INVESTIGATION TO DETERMINE THE CAPACITY OF PROTECTED LEFT-TURN MOVEMENTS

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This research evaluated the capacity of protected left-turn movements at signalized intersections where both separate turning lanes and separate signals were provided. Capacities were determined by field observations at selected urban intersections where signals had varying cycle lengths. Observed capacities were found to be significantly larger than capacities determined by the Highway Capacity Manual. The validity of observed results was checked by studying different intersections; no significant differences were observed. This research shows that protected left-turn capacities can be as much as one-third greater than those calculated by current procedures.

•OF all the problems of interest to the traffic engineer, the urban intersection at grade is one of the most important. If one considers that approximately one-half of all urban accidents and more than three-quarters of all urban delays are caused by, or are related to, urban intersections, the range and far-reaching consequences of the problem are more fully understood (1).

Efficiency and safety of movement through intersections is provided by regulating vehicles and pedestrians through the use of various types of traffic control devices. In many cases, the actual warrants used for the application of these control devices need much more refinement and development and are often subjects of controversy. The application of the protected left-turn type of signal control has been controversial, and a uniform acceptance has not yet been attained. Protected left-turn phases have been used either with or without a permissive left-turn phase following the protected movement.

Little factual study has been conducted in the past to establish uniform warrants for the installation of protected left turns. The existing warrants are not specific and are usually based on an expected increase in left-turn capacity or accident-reduction potential.

STATEMENT OF THE PROBLEM

The number of vehicles that can execute a left turn at a signalized intersection with a protected left-turn phase during a given period of time depends basically on two factors. The first is how soon the vehicles begin to move after the signal indication changes to green. The second is how fast each individual vehicle in the queue reacts to the vehicle immediately ahead. This process continues until all cars in the queue have entered or have progressed through the intersection or until the flow is stopped by a red signal indication. The amount of time required to dissipate a queue of vehicles after the signal changes to green depends on the reaction time and acceleration characteristics of each individual driver and vehicle. The total time for a group of vehicles to negotiate a left-turn movement at a signalized intersection can vary considerably.

Other factors affecting left-turn capacity at intersections with protected left-turn movements are physical and operating conditions such as approach width and parking conditions; load factor, peak-hour factor; metropolitan area population and location within the metropolitan area; traffic characteristics such as trucks, through buses, and local transit buses; and control measures such as type of traffic signals and marking of approach lanes (2).

PURPOSE OF THE STUDY

The primary purpose of this study was to determine the capacity of the left-turn movements at signalized intersections where both separate turning lanes and separate signal controls were provided for the left-turn movement and compare these capacities to Highway Capacity Manual (HCM) estimates.

A secondary purpose of this study was to investigate the effect of cross-traffic left-turning vehicles on the capacity of protected left-turn movements. Protected left-turn control is often installed at intersections where the cross-traffic left-turning vehicles are not controlled but are given a permissive movement. These permissive left-turning vehicles often fail to clear the intersection prior to their red indication, which means that they are blocking the intersection during the initial portion of the protected left-turn green phase.

VEHICLE HEADWAY AS A MEASURE OF CAPACITY

Average vehicle headways have been found to be a very practical unit in calculating the capacity of signalized intersections. Any given phase time divided by the average headway will give the actual number of vehicles that can pass the intersection during that period of time. To determine the capacity of a protected left-turn movement, we must obtain the average vehicle headways for the left-turning vehicles under loaded conditions. The phase length of the separate signal indication divided by the average headway for loaded conditions yields the capacity of the movement per cycle. The service volume per hour at capacity can readily be obtained by multiplying the capacity per cycle by the number of cycles per hour.

It has been found that the following factors affect average headways for through traffic: length of green phase, percentage of trucks, percentage of turning traffic, lane width, and grade. These same factors, with the exception of the percentage of turning vehicles, apply to average headways for left-turning vehicles (3).

LEFT-TURN STORAGE LANES

Intersections equipped with separate left-turn signal indications should normally also have separate turning lanes to store vehicles waiting for the green arrow. It has been found that both the length and the width of these lanes have an effect on the capacity of the movement.

Separate turn signal phases are often red, whereas the other through movements have a green indication; therefore, it is desirable to have the storage lane long enough to prevent blockage of a through lane. To ensure that all or nearly all vehicles are accommodated during each through green phase, the HCM suggests that, where possible, the storage lane be long enough to accommodate twice the average number of turning vehicles arriving per cycle (4). George and Heroy found that approximately 25 ft were required for each stopped vehicle at an intersection approach (5).

Leisch (6) felt that another consideration should be investigated in the determination of turning-lane lengths with separate signal phasing. He proposed that the turning lane should be long enough to allow entry of turning vehicles past a line of stopped, through vehicles.

A minimum length, based on 1.5 times the average number of through vehicles arriving per cycle, is needed to meet the requirements for through-traffic storage. This aspect often calls for a longer storage lane than that required to store the turning vehicles.

INTERSECTIONS STUDIED

The existing capacities of protected left-turn movements in Tempe, Arizona, were determined by studying three intersections. All intersections studied were at-grade, 90-deg crossings of signal-controlled arterial streets. Each intersection had four legs, protected left-turn lanes, and two-way traffic. Approaches studied were three lanes including the protected left-turn lane. The intersections studied were selected because of high volumes during peak hours. Curb parking is prohibited on all approaches.

DATA COLLECTION

The volumes of vehicles turning left were observed and recorded for the intersection approaches studied. Because the study was conducted with the cooperation of the Tempe traffic engineering department, the data collection was restricted to the afternoon peak so that a city employee could be present during data collection to adjust the traffic signal controllers. The controllers were adjusted to provide left-turn phase lengths both longer and shorter than the normal settings to permit data collection over a range of phase lengths. The adjustments made were in 1-sec increments so that adverse traffic conditions would not be generated.

Approximately 5 hours of data were collected at two of the intersections with 10 hours collected at the other—5 hours during a 70-sec cycle and 5 hours during an 80-sec cycle.

The left-turn movements at the intersections observed were not operating at capacity; therefore, it was deemed necessary to record the observed volumes on a per-cycle basis. Loaded cycles were recorded separately from partially loaded cycles. A loaded cycle was defined as the condition where the entire green phase was utilized by traffic with a backlog of at least one vehicle at all times. In other words, vehicles were continually present during the protected left-turn green phase, and at least one vehicle was restrained at the end of the phase by the amber or red signal indication.

The protected left turns studied were all located at intersections where the cross-traffic left-turn movements were permissive. It was observed that these permissive left-turning vehicles often remained in the intersections through their amber phase and into their red phase. The presence of vehicles in the intersection during their red phase (the green phase for the protected left-turn movement) interfered with the protected left-turn movements. In view of this situation, the recorded left-turn volumes were identified as having interference or no interference.

ANALYSIS OF FIELD OBSERVATIONS

The data obtained in the field for this study were reduced to a form that would permit the application of statistical tests. Statistical tests were used to determine the significance of the observations.

The observed protected left-turn volumes were recorded in one of four categories: loaded phases with interference from cross-traffic left-turning vehicles, loaded phases without interference, nonloaded phases with interference, and nonloaded phases without interference. Mean values that represent vehicles per protected left-turn phase were calculated for all loaded phases, loaded phases with interference, and loaded phases without interference. An adjusted mean was also calculated for the same three columns, which included the volumes from the partially loaded phases that had a greater number of vehicles per phase than the calculated means of the loaded phases. The adjusted means are the maximum average number of vehicles per protected left-turn phase that could pass the intersection, therefore representing the capacity condition. The standard deviations and the average vehicle headways were also calculated for the same data used to obtain the adjusted sample means.

Methods of Comparing Observed Capacity and HCM Capacity

To determine if a significant difference existed between the observed protected left-turn capacities and the capacities estimated by the HCM, we used a statistical test, the t-test. The hypothesis tested was that the adjusted mean number of vehicles per phase as calculated from field observations was equal to or less than the mean number of vehicles per phase as determined from the HCM.

Methods of Analyzing the Effect of Cross-Traffic Left-Turning Vehicles on Protected Left Turns

It was desired to test statistically the adjusted mean number of vehicles per loaded protected left-turn phase with interference from cross-traffic left-turning vehicles ($\bar{y}$) against the mean number of vehicles per loaded protected left-turn phase without interference ($\bar{x}$). It was considered important to test the hypothesis that $\bar{x}$ was less than or equal to $\bar{y}$, desiring to reject whenever $\bar{x}$ was larger than $\bar{y}$ (using $\alpha = 0.05$).

RESULTS OF THE STUDY

Field Observations Compared to HCM Estimates

The t-test was applied three times to each of the 31 approach conditions studied. For each approach condition, the test was used to determine if any significant difference existed between observed capacities and HCM estimates for testing all loaded phases, loaded phases with interference, and loaded phases without interference separately. (At one intersection data were not available for phase lengths of 14 and 16 sec without interference; at another, data were not available for the northbound approach during the 80-sec cycle with an 8.8-sec left-turn phase with interference.)

The hypothesis that the adjusted mean number of vehicles per phase from field observations was less than or equal to the mean number of vehicles per phase, as estimated from the HCM, was rejected 80 times out of 90 tests conducted. It was observed that of the 10 tests not rejected seven were for loaded phases with interference, two were for loaded phases without interference, and only one was unable to be rejected in the all-loaded category.

Effect of Cross-Traffic Left-Turning Vehicles on Protected Left-Turn Capacities

The t-test was used to determine if cross-traffic left-turning vehicles did significantly reduce the capacity of protected left-turn movements. The hypothesis that the adjusted mean number of vehicles per loaded phase without interference was equal to or less than the adjusted mean number of vehicles per loaded phase with interference was rejected 10 times out of 28.

DISCUSSION OF RESULTS

The analysis of data indicated that the capacity of the protected left-turn movements observed for all loaded phases was significantly greater than that estimated by the HCM for 30 of 31 approach conditions studied. The capacities determined from field observations for all loaded phases represented the existing capacity of the movements.

A plot of left-turn phase time versus left-turn vehicles per phase is shown in Figure 1, giving the difference between observed capacities and HCM estimates. Equations were produced that represent the best linear estimate of the data presented in the graphs. The equations

$$Y_o = 0.5066 + 0.3888X \tag{1}$$

and

$$Y_H = 0.0222 + 0.3388X \tag{2}$$

were produced for the observed capacities and HCM estimates respectively. The correlation coefficients of 0.9513 and 0.9999 for Eqs. 1 and 2 respectively indicated that the relations were a good linear fit.

The primary purpose of this study was to compare observed protected left-turn capacities with HCM estimates; however, it was felt that an explanation of the results should be proposed.

The HCM was developed from data collected throughout the United States with the stated purpose of creating a manual that could be used with confidence throughout the country. Variations in driver characteristics and composition among different regions would tend to indicate that one manual may not accurately represent all existing conditions.

The study location, in a city with a major university, probably contains a driver population somewhat younger than the national average.

The HCM does not specify when the data collections were conducted for the protected left-turn capacity analysis. It does indicate that data collections for the Manual began in 1954. The horsepower output of American-manufactured automobile engines has increased considerably since 1954 when less than 40 percent were V8's compared to 84 percent in 1969.

The results of the investigation into the effect of cross-traffic left-turning vehicles on protected left-turn movements were not as expected and warrant further study. Initially it was felt that a protected left-turn movement with interference would exhibit a capacity significantly less than the same movement without interference. This assumption was found to hold only 10 times in 30 tests.

The fact that the original assumption was not rejected ten times would tend to indicate that a more comprehensive analysis may be warranted to determine if the intensity of interference varies under different conditions. It was observed that, if a backlog of left-turning vehicles developed on the cross street, the drivers, after having waited through several cycles to reach the front of the queue, would often enter the intersection late in their amber phase or in the early seconds of their red phase, thus remaining in the intersection for several more seconds of the green arrow time than the usual permissive left-turn drivers.

Validity Check

To check the validity of the results, we conducted a limited study at three additional intersections in Tempe. The characteristics of these approaches are similar to those of the original intersections studied.

One hour of additional data was collected at each approach and then compared to the capacities expected as determined from this study. The expected capacities used were obtained from Figure 1. The t-test of hypothesis about a single parameter was used to determine if the capacities at the test approaches were statistically equivalent to the expected capacities from previous tests. The hypothesis of equality was not rejected at any test approach. The average percentage of variation from expected capacity was 8 percent.

Application of Results

The information obtained from this study has application to protected left-turn capacity analysis in Tempe, Arizona. Figure 1 could be used to predict the capacity service volume in vehicles per phase; however, because service volumes are usually expressed in vehicles per hour, an additional graph was constructed. Figure 2 provides a graphical solution for capacity service volumes in vehicles per hour for a variety of cycle lengths with protected left-turn phase lengths between 6 and 16 sec. Lines representing capacity service volumes (level of service E) estimated by the HCM were also placed on the graph.

Analytical solutions for the graph are provided through the following equations:

Cycle Length (sec)	Observed Capacity	HCM Capacity
50	$Y = 36.4752 + 27.9936X$	$Y = 1.5984 + 24.3936X$
60	$Y = 30.2761 + 23.3442X$	$Y = 1.3320 + 20.3280X$
70	$Y = 25.8366 + 19.8288X$	$Y = 1.1322 + 17.2788X$
80	$Y = 22.7970 + 17.4960X$	$Y = 0.9990 + 15.2460X$

In the preceding equations Y is the service volume at capacity in vehicles per hour, and X is the protected left-turn phase time in seconds.

Figure 1. Left-turn vehicles per phase versus left-turn phase time.

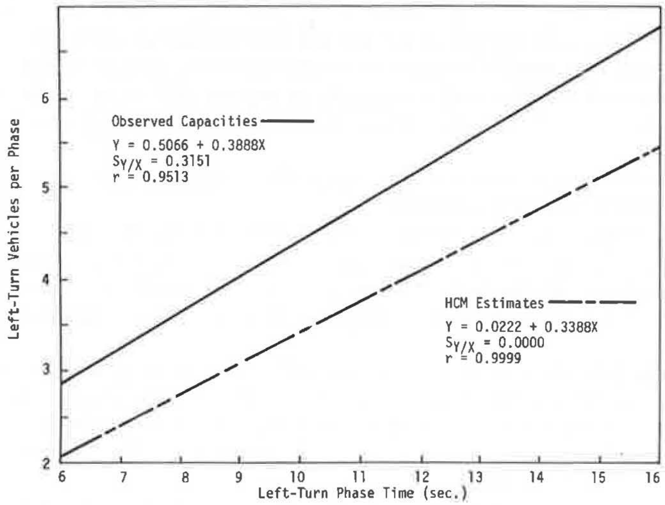

Figure 2. Left-turn volume versus left-turn phase time.

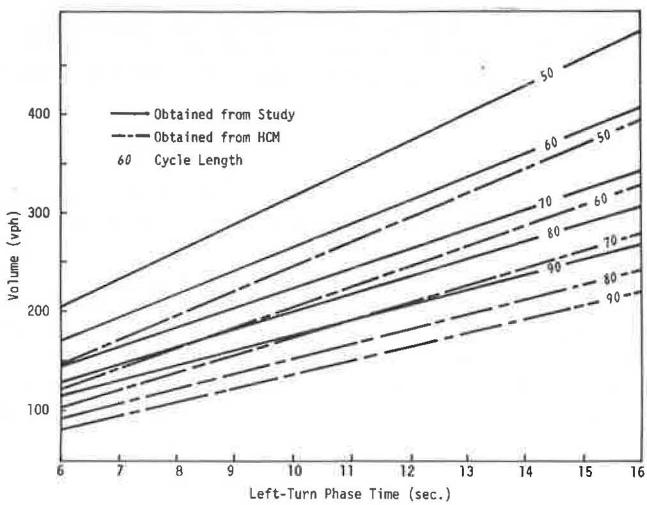

Table 1. Service volume per hour for 60-sec cycle.

Phase Length (sec)	Volume	
	HCM Estimate	Observed
6.3	129	177
7.0	143	194
7.2	147	198
7.7	157	210
8.0	163	217
8.4	171	226
8.8	179	236
9.0	184	240
9.1	186	243
9.6	196	254
10.0	204	264
10.4	212	273
10.5	214	275
11.0	224	287
12.0	245	310
13.0	265	334
14.0	286	357
15.0	306	380
16.0	326	404

Note: Average percentage of difference is 33 percent.

It should be pointed out that the scope of this study limited the investigation of these equations to left-turn phase lengths between 6 and 16 sec. The application of the equations for a 60-sec cycle length is given in Table 1. The observed capacities were on an average approximately 33 percent greater than HCM estimates.

CONCLUSIONS

The two main purposes of this investigation were to determine protected left-turn capacities at signalized intersections in Tempe, Arizona, and compare them with HCM estimates and investigate the effect that cross-traffic left-turning vehicles have on the capacity of protected left-turn movements.

By analyzing the volume of left-turn vehicles on four approaches at three different intersections, we made the following conclusions:

1. The protected left-turn capacities observed were significantly greater than those estimated by the HCM, and
2. The presence of permissive cross-traffic left-turning vehicles did not significantly reduce the capacity of protected left-turn movements in two-thirds of the observations.

AREAS OF FUTURE RESEARCH

In the course of collecting the data and preparing this report, several areas were encountered where further research could have been conducted.

One area of study would be an investigation into the effect of the time of day on intersection capacities. Other variables in capacity analysis that could be investigated include driver adherence to the laws related to protected left-turn movements, the presence of compact cars, and the composition of the driver population at various locations.

A study could be conducted to determine if regional variations in capacity exist and evaluate the feasibility of updating the HCM to adjust for regional variations if they do exist.

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