Conversion from Permissive to Exclusive/ Permissive Left-Turn Phasing: A Before-and-After Evaluation

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A before-and-after study was conducted to determine the effects of converting left-turn signal phasing from a permissive condition to an exclusive/permissive condition. Data collection was conducted in April 1984 and February 1985. Time-lapse photography was used to collect data on the numbers of vehicles already stopped, stopping, or not stopping at 5-sec intervals. Each movement (left-turn and through) and direction were separately recorded. These data, in turn, were analyzed to determine traffic volumes, average and total amounts of vehicle stopped delay, the percentage of vehicles stopping, and the percentage of left-turn vehicles. Mean values of these factors for before and after data were compared to determine the significance of any differences. The results showed that left-turn volumes increased significantly in the after phase. However, when these volumes were expressed as a percentage of total volume (which also increased), the increases were not significant. The percentage of vehicles that stopped increased dramatically from 43 percent of all vehicles in the before phase to 71 percent of all vehicles in the after phase. Average delays to southbound through traffic more than quadrupled in the after phase, whereas those to northbound through traffic more than tripled. Average delay to left-turn vehicles decreased to 82 percent of the before values; not a statistically significant amount. The conversion resulted in 87.9 veh-hr of additional delay per day. This delay converts to a cost of $398,587/year in additional vehicle operating, travel time, and vehicle emissions costs. Longer cycles, loss of progression, and inefficient use of green time increased the number of stopping vehicles and vehicle delay. The improvements in processing left-turn vehicles were obtained at the expense of inconveniencing the through movement. A comparison of before- and after-accident experience was not included in this study.

Described in this paper is a before-and-after study that evaluated the effects of converting left-turn signal phasing from a permissive condition to an exclusive/permissive condition.

Three types of left-turn phasing are in general use:

- *Permissive left turn.* Vehicles are allowed to make a turn on a circular green indication but must yield to opposing traffic.
- *Exclusive left turn.* Vehicles are allowed to make a turn only on a green arrow indication and have the right of way while the green arrow is displayed.
- *Exclusive/permissive.* Vehicles are allowed to make a turn either on a green arrow indication or on the circular green after the green arrow has been terminated and after yielding to oncoming traffic.

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At present, there is no uniform method of application of left-turn phasing throughout the United States. A 1985 survey by the Colorado-Wyoming section of the Institute of Transportation Engineers drew the response of 218 jurisdictions. These jurisdictions listed 175 different criteria (based on delay, accidents, volumes, or other factors) for installing exclusive or exclusive/permissive phasing *(1)*. The multitude of different criteria being used strongly suggests that additional data on the effects of different types of left-turn phasing are needed to develop more uniform methods of application.

In addition to the Colorado–Wyoming study, other researchers have summarized current practice or have conducted studies to develop criteria or warrants. Agent and Deen prepared an excellent summary of state warrants or guidelines in 1978 *(2)*. Mohle and Rorabaugh documented the effects of installing exclusive left-turn phasing *(3)*. Warren reported on accident experience *(4)*. Upchurch used matched pairs of intersections to determine delay and other impacts *(5)*.

Few conversions from permissive to exclusive/permissive phasing are documented in the literature. Most of the intersections used as the subject of before-and-after studies were changed from permissive to exclusive or vice versa. Upchurch's work *(5)*, using matched pairs of intersections, produced much useful information. However, it was not possible in that study to duplicate intersection geometry, cycle length, turning movement percentages, and vehicle arrival patterns. These observations suggested that a before-and-after study of a permissive to exclusive/permissive conversion would be very useful. Before-and-after data collection at one location would minimize the number of confounding factors in the analysis.

The city of Phoenix has recently developed a strong interest in the subject of left-turn phasing. Political and engineering decisions in 1984 led to the opportunity to conduct a before-and-after study.

Phoenix has an excellent 1-mi grid system of major arterial streets, most of which are six or seven lanes wide. Arterials are heavily relied on because the city has fewer miles of freeway per capita than any other urban area of its size. Dramatic population and traffic growth have strained the surface street system. A frustrated public has come to believe that a left-turn arrow is the quick-and-easy solution to the problem. This belief is so popular and widespread that a mayoral candidate (subse-

quently elected) adopted "more left-turn signals" as part of his campaign agenda.

