3. The simulation scans the system every second in the periodic scan mode, updating from front to back all storage positions that should be changed. Operational measures of effectiveness are recorded.
4. Automobiles arrive according to the Poisson distribution and are put into the system at storage position 26.
5. Automobiles were not permitted to enter the system at headways less than 2 s.
6. Every input automobile is tagged as being a left turner or a through automobile in a random manner at the desired average rate of left turners.
7. Every storage position can have only one of three states: (a) empty, (b) moving (M), or (c) stopped or queued (Q).
8. Moving automobiles (M) can move forward only into an empty position.
9. Where possible, all M move forward into the next position every 1-s scan period.
10. When an M cannot move forward into the next position, its status and storage position are changed to a queued automobile (Q), and it is delayed 1 s.
11. When a Q occupies the position immediately behind another Q for the scan period being analyzed, the first Q remains queued and is delayed 1 s.
12. When the signal is red, position zero acts like a Q so that no one can leave position 1 and enter the intersection.

Figure 1. Simulation model of actual intersection approach.

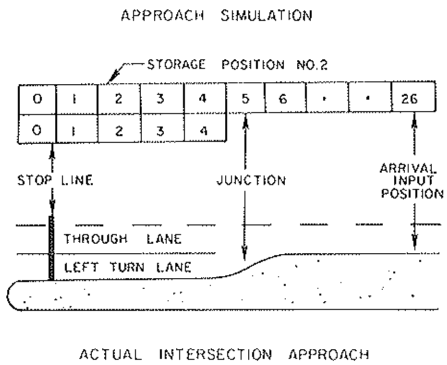


Figure 2. Movement characteristics of left-turning vehicles at busy intersections.

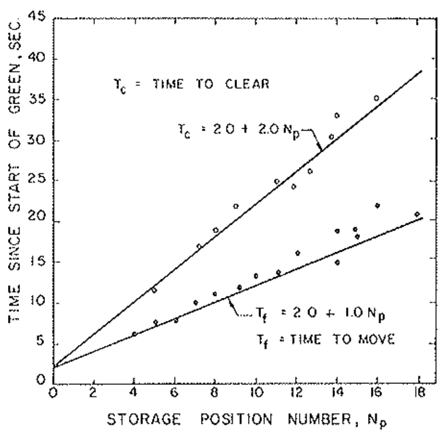


Figure 3. Signal phase sequences.

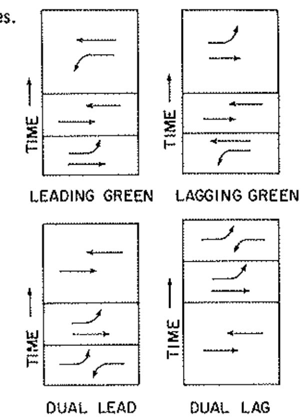
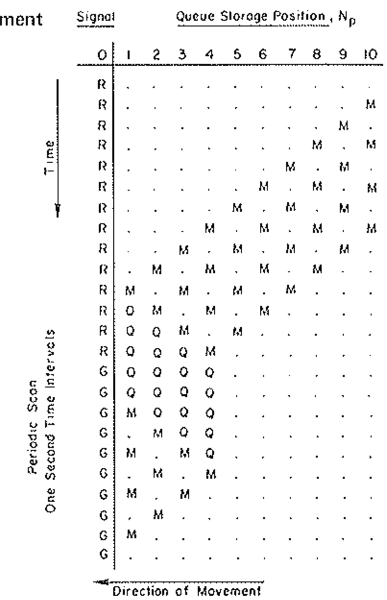


Figure 4. Queue movement in one lane.



13. When the signal turns green, position zero is immediately set to the moving state. Two scanning periods later, the Q in position 1 is changed to M.

14. When a Q is behind an M or an empty space, its status is changed to an M, but it does not move forward until the next scan period. It is therefore delayed 1 s.

The execution of these queue behavior rules is illustrated in Figure 4. The movement and clearance times of the queues obey Equations 1 and 2, as required to simulate the actual traffic conditions.

