EFFECTS OF OPPOSING FLOW ON LEFT-TURN REDUCTION FACTORS AT TWO-PHASE SIGNALIZED INTERSECTIONS

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This paper reports results of a field study to evaluate the effects of opposing flow on left-turn reduction factors in computing capacity of two-lane approaches to two-phase signalized intersections with no separate left-turn lanes. Time-lapse photography was used to gather data on the approaching and opposing volumes and the delaying effects of left turners. Reduction factors were computed for different numbers of left turns per cycle by using regression analysis. The two variables that explained most of the variance were the ratio of the opposing flow in the curb lane to its capacity and the ratio of the arrival time of the first left-turning car to the green-plus-yellow time. Results indicate that, when the opposing curb lane is loaded, left turns have a much greater reducing effect than that given in the Highway Capacity Manual. The capacity-reducing effect of a single left-turning vehicle is greater than the incremental reduction effect of the second, third, and fourth left turners in a signal phase.

• THE CAPACITY of intersections controlled by two-phase traffic signals is adversely affected by left-turning vehicles, especially when the opposing traffic volume is high. Reduction factors for left turns, as given in the Highway Capacity Manual (1) for the basic case of no separate left-turn lanes or signals, do not reflect the effects of different levels of opposing traffic volume.

The purpose of this study was to evaluate the effects of opposing flow on left-turn reduction factors and capacity for two-phase signalized intersections with no separate left-turn lanes.

STUDY SITE

The field study was conducted at a suburban intersection in Skokie, Illinois (Fig. 1). The traffic being studied entered on the two two-lane approaches of Golf Road during the same signal phase, with green times varying from 20 to 60 s, as controlled by a fully traffic-actuated controller. Parking was prohibited, and interference from pedestrians and buses was negligible. Right turns were not permitted on red. Golf Road carries predominantly commuter traffic and has very few commercial vehicles in the evening peak hours. The speed limit is 40 mph (64 km/h). Volumes per cycle arriving from the west vary considerably because of the presence of an eight-phase fully traffic-actuated signal at Waukegan and Golf Roads 0.35 mile (0.56 km) west of the Gross Point intersection. This resulted in considerable variation in opposing volumes for different cycles. In the evening peak hours, right turns average 2.8 percent and left turns about 10 percent.

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DATA COLLECTION

Time-lapse photography was used to record entering and opposing volumes on Golf Road and the delaying action of left-turning vehicles, as affected by their arrival times. The films were taken in evening peak hours in February and March 1973; some films were taken in 1970 (7). Film speeds of 60 and 100 frames/min were used. A total of 364 cycles were analyzed, with analysis confined to the green-plus-yellow intervals for Golf Road. Filming was done only on clear days and under dry pavement conditions.

Separate field measurements were also made by cycle for entering volumes and headways in lane 1 (the curb lane) for both approaches on Golf Road by using hand tally counters and stopwatches. These counts, made only for loaded portions of cycles in evening peak hours, provided data on starting time delays, entering headways, and percentages of right-turning vehicles and permitted computation of capacity of these lanes for use in computing opposing volume-capacity (v/c) ratios for opposing lane 1 volumes. Results given in Table 1 are for through-car equivalents and conform to values obtained in earlier studies in the area (9).

DATA PROCESSING

A modified 16-mm Kodak Analyst projector was used in projecting the films taken. Traffic volumes for each lane for each direction were counted, and delays for individual left-turn movements were recorded. Only phases having at least one left-turning vehicle were analyzed. The data were analyzed by converting volumes to equivalent through-car units (TCUs), with commercial vehicles considered as equivalent to 2.0 TCUs and right-turning cars equivalent to 1.25 TCUs, as used in the Australian method of computing capacity (4). Delays due to left turns were determined from the film frame numbers recorded when the rear wheels of through and left-turning cars crossed the reference lines shown in Figure 1. All times as recorded in frame numbers were punched on computer cards for analysis.