Phoenix's traffic engineering department has historically been reluctant to use exclusive or exclusive/permissive phasing because it (a) takes away green time from the through movement, (b) increases overall intersection delay and reduces capacity, and (c) disrupts the progression that works exceptionally well on the 1-mi grid system. Intuitively, the traffic engineers believed that left-turn arrows would have serious drawbacks. In response to political pressure, exclusive/permissive phasing was installed on an experimental basis at several locations to evaluate the impacts. One of these locations—44th Street and Thomas Road—was the site of this research project.

This intersection was chosen because it presented the opportunity to conduct a before-and-after study of the effects of the conversion from permissive to exclusive/permissive left-turn phasing. However, the researchers could not control or eliminate the other factors (cycle length, loss of progression, etc.) that confounded the analysis. The scope of the study did not allow any modifications to the intersections needed to determine the individual contribution of each factor to changes in "after" intersection operations.

"After" data were collected 7 months after installation of exclusive/permissive phasing. Therefore, drivers had 7 months to become aware of and adapt to the new signal phasing.

An analysis of before-and-after accident experience was not included in the scope of the study. The after condition described in this paper existed for less than 1 year; significant changes in traffic signal progression were made at the end of the after period. The short after period prevented any conclusive analysis of accident experience. Driver surveys were not within the scope of the study.

OBJECTIVE

The overall objective of the study was to evaluate the changes in intersection operation as a result of the installation of exclusive/permissive phasing at 44th Street and Thomas Road. Specific objectives were to answer the following questions:

1. What was the net change in delay to the 44th Street approaches, considering both through and left-turn vehicles?
2. Did delay to left-turn vehicles increase or decrease with the addition of exclusive/permissive phasing?
3. Did delay for nonturning vehicles increase?
4. What was the effect of the change in left-turn phasing on the ratio of green time to cycle length for the through movement?
5. What effect did left-turn arrows have on vehicle operation cost, air polluting emissions, fuel consumption, and person-hours of travel?
6. Have left-turn volumes increased as a result of the installation of exclusive/permissive phasing?

INTERSECTION DESCRIPTION

Forty-Fourth Street and Thomas Road are both major arterials with three through lanes in each direction and left-turn bays on each approach. The left-turn bays on the 44th Street approaches are about 200 ft long with storage space for 10 vehicles. Concrete medians channelize the traffic on all approaches. Signal heads are mounted on poles in the medians and on the corners as well as overhead. The signal heads in the medians were changed from the standard two-phase, three-section type to a five-section stacked type that includes green and yellow arrows.

Data were collected, via time-lapse film, only for the 44th Street approaches (northbound and southbound). Data were not collected on the Thomas Road approaches because of limited resources. In the before phase, the 44th Street average daily traffic (ADT) was 43,500 vehicles per day. The basic traffic patterns in the after phase were quite similar to those in the before phase. The before-and-after volumes for each direction and movement by hour of filming are given in Table 1.

Signal Timing

The signal timing for the before phase is given in Table 2. Cycle lengths ranged from 50 to 65 sec. North-south green time varied from 19 to 29 sec. The ratio of green time to cycle length (G/C ratio) ranged from 36.4 to 48.3 percent. The signals were two-phase, pretimed, and part of a progressive signal system. Progression speeds varied with cycle length from 28 to 36 mph.

The timing schedule for the after phase is given in Table 3. It should be noted that between 6:30 p.m. and 6:30 a.m., only permissive phasing is used on the north and south approaches. Except for this time period, G/C ratios for the through movement decreased in the after phase. This was because the increase in through green time was not as large as the increase in cycle length. G/C ratios for the through movement ranged from 36.4 to 48.3 in the before phase and from 28.5 to 36.7 in the after phase.

The cycle lengths shown are maximum values. Cycle lengths actually varied with demand throughout the day, but were not measured on a cycle-by-cycle basis. Upstream detectors determined the length of the through-clearance interval up to a maximum of 4.6 sec. The minimum arrow display time was 6 sec; the maximum, 10 sec.