15. Automobiles at the junction position can be either left turners or through automobiles. Left turners obey the status of the next lower position in the left-turn lane; through automobiles obey the status of the next lower position in the through lane. If a through automobile is queued in the junction position, then no left-turning automobile can enter the left-turn bay until the through automobile has cleared the junction, and vice versa. Through automobiles can block left turners and left turners can block throughs.

SIMULATION OUTPUTS

Several traffic flow measures of effectiveness are calculated by the simulation program. These are (a) output volume for each movement (automobile/h), (b) delay/automobile for each movement (s/automobile), and (c) frequency plots of queue length and individual delay/automobile.

PROGRAM TESTING

The computer program was written in a combination of FORTRAN IV and Assembly and was tested in two ways. First, computer printouts were made of the simulated movement of automobiles on the approaches as the signals changed from green to red over several cycles. Movements of individual automobiles were observed for realism and obedience to the simulation rules for movement, blockage, and stoppage. Second, unimpeded delays calculated from the simulation program were found to be consistent with the results obtained from Webster's theoretical delay equation. In addition, subsequent simulated delay calculations followed expected trends as queue interactions and blockages occurred.

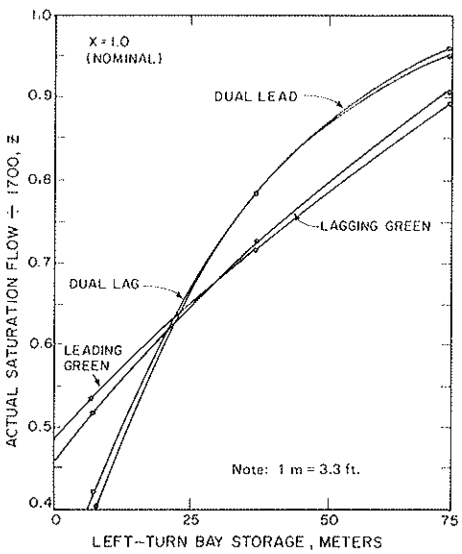
SIMULATION RESULTS

The results were most encouraging and revealed consistent trends and realistic outcomes. Many of the results were determined over 300 simulated cycles of operation for each data point. No fewer than 60 cycles were ever used. Five cycles were used to initialize the simulation model before we simulated the analysis cycles from which average values of the measures of effectiveness were calculated.

Table 1. Simulated average delay per vehicle movement.

Saturation Ratio	Left-Turn Demand (APH)	Through Demand (APH)	Left-Turn Bay Length (automobiles)	Left-Turn Delay (s/automobile)	Through Delay (s/automobile)
0.21	80	120	1	22	16
			5	22	16
			10	21	16
			20	21	16
0.42	160	240	1	39	26
			5	24	17
			10	24	17
			20	23	17
0.64	240	360	1	133	112
			5	39	29
			10	28	18
			20	28	18
0.85	320	480	1	121	106
			5	90	82
			10	56	45
			15	39	32
			20	35	30
0.95	360	540	1	137	117
			5	100	83
			10	94	57
			20	81	35

Figure 5. Reduction in left-turn saturation flow by phasing.

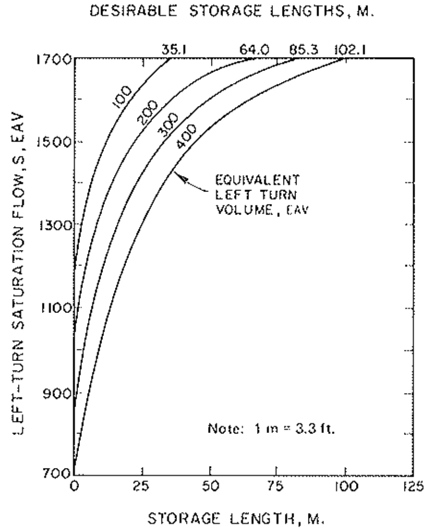


Delay

The initial analysis phase of the simulation study focused primarily on evaluating the effects of left-turn bay length and signal phasing on average automobile delay. Two signal phasing arrangements were studied: the leading left-turn and the lagging left-turn phase sequences. Cycle lengths of 60 and 80 s were studied. Approximately equal nominal volume-capacity (saturation) ratios were simulated for both left-turn and through movements. A nominal saturation ratio is defined as the normal demand on the movement divided by the phase's capacity when the left-turn bay is long enough to prevent blockages or interactions between the left turners and the throughs. In other words, the left-turn saturation flow is assumed to be 1700 automobiles/h of green (APHG), the nominal value for long bay lengths (3).

Simulation results of one of the delay studies is presented in Table 1. In this study green times were proportioned to yield uniform demand-capacity ratios for a 60-s cycle leading left. Delay increases with increasing volume, nominal saturation ratio, and cycle length. Delay also increases as the length of the left-turn bay shortens. Lagging green resulted in a slight reduction in delay for the conditions studied. Nominal saturation ratios of about 0.6 to 0.8 appear to be critical for bay lengths of 5 to 10 automobiles insofar as experiencing increased blockages and delay are concerned. These results indicate that the actual saturation ratio for the shorter bay lengths must have been considerably higher than the nominal value and that the saturation flow (and capacity) must have been correspondingly less than 1700 APHG.

Figure 6. Left-turn saturation flow and desirable storage lengths.



Left-Turn Capacity

Left-turn capacity and saturation flow studies were conducted in view of the previous findings. Most of these subsequent simulation runs were made at nominal saturation ratios of about 1.0. During these capacity studies, two additional phase sequences of left turners first (dual lefts leading) and through movements first (dual lefts lagging) were added. Average results of these simulation studies are depicted in Figure 5. For the conditions evaluated, we observed some differences in saturation flow with lagging and leading left-turn green phasing slightly better for extremely short bay lengths; dual lefts leading or lagging performed better at bay lengths of 5 to 10 automobiles.

It is important to note, however, that all of the phasing arrangements experienced reductions in capacity for these conditions, a nominal saturation ratio of 1.0. A left-turn bay length of 5 automobiles experienced a 20 to 30 percent reduction in capacity. General reductions in capacity were observed in most of the 90 simulation runs, and greater reductions in capacity occurred at higher volumes. Similar reductions in capacity were experienced by the adjacent through lane. Reductions in capacity also varied with the percentage of traffic turning left and the green split between the two movements in an apparently complex manner. No overall mathematical model that included all the identified variables was developed.

To aid design and operations engineers in estimating a reasonable capacity and saturation flow for a given left-turn bay storage length, the combined simulation results of all 90 runs were pooled, from which the following multiple regression model (statistical R-squared value 0.80) was developed:

$$Z = 0.98 - 0.14 \times V - 0.19 \times X_L \times V + 0.24 \times X_T \times V \quad (3)$$

where

- Z = actual left-turn saturation flow divided by the nominal saturation flow (Z = S/1700);
- X_L = nominal left-turn saturation ratio;
- X_T = nominal through movement saturation ratio; and
- V = $X_L \times X_T \times K$, where K is the average number of left turners arriving for each cycle divided by the storage length of the bay.

This equation was used to develop the saturation flow and storage design curves shown in Figure 6. Inputs selected for design were X_L is 0.8; X_T is 0.8; nominal saturation flow is 1700 APHG; assumed storage requirement is 7.6 m/automobile; and cycle length is 75 s. The saturation flow (S) for left turns in Figure 6 was equal to 1700Z. Volumes are equivalent automobile volumes (EAV) in automobiles per hour.

At the top of Figure 6 are the left-turn bay storage lengths that will result in practically no reduction in capacity for the intercept left-turn volume level. These storage lengths can be used as practical design storage lengths. Interpolated storage lengths can be calculated for intermediate left-turn volumes. These storage lengths compared favorably as design values for 12 queue distributions of automobile storage available from the simulation runs. Computer plotting costs allowed only 12 plots of queue distributions.

A special set of simulation runs was made to test and illustrate the capacity results of Figure 6. An intersection was assumed to have a left-turn bay of 7.6 m and a leading left-turn signal phasing sequence. It was also assumed that the left-turn volume was 320 EAV and that the through movement volume was 480 EAV. Corresponding (effective) green times were 14 and 20 s. Nominal saturation ratios of about 0.8 existed on both movements. According to Figure 6, however, the 7.6-m bay length combined with a 320 left-turn volume should result in a large reduction in left-turn capacity and saturation flow from 1700 APHG to an actual flow of about 1060 APHG. If this reduction in capacity does exist, then the given conditions are overloaded and large delays should result. The actual saturation ratios, X, would be about 1.30 on both movements.

Table 2 illustrates the consequences of the short bay and reduced capacity. The first row of Table 2 contains initially given conditions and results. Low flows and excessively long delays occurred. As movement green times are lengthened, flows climb to the volume levels being simulated, while delays drop to acceptable levels. In order to compensate for the 38 percent reduction in saturation flow estimated from Figure 6 (640/1700 = 0.38) and to provide actual saturation ratios of about 0.8, large increases in green are required. Green times of 22 s for the left turners and 32 s for the throughs provide the needed 57 to 60 percent increase. It would appear for this one extreme example that the reduction in capacity is slightly larger than estimated by Figure 6, although delay variations are very sensitive in the region being analyzed. However, the general trend and practical magnitude of expected left-turn saturation flows given in Figure 6 are supported.

LEFT-TURN BAY LENGTH—MODIFIED POISSON APPROACH

The previous simulation studies of the capacity and desirable length of left-turn bays were an outgrowth from an earlier project analysis that utilized a simpler approach, which was an extension of the Poisson procedure frequently used by traffic engineers. The Poisson approach forms the basis for storage length recommendation given by the American Association of State Highway Officials' red book (1), which states that

> At signalized intersections, the required storage length depends on the cycle length, the signal phasing arrangement, and rate of arrivals and departures of left-turning vehicles. The storage length should be based on 1.5 to 2 times the average number of vehicles that would store per cycle, predicated on the design volume.

The modified Poisson approach we shall present subsequently provides guidance in determining the relationship between the multiplier (1.5 to 2 times) and the design left-turn volumes. In addition, these results will support the previously recommended storage bay lengths given in Figure 6. Other important interrelationships will be presented between design and operational variables.

In the following equation, which we adapted with some minor changes in notation from Miller (4), we estimate the average number of automobiles remaining in the queue at a pretimed signal at the end of the green phase:

$$A = \exp^{-1.3}[(1 - X/X)(qC/X)^{1/2}]/2(1 - X) \quad (4)$$

where

- A = average number of automobiles in the left-turn bay at end of green;
- q = left-turn flow rate (automobile/s);
- C = cycle length (s);
- X = left-turn saturation ratio (qC/gs);
- g = left-turn effective green (s); and
- s = left-turn saturation flow (automobile/s·green).

The number of left-turning automobiles, in addition to A, arriving during the effective red that must be stored in the left-turn bay is

$$B = q \times R \quad (5)$$

where

- B = number of left-turning automobiles arriving on red;
- q = left-turn flow rate (automobile/s); and
- R = left-turn effective red time (s).

After the left-turn signal turns green, additional left-turning automobiles are joining the rear of the stopped left-turn queue for a time (T) until it is time for the automobile in queue position N_p to begin moving forward (see Equation 1). If T_f is set equal to the arrival time of automobile N_p after the start of green, then

$$T_f = 2 + 1 \times N_p = (N_p - A - B + 2 \times q)/q \quad (6)$$

and

$$N_p = (A + B)/(1 - q) \quad (7)$$

The left-turn flow rate (q) should be higher than the average left-turn flow rate to account for the short-term peak flows that occur cycle by cycle during random (Poisson) flow. The flow rate was selected so that the average number of cycle failures during the peak 15-min period of the design hour would equal 0.50. That is

$$\Sigma P_q \times 3600/C \times 1/4 = 0.50 \quad (8)$$

where ΣP_q is the cumulative Poission probability of exceeding flow rate q (5), and C is cycle length (s). Letting the design storage capacity of the bay be N_p, which in turn is calculated from q, then the above probability of overflow criterion can be expressed in design level of performance terms as follows: The odds are 50/50 that the left-turn storage demands will exceed capacity only once during a peak 15-min period of the design hour. Table 3 summarizes input values used to develop modified Poisson left-turn bay storage requirements from Equation 7.

Results of this approach are presented in Figures 7, 8, and 9. Figure 7 shows that the length of storage required increases with left-turn volume and with the signal phase's saturation ratio (X). This latter fact is important for several reasons. The normal Poisson approach to left-turn bay storage design (1) does not account for the signal's operating saturation ratio. If the saturation ratio exceeds 0.85, the length of storage needed to reduce the likelihood of interaction and blockage increases dramatically. As was shown in the earlier section on simulation of left turns, blockages cause a reduction in saturation flow. A maximum saturation ratio of 0.8 seems practical for use in design, although 0.85 would be more conservative.

Figure 8 presents the length of storage required as a function of cycle length and left-turn volume for the assumed design saturation ratio of 0.8. The storage length increases with increasing cycle length, but the rate of increase is only about 40 percent as large as suggested by the normal Poisson approach. This is explained by the fact that while longer cycle lengths require more automobiles to be stored per cycle, there are fewer cycles that have the opportunity to "fail" during the peak 15-min period of the design hour. This reduction is not accounted for in the normal Poisson approach.

Figure 9 presents comparative results between the design guidelines (1) previously noted and results obtained from the modified Poisson approach using a saturation ratio of 0.8 and a cycle length of 75 s. The variable m in Figure 9 is the normal Poisson parameter, i.e., average number of left turns per cycle. The guidelines of 1.5 to 2 m bound the modified Poisson curve up to left-turn volumes of 350 automobiles/h. The left-turn bay length required in Figure 9 is within 10 percent of those storage lengths, shown at the top of Figure 6, that were developed from the simulation analyses. In general, cycle lengths in excess of 80 s in Figure 8 result in slightly longer storage requirements than those given in Figure 6.

SUMMARY AND RECOMMENDATIONS

The results of this study show that traffic delay increases and signal capacity decreases for a left-turn bay when traffic interactions and flow blockages occur between left-turning and through automobiles. High left-turn volumes and short bay storage lengths experience the most severe reductions in capacity. Delay begins to occur when the signal saturation ratio reaches 0.6 to 0.8 for bay storage lengths of 5 to 10 automobiles, respectively.

The operational quality of service provided by a left-turn bay design was shown to depend to a significant degree on how well the traffic engineer signalized the intersection. A design can fail simply because the signal saturation ratio approaches 1.0. In addition, the signal phase sequence was found to affect operational performance. The leading and lagging phase sequences performed slightly better for short bay lengths, and the dual lead and dual lag sequences were superior for bay storage lengths over 22.9 m (75 ft). However, all four signal phase sequences experienced considerable reductions in capacity at high saturation ratios and short bay lengths.

The following left-turn bay storage design recommendations are offered on the basis of supporting results from two different study approaches. However, if a higher saturation ratio, 0.85 for example, is anticipated at an intersection, Figure 7 could be used to scale recommended distances up to this higher level. On the basis of the study results using a saturation ratio of 0.8, the length of storage for automobiles in left-turn bays at signalized intersections should not be less than the recommended values shown below (1 m = 3.3 ft).

Left-Turn Volume (equivalent automobiles/h)	Storage Length (m)
100	35.1
200	64.0
300	85.3
400	102.1

Automobile storage is assumed to be 7.6 m/automobile and does not include any distance provided in advance of the stop line or within the transition section into the bay. Truck and bus volumes should be converted into equivalent automobile volumes at a rate of two automobiles per truck or bus. Figures 6 and 8 or both may also be used to determine bay storage requirements.

The phase timing of left-turn signals at pretimed signalized intersections should account for the reduction in saturation flow that may occur during rush-hour traffic conditions as illustrated in Figure 6.

Table 2. Simulation of reduced saturation flow effects.

Green (s)		Flow (EAV)		Green Increase (%)		Delay (s/automobile)	
Left	Through	Left[a]	Through[b]	Left	Through	Left	Through
14	20	220	320	0	0	121	107
18	26	265	402	28	30	87	74
22	30	315	459	57	50	60	51
22	32	316	467	57	60	53	44
24	32	319	481	71	60	34	27
26	32	317	480	85	70	23	18

[a] Left-turn simulated volume = 320 automobiles/h (EAV).
[b] Through simulated volume = 480 automobiles/h (EAV).

Table 3. Input values of left-turn bay storage requirements for modified Poisson approach.

Cycle Length (s)	Cumulative Poisson Probability	Input Left-Turn Volume by Peak 15-Min Volumes					
		50 EAV	100 EAV	150 EAV	200 EAV	300 EAV	400 EAV
60	0.033	132	234	312	396	540	672
70	0.039	129	216	295	365	509	643
80	0.044	122	207	279	347	486	617
90	0.050	116	200	268	336	468	596
100	0.055	108	190	259	324	454	576

Figure 7. Left-turn bay storage versus saturation ratio.

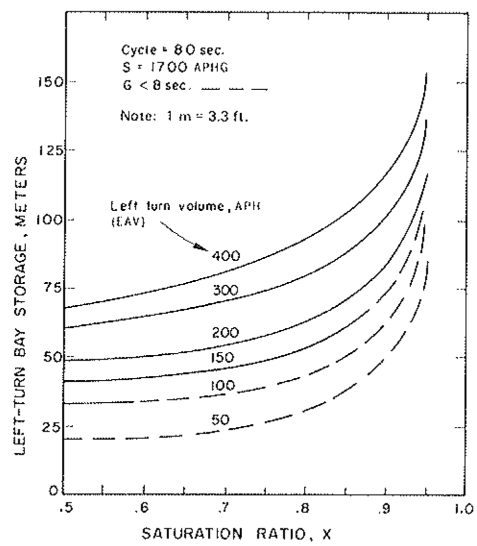


Figure 8. Left-turn bay storage versus turning volumes for various cycle lengths.

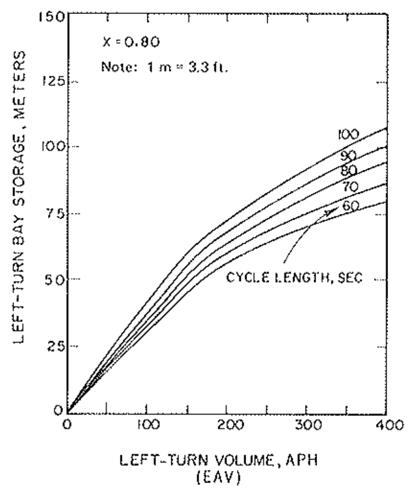


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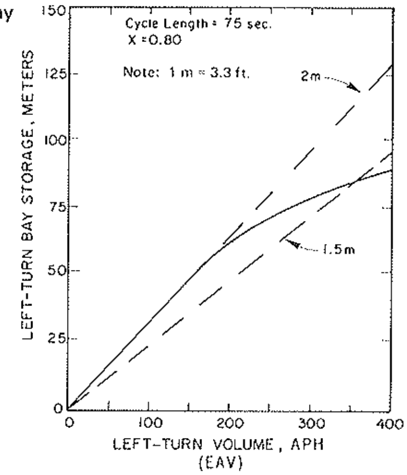
Figure 9. Left-turn bay storage versus turning volume.



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