CAPACITY REDUCTION FACTORS

The capacity of the approach with no left turns, in TCUs, was considered to be double the through-car capacity (TRUCAP) of lane 1, as determined from the field stopwatch study. The possible capacity (POCAP) of the center lane (lane 2) when left turners were present was defined as the number of left-turning cars that turned during the cycle plus the number of through cars that could have entered during the remaining green time of the cycle while the lane was not blocked by left turners.

The left-turn reduction factor (REFA) was defined as

$$\text{REFA} = \frac{\text{TRUCAP (lane 1)} + \text{POCAP (lane 2)}}{2\ \text{(TRUCAP)}}$$

REGRESSION ANALYSIS

To calculate the capacity and the left-turn reduction factors for an approach with varying opposing flows and left-turn movements, we used the BMDO2R computer program for a stepwise multiple regression analysis. In the regression analyses, the only cycles analyzed were those in which there was at least one left-turning vehicle in the approach being studied. Corrections were made later for the proportion of cycles having no left-turning vehicles (see Table 3).

Many variables were examined in the regression analysis. Those that remained after preliminary runs include the following:

1. Volume-capacity ratio of equivalent through cars in lane 1, opposing (VITRCO);
2. Volume-capacity ratio of equivalent through cars in lane 1, approaching (VITRCA);
3. Ratio of arrival time of the first left-turning car in lane 2, approaching, to the green-plus-yellow time of the phase (RAT); and
4. Number of left-turning vehicles, approaching, in the cycle (ALTA).

Regression analyses were made with data grouped according to light, medium, and heavy opposing flows (v/c ratios for lane 1, opposing, of 0 to 0.5, 0.5 to 0.75, and 0.75 to 1.00). The coefficients for computing REFA for cycles in each of the three groups of v/c ratios of lane 1, opposing, are given in Table 2.

The multiple correlation coefficients obtained were between 0.60 and 0.70 for the three stratified groups of opposing v/c ratios for lane 1. Inasmuch as many factors influencing the intersection performance are difficult to control, such as gap acceptance of left-turn vehicles and the arrival patterns of opposing queues, which were not considered in this study, the results obtained can be considered reasonably accurate.

Figure 2 shows an example of the extent of scatter for data points for a subgrouping of v/c ratios of lane 1, opposing, of 0.6 (0.55 to 0.65). Each data point represents one cycle and has an RAT value noted beside the point. The scattering of points along each vertical line reflects in part the effects of different RATs.

Of the variables considered in the regression analysis, RAT and VITRCO explained most of the variance of the reduction of capacity. ALTA makes only a minor additional contribution to the variance explained by the regression analysis, whereas the opposing left-turn movement and the opposing through-car traffic in the center lane were found to be covered by other variables and of little added value in predicting the reduction of capacity.

The importance of the ratio of arrival time of an approaching left turner to the green-plus-amber time on capacity can easily be verified by observing the traffic performance of a similar intersection. When no left-turn vehicles arrive in the center lane at the beginning of green, drivers of through cars in lane 2 approaching the intersection will usually use the center lane until the lane is blocked by an approaching vehicle desiring to make a left turn. If a left-turn car arrives at the beginning of the green period or has been left over from a previous cycle, through-car drivers will shift to lane 1 to avoid being trapped in the center lane, thereby leaving the lane primarily to a few left-turn vehicles.

The higher the opposing traffic flow is, the longer the delay experienced by left-turning cars will be, which will result in fewer through cars being able to use the center lane. This is evident from computations of distribution of volumes by lane. The ratios of approaching traffic volumes using the curb lane versus the center lane were observed as 1.53, 4.0, and 5.85 for opposing v/c ratios in lane 1 of 0 to 0.50, 0.51 to 0.75, 0.76 to 1.00. This explains why the through traffic in the opposing center lane is of little importance in predicting the reduction of capacity when there is high opposing traffic flow with some left turns. Most of the opposing through traffic used the curb lane.

MODIFICATION OF RESULTS OF REGRESSION ANALYSIS

In the regression analysis, only cycles having at least one left-turn car per green-time phase were included. Therefore, adjustments were made for the regression equations to consider the percentage of cycles having 0 left-turn cars for given average numbers of left-turn cars per cycle.

The frequency of cycles with different numbers of left turns per cycle was examined. The arrival pattern was found to follow the Poisson distribution (Fig. 3). The Poisson distribution thus was used to compute the proportion of cycles with 0 left turns (approaching) for different average numbers of left turners per cycle.

For cycles with 0 left turns (approaching), it is assumed that the capacity of lane 2 (approaching) is the same as for lane 1 approaching. The modified reduction factors for different average numbers of left-turning cars per cycle are given in Table 3.

These equations in Table 3 are being studied further to determine whether it is proper to assume that the capacity of the approach in cycles with no left turns is double that of lane 1. Preliminary studies of cycles with no left turns show that drivers still tend to queue in the right lane to avoid the possible effect of a left turner. This effect seems to vary with the average percentage of left turns. Full capacity of lane 2 appears to be attained only by prohibiting left turns.

Figure 4 shows the modified reduction factors for an opposing v/c ratio in the curb lane of 0.6 for various values of ALTA and RAT. This figure also shows a dashed line

Figure 1. Study site.

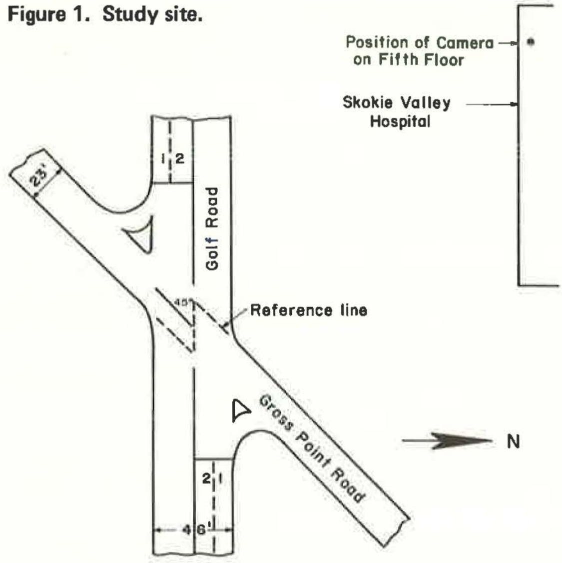


Table 1. Lane 1 discharge data for Golf Road for loaded portions of cycles.

Direction	Number of Cycles	Average Starting Time Delay (s)	Average Headway (s)
Eastbound	41	3.10	2.09
Westbound	29	3.05	2.08

Table 2. Coefficients from multiple regression for computing REFA.

	v/c for Lane 1, Opposing		
Variable	0 to 0.50	0.50 to 0.75	0.75 to 1.00
Constant	0.92948	0.97550	0.76049
VITRCO	-0.38648	-0.54134	-0.20251
RAT	0.28638	0.37936	0.31750
ALTA	-0.00564	-0.00770	0.00162
VITRCA	0.02973	0.05052	-0.01417

Figure 2. Regression results for v/c = 0.6 in opposing lane 1.

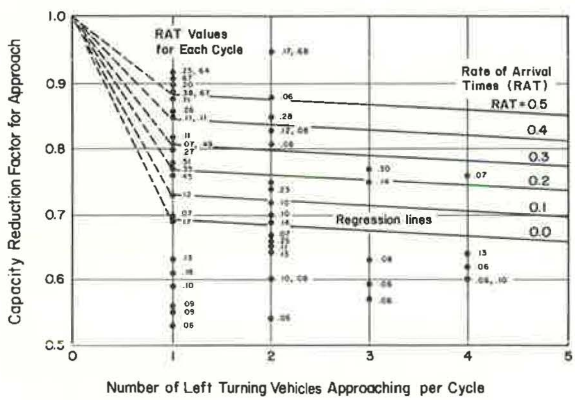


Figure 3. Observed distribution versus Poisson distribution.

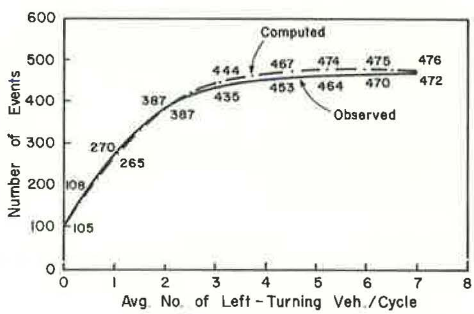
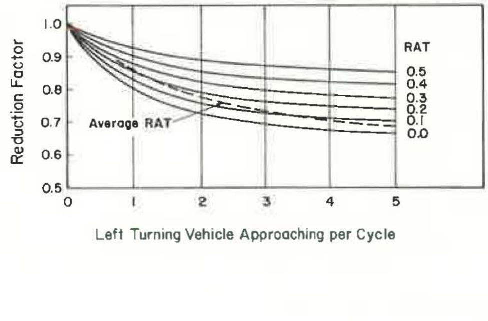


Table 3. REFA modified to include cycles with 0 left turns.

Average No. of Left-Turning Cars per Cycle	Probability of Cycles With 0 Left Turns	Modified Reduction Factor
1	0.368	0.368 + 0.632 × REFA[a] 1
2	0.135	0.135 + 0.865 × REFA 2
3	0.049	0.049 + 0.951 × REFA 3
4	0.018	0.018 + 0.982 × REFA 4
5	0.007	0.007 + 0.993 × REFA 5
6	0.002	0.002 + 0.998 × REFA 6
7	0.001	0.001 + 0.999 × REFA 7

[a]Reduction factor as obtained by the regression analysis, Table 2.

Figure 4. Reduction factors in relation to arrival times for v/c = 0.6 for opposing lane 1.



representing the average arrival times of the first left-turn vehicle for one, two, three, and four left turners per cycle.

Figure 5 shows the overall effects of left-turn vehicles on capacity, considering the observed mean values of the ratio of arrival rate for various average numbers of left-turn vehicles for the entire range of v/c ratios of opposing lane 1. This figure presents reduction factors that could be applied in capacity computations for percentages of left-turn vehicles, which correspond to the average number of left turners per cycle.

COMPARISON OF RESULTS

Left-turn reduction factors were calculated for varying conditions of opposing volumes and compared with those computed according to the Australian method and by the Highway Capacity Manual, as shown in Table 4. The results indicate that the values obtained in this study are somewhat lower than the values obtained by the Australian method for high v/c ratios in lane 1, opposing. The values are higher than those obtained by Lombaard (see Appendix). These differences warrant further study.

CONCLUSIONS

The following conclusions apply primarily to two-lane approaches to signalized intersections having conditions similar to the study site (two-phase signals, no separate turning lanes, no parking interference, and left turns from each of the opposing approaches in most cycles).

1. The v/c ratio of opposing traffic in the curb lane has a very significant effect on the capacity-reducing effects of left turns.
2. The time of arrival (RAT) of the first left-turning car (expressed as a ratio of arrival time to the green-plus-yellow phase length) also significantly affects the capacity-reducing effects of left turns (Fig. 4). RAT is related to the number of left turns per cycle and to whether any left-turn vehicles are held over from the previous cycle.
3. The capacity-reducing effect of a single left-turning vehicle in a cycle is greater than the incremental reduction effect of the second, third, or fourth left-turning vehicle in a cycle. In contrast, for the Australian method, the through-car equivalents for left-turn reduction factors are constant for different numbers of left-turning vehicles per cycle.
4. Left-turn reduction factors for 10 percent left turns, as computed in this study, appear to be affected slightly more by opposing flow than are left-turn reduction factors computed by the Australian method. At high opposing flows, the Highway Capacity Manual procedure underestimates the reducing effects of left turns.
5. The numbers of left turns and through cars in the opposing center lane do not contribute to the regression equation. Their effects, however, are reflected in the

Figure 5. Effects of left turns on capacity of a two-lane signalized approach.

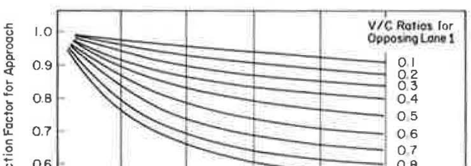


Table 4. Comparison of REFAs by Australian method, present study, and Highway Capacity Manual.

		Opposing Flow, vph		
Method	Factor	400	800	1,000
Australian	E_{LT}	2.1	3.1	3.7
	Capacity, vph	1,946	1,782	1,700
	Left turns, vph	195	178	170
	REFA	0.90	0.83	0.79
Present study, opposing lane 1	Capacity, vph	1,080	1,080	1,080
	Volume, vph	240	560	750[a]
	v/c ratio	0.22	0.52	0.69
	REFA	0.93	0.84	0.77
Highway Capacity Manual	REFA	0.91	0.91	0.91

Note: Data for two-lane approaches, saturation flow of 3,600 vphg, 10 percent left turns, two-phase signal with 60-s cycle and G/C = 0.60, no left-turn lane, and no parking or standing.

[a]Assumes that the opposing volume distribution by lane is 75/25; this depends on the percentage of opposing left turns and the v/c ratio of approaching lane 1.

v/c ratio of the opposing lane 1 flow, which is higher when opposing vehicles are diverted to lane 1 because the center lane is blocked by left turners.

6. The center lane can carry a full load of traffic only if left turns are prohibited. When left turns are allowed and more than half the cycles have at least one left-turning vehicle, drivers shy away from the center lane, and its output with 0 left turns may be much lower than the curb lane.

Further study is needed of how to adjust for cycles with 0 left turns, for different average percentages of left turns. Study of procedures for estimating the proportion of opposing traffic in lane 1, for different percentages of left turns in lane 2, opposing, and for different v/c ratios of lane 1, approaching, also is needed.

This approach to left-turn reduction factors should be studied for additional intersections, including those controlled by pretimed signals.

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APPENDIX

EARLIER RESULTS BY LOMBAARD

Lombaard (7) studied left-turn reduction factors at six two-lane approaches on Golf Road in 1970, utilizing time-lapse photography. He undertook regression analyses, using as a variable the v/c ratio of opposing traffic in the two lanes. Data were combined for those approaches in which the downstream signal was more than 0.70 mile (1.3 km) away and for those with short opposing distances (when the downstream signal was only 0.35 mile (0.6 km) away, as at the Gross Point Road intersection).

His results identified the problem of the changing distribution of flow in lane 1 and the center lane, as the v/c ratio increased for opposing flow. He found ratios of lane 1/lane 2 volumes of 2.2 for v/c ratios, opposing, of 0 to 0.50, 4.28 for v/c of 0.51 to 0.75, and 6.13 for v/c of 0.76 to 1.00. Left-turn movements declined from 11.0 to 7.7 to 6.8 percent for the three v/c stratifications.

Lombaard's reduction factors for data aggregated by cycle yielded mean left-turn reduction factors of 0.82, 0.65, and 0.62 for short opposing distances, for the three opposing-flow v/c ratio groupings of 0.0 to 0.5, 0.51 to 0.75, and 0.76 to 1.00. He concluded that, with at least one left-turning vehicle per cycle, the opposing v/c ratio affects the left-turn reduction factor more than the percentage of left-turning vehicles in the approach. He also concluded that when opposing left-turn movements are encountered, iterative or trial-and-error solutions are needed to deal with the effects of left turns on the opposing v/c ratios.