Intersection Operation

In the after phase of the study, the intersection continued to operate with only permissive phasing from 6:30 p.m. to 6:30 a.m. From 6:30 a.m. to 6:30 p.m., the exclusive left-turn phase is actuated only if there are three or more vehicles in the left-turn lane. This is accomplished by using two detection loops in the left-turn bay. One loop is just behind the stop line and the second is 50 ft behind the stop line. The presence of vehicles on both detectors is required to call the exclusive phase. The exclusive phase is not called when there are less than three vehicles in the queue; in this case the through clearance interval can process two left-turn vehicles.

When used, the left-turn arrow leads the through-green phase. Overlaps are used if the exclusive phase is actuated for left turns in one direction but not the other.

The previously described operation of the exclusive phase was planned so as to limit the following disadvantages of the additional phase:

1. Loss of progression,
2. Increased cycle length,
3. Decreased G/C ratio for the through movement, and
4. Increased delay to through traffic.

Restricted hours of exclusive phase operation and minimum left-turn demand thresholds were efforts to limit its use. The main advantages of the addition of the exclusive phase were

1. Reduced left-turn delays,
2. Quicker dispersal of left-turn queues,
3. Additional left-turn capacity,
4. Reduced interference with through traffic due to "spillover" from the left-turn bay, and
5. Satisfaction of public demand to install left-turn arrows.

A comparison of traffic flows from the before-and-after films shows that the after-phase operation was neither as smooth nor as efficient as it was in the before phase.

A before-and-after type study was used to reduce, as much

TABLE 1 VOLUMES BY HOUR OF FILMING

	Northbound			Southbound		
Hour[a]	Before	After	Percent Difference	Before	After	Percent Difference
Through Volumes (vehicles per hour)						
1	942	949	+0.7	1,294	1,209	−6.6
2	904	1,036	+14.6	1,012	1,123	+11.0
3	1,037	1,221	+17.7	1,087	1,194	+9.8
4	1,309	1,267	−3.2	1,239	1,215	−1.9
5	1,243	1,367	+10.0	1,070	1,233	+15.2
6	1,330	1,513	+13.8	1,272	1,301	+2.3
7	1,498	1,790	+19.5	1,335	1,239	−7.2
8	1,748	1,798	+2.9	1,185	1,295	+9.3
Left-Turn Volumes (vehicles per hour)						
1	159	169	+6.3	131	140	+6.9
2	182	208	+14.3	129	156	+20.9
3	217	251	+15.7	154	172	+11.7
4	209	260	+24.4	160	203	+26.9
5	196	273	+39.3	158	176	+11.4
6	192	238	+24.0	151	168	+11.3
7	190	264	+38.9	143	185	+29.4
8	181	217	+19.9	139	195	+40.3

[a] Each hour represents one reel of exposed film. Filming began at about 8:15 a.m. and concluded at about 5:15 p.m.

TABLE 2 SIGNAL TIMING AND G/C RATIO BEFORE

Time of Operation	Cycle Length (sec)	N–S Green (sec)	N–S Yellow (sec)	Progression Speed (mph)	Green Time G/C ratio (%)
6:45 a.m.–8:15 a.m.	60	29	4	30	48.3
8:15 a.m.–4:00 p.m.	50	19	4	36	38.0
4:00 p.m.–5:10 p.m.	55	20	4	33	36.4
5:10 p.m.–5:40 p.m.	65	29	4	28	44.6
5:40 p.m.–6:00 p.m.	55	20	4	33	36.4
6:00 p.m.–6:45 a.m.	50	19	4	36	38.0

TABLE 3 SIGNAL TIMING AND G/C RATIO AFTER

Time of Operation	Cycle Length (sec)	N–S Through Green (sec)	N–S Through Yellow (sec)	N–S Left-Turn Arrow (sec)	N–S Left-Turn Yellow (sec)	Green Time for N–S Through (G/C ratio, %)
6:30 a.m.–9:00 a.m.	105.2 max	30	4.6	10 max	3	28.5
9:00 a.m.–3:30 p.m.	77.2 max	25	4.6	6 max	3	32.4
3:30 p.m.–6:00 p.m.	105.2 max	30	4.6	10 max	3	28.5
6:00 p.m.–6:30 p.m.	77.2 max	25	4.6	6 max	3	32.4
6:30 p.m.–6:30 a.m.	68.2 max	25	4.6	0	0	36.7

as possible, differences in intersection characteristics and operation when comparing permissive phasing to exclusive/permissive phasing. It is emphasized that some factors, which were beyond the control of the researchers, did change. The cycle length was increased, the ratio of through green time to cycle length was decreased, volumes increased slightly, and the previous pattern of traffic progression was disrupted. Although it would have been desirable for a perfect before-and-after comparison to have the same cycle length, progression patterns, volume, and ratio of north-south to east-west green time, these characteristics could not be controlled.

DATA COLLECTION

Time-lapse photography was used for data collection; it is the only practical data collection method for accurately obtaining information on volume and associated vehicle delay. The films were used to determine left-turn volumes, opposing volumes, and delay (both to left-turn and through vehicles).

The time-lapse camera was located on a lift truck adjacent to the right lane of the south approach and approximately 300 ft from the intersection. The camera was approximately 30 ft above the roadway. From this location the through and left-turn movements on the north and south approaches were observed and recorded on film.

Eight hours of film were exposed in both the before and after phases. The 8 hr covered a time period from about 8:15 a.m. to 5:15 p.m. (including short breaks for changing film). The traffic observed in the 8-hr period accounted for about 51 percent of ADT. A speed of one frame per second was used for all filming. Filming was continuous in order to be able to calculate delays based on 1-sec intervals. Each roll of film had 3,600 frames (50 ft roll) and ran for 1 hr. Filming was done for the before phase on Friday, April 13, 1984, and for the after phase on Friday, February 22, 1985.

DATA REDUCTION

The basic types of information obtained from the time-lapse films were volume and delay data. Stopped time delay was the specific type of delay calculated in this study. It measures the time a vehicle is stopped and does not include time losses caused by deceleration and acceleration. Wherever the term delay is used in this paper, it refers to stopped time delay.

The time-lapse film was projected using a time-lapse projector at a slow rate of speed. Viewing of the films, observation of vehicle movements, and tabulation of data resulted in the collection of data on volume, the number of vehicles stopping, the number of vehicles not stopping, total delay, average delay per stopped vehicle, average delay per approach vehicle, and the percent of vehicles that stopped. These data were collected separately for left-turn and through movements and for the near- and far-side approaches to the intersection. These data were tabulated for 5-min intervals.

Although the time-lapse film was exposed at a rate of one frame per second, 5-sec intervals were used for recording volume and delay data. This interval facilitated data reduction and analysis. A 5-sec interval of film was projected, and the number of vehicles that (a) were stopped, (b) came to a stop in that interval, and (c) did not stop at all while traversing the intersection were observed and tallied. A stopped vehicle was defined as one that was stopped and waiting for the signal to turn green or for a suitable gap (in the case of left-turn vehicles).

Stopped time delay was used for calculating delay. In this study, stopped vehicles were counted in 5-sec intervals. Every 5 sec, the number of vehicles stopped (in through or left-turn lanes) was recorded. The total delay (for all vehicles on the approach) was calculated as the total number of vehicles observed multiplied by the observation interval (5 sec).

Volume and delay data were summed for 5-min periods. Average delay per stopped vehicle, average delay per approach vehicle (vehicles on the approach), and the percent of vehicles that stopped were calculated from the volume and delay data. In addition, the percentage of all vehicles on an approach that turned left was calculated. Data were further summarized by summing the preceding factors for 1-hr periods.

STUDY FINDINGS AND ANALYSIS

Volume

Traffic volume increased on all four movements between April 1984 and February 1985. The number of vehicles per hour observed for each movement are listed in order of hour of filming in Table 1. This hourly breakdown shows the variations throughout the day. The 8-hr totals and overall average volumes are given in Tables 4 and 5.

The largest increases were in left-turn volume. Average hourly southbound left-turn volume increased from 146 to 174 vehicles, a 19.2 percent increase. The increase was statistically significant at the 95 percent level of confidence.

The increase in northbound left-turn volume is even greater.

TABLE 4 VOLUME—8-HR TOTAL IN VEHICLES

	Before	After	Percent Difference
Through volume (NB and SB)	19,505	20,750	+6.4
Left-turn volume (NB and SB)	2,691	3,275	+21.2
Southbound volume (through and left turn)	10,659	11,204	+5.1
Northbound volume (through and left turn)	11,537	12,821	+11.1
Total NB and SB volume	22,196	24,025	+8.2

NOTE: NB = northbound; SB = southbound.

TABLE 5 VOLUME—8-HR AVERAGE IN VEHICLES PER HOUR

	Before	After	Percent Difference
Southbound through	1,187	1,226	+3.3
Northbound through	1,251	1,368	+9.3
Southbound left turn	146	174	+19.8
Northbound left turn	191	235	+23.2

Hourly average northbound left-turn volumes increased by 23.2 percent from 191 to 235 vehicles per hour. The increase was statistically significant at the 95 percent confidence level. Total left-turn volume for both directions increased by 21.2 percent.

Hourly average southbound through volume increased by 3.3 percent from 1,187 to 1,226 vehicles per hour. This increase is not statistically significant. Northbound through volume rose from 1,251 to 1,368 vehicles per hour. The increases in through volume are not statistically significant.

The total north-south volume rose 8.2 percent from 22,196 to 24,025 left-turn and through vehicles in 8 hr.

Left-Turn Volume as a Percentage of Total Volume

The combined increases in southbound through and left-turn volumes over an 8-hr period raised total southbound volume by 5.1 percent from 10,659 to 11,204 vehicles (see Tables 4 and 6). Southbound left-turn volume grew from 10.9 percent to 12.5 percent of total (left-turn and through) southbound volume for a relative increase of 14.7 percent in the after phase. This increase is statistically significant at the 95 percent confidence level, but not at the 99 percent level.

TABLE 6 LEFT-TURN VOLUME AS A PERCENTAGE OF TOTAL VOLUME

	Before	After	Percent Difference
Southbound volume (through and left turn)	10,659 vehicles	11,204 vehicles	+5.1
Southbound volume (left turn only)	1,165 vehicles	1,395 vehicles	+19.7
Left-turn percentage of through + left	10.9%	12.5%	+14.7
Northbound volume (through and left turn)	11,537 vehicles	12,821 vehicles	+11.1
Northbound volume (left turn only)	1,526 vehicles	1,880 vehicles	+23.2
Left-turn percentage of through + left	13.2%	14.7%	+11.4
SB and NB volume (through and left turn)	22,196 vehicles	24,025 vehicles	+8.2
SB and NB volume (left turns only)	2,691 vehicles	3,275 vehicles	+21.7
Left turn percentage of through + left	12.1%	13.6%	+12.4

Total northbound volume rose by 11.1 percent, from 11,537 to 12,821 vehicles in 8 hr. The portion of this volume demanding left turns increased from 13.2 percent to 14.7 percent for a relative increase of 11.4 percent. The increase in northbound left-turn volume, expressed as a percent of total northbound volume, is not statistically significant.

Whether or not the relatively larger growth of left-turn demand is a result of the addition of left-turn phasing could only be answered by a survey of drivers. It is likely that the exclusive phase attracts some drivers because they perceive it as safer and more convenient. It may also attract drivers who previously used circuitous routes to avoid a lengthy left-turn delay.

Total Delay

Definite changes have occurred in the amount of total delay and its distribution. Table 7 gives 8-hr totals for delay in vehicle hours. The most dramatic changes have been the increases in through delay. Total southbound through delay for 8 hr increased from 11.59 to 49.34 vehicle-hours. The after value is 4.26 times the before value.

TABLE 7 DELAY—8-HR TOTAL IN VEHICLE-HOURS

	Before	After	Percent Difference
Southbound through	11.59	49.34	+326
Northbound through	14.72	52.31	+255
SB + NB through	26.31	101.64	+286
Southbound left turn	18.98	15.25	−19.6
Northbound left turn	42.96	35.26	−17.9
SB + NB through and left-turn combined	88.24	152.16	+72.4

Northbound through delay also increased markedly, from 14.72 vehicle-hours to 52.31 vehicle-hours. The after value is just over 3.5 times that of the before data.

The total through delay for the before phase is 26.31 vehicle-hours in 8 hr; for the after phase, 101.64 vehicle-hours or 3.86 times that of the before phase. Total volume in the after phase was only 1.08 times larger.

Left-turn delay decreased, as expected. Total southbound left-turn delay for 8 hr decreased by 19.6 percent, from 18.98 to 15.25 vehicle-hours. Total northbound left-turn delay decreased by 17.9 percent, from 42.96 to 35.26 vehicle-hours.

Total before north-south delay (through and left-turn movements combined) was 88.24 vehicle-hours in 8 hr. After the change in phasing and cycle length, total north-south delay was 152.16 vehicle-hours in 8 hr. The increase was 63.92 vehicle-hours or 72.4 percent.

The decrease in total left-turn delay did not offset the increase in total through delay. The through movements (86.3 percent of total north-south traffic) were penalized to benefit the left-turn movements that comprised only 13.7 percent of the total north-south volume.

The increase of 63.92 vehicle-hours of delay is for an 8-hr period during which filming was conducted. There are a total of 12 hr in the day during which exclusive phasing can be actuated. Based on relative volume levels in the 4 hr that were not filmed and the fact that volume increased 8.2 percent between the before and after phases, it is estimated that the total daily increase in delay as a result of the change in phasing is at least 87.9 vehicle-hours.

The use of green time for handling left-turn instead of through vehicles resulted in inefficient use of green time, which was a primary cause of increases in total delay. The longer cycle length caused the stopped through vehicles to be delayed longer than before; the loss of progression increased the number of vehicles forced to stop.

Average Delay

The impacts of the increase in total delay have already been discussed; however, the relationship of total delay to volume

has not yet been explored. Average delays to through and left-turn movements for both directions are a direct expression of the volume/total delay interaction. Table 8 gives average delay, in units of vehicle-seconds per vehicle, for the 8 hr of filming.

Average delay to all southbound through vehicles increased from 4.4 to 18.1 vehicle-seconds per vehicle, a 311 percent increase. The corresponding change in northbound values was from 5.3 to 17.2 vehicle-seconds per vehicle, a 225 percent increase. Average delay to all through vehicles increased by 259 percent, from 4.9 to 17.6 vehicle-seconds per vehicle. All of these changes were shown to be statistically significant.

Average delay to southbound left-turn vehicles decreased from 58.6 to 39.4 vehicle-seconds per vehicle, a drop of 32.8 percent. The 32.8 percent decrease in average delay per vehicle is considerably more than the 19.6 percent decrease in total delay reported in the preceding section. This emphasizes the importance of examining average delay. Left-turn volume increased while total delay decreased, resulting in a much larger drop in average delay.

TABLE 8 DELAY—AVERAGES OVER 8-HR IN VEHICLE-SECONDS PER VEHICLE

	Before	After	Percent Difference
Southbound through	4.4	18.1	+311.4
Northbound through	5.3	17.2	+224.5
SB + NB through	4.9	17.6	+259.2
Southbound left turn	58.6	39.4	−32.8
Northbound left turn	101.3	67.5	−33.4
SB + NB left turn	82.8	55.7	−32.7

Average northbound left-turn delay was reduced from 101.3 to 67.5 vehicle-seconds per vehicle, a decrease of 33.4 percent. Again, the decrease in average delay is magnified by a concurrent rise in volume. The average delay to all left-turn vehicles (both directions combined) decreased from 82.8 to 55.7 vehicle-seconds per vehicle. Surprisingly, analysis of variance showed that all of the reductions in average left-turn delay were not statistically significant.

Graphical Analysis of Left-Turn Delay

Opposing Volume Ranges

Figure 1 shows average left-turn delay plotted as a function of opposing volume. One curve shows left-turn delay for the before phase; the other curve shows it for the after phase. The graph was constructed by partitioning average left-turn delays for 5-min intervals into ranges of opposing volume. The 5-min average delay values were used to calculate a mean left-turn delay for each volume range.

The before plot indicates a general tendency for average left-turn delays to increase with increasing opposing volume. Larger opposing volumes result in fewer gaps for left turns; thus, left-turn delay increases. The after plot shows a much narrower range of left-turn delay. The shape of the curve reflects the fact that larger opposing volumes cause longer left-turn queues. When such volumes persist, the exclusive phase may be called for each cycle. This hastens dispersal of the queues, thus reducing delay.

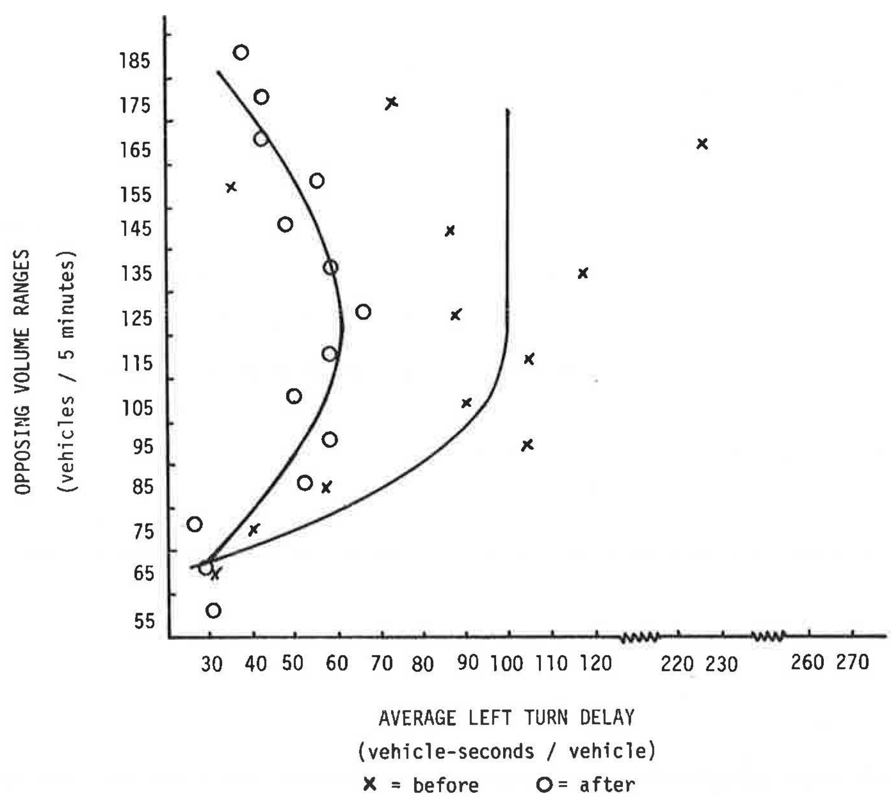

FIGURE 1 Plot of average left-turn delay versus ranging of opposing volume.

Volume Cross Product

As described, Figure 1 relates left-turn delay only to opposing volume. Figure 2 shows the relationship between average left-turn delay and volume cross product (VCP). Volume cross product is the opposing volume multiplied by the left-turn volume. As such, it is a simplified index of conflicts between left turn and opposing traffic. Volume cross product is a useful measure for relating average left-turn approach delay to traffic stream conditions.

The VCP ranges in Figure 2 represent increments of 200 vehicles^2/5 min. The only difference between the generation of this graph and that for the volume ranges (Figure 1) is the partitioning of average delays.

The data in Figure 2 indicate little change in average left-turn delay at low-volume levels (volume cross product of 500 to 700 vehicles^2/5 min). At these volumes the exclusive/permissive system functions like a permissive system because left-turn demand is low. As volume increases (higher-volume cross products), however, left-turn demand is sufficient to call the exclusive phase. As a result there is a significant reduction in left-turn delay.

Percent of Vehicles Stopping

The addition of the exclusive left-turn phase was not the only change made on 44th Street. As the cycle length was increased, the ratio of through-green time to cycle length was decreased. As a result of the change in cycle length, progression on 44th Street could no longer be achieved. The percentage of arriving vehicles that were forced to stop at the intersection increased.

In the before phase, the average fraction of southbound through traffic that stopped was 34.7 percent over 8 hr. This percentage nearly doubled in the after phase, to 64.5 percent stopping (see Table 9). The average percent of northbound through traffic that stopped also rose—from 35.7 to 67.7 percent. The increases in the percent of through traffic that stopped

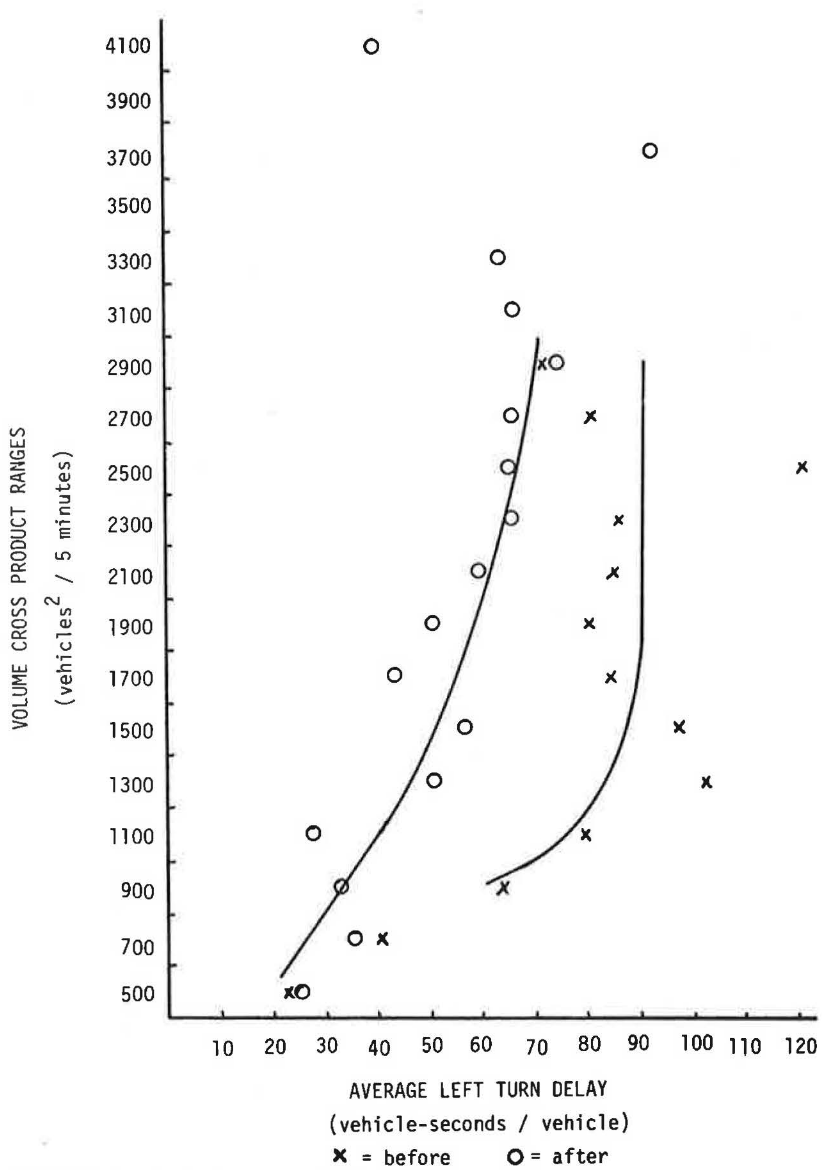

FIGURE 2 Plot of average left-turn delay versus volume cross-product ranges.

TABLE 9 PERCENT OF VEHICLES STOPPING (8-hr average)

	Before	After	Percent Difference
Southbound through	34.7	64.5	+85.7
Southbound left turn	94.9	98.0	+3.2
Northbound through	35.7	67.7	+89.8
Northbound left turn	98.4	97.6	−0.8
SB + NB through and left-turn combined	42.7	70.6	+65.4

were statistically significant. The through-traffic movements accounted for a very large proportion of the approach volume (86.3 percent of total observed volume in the after phase).

The slight changes in the fraction of left-turn vehicles that stopped were minimal. At least 95 percent of left-turn vehicles stopped in both the before and after phases.

For all movements combined, the percent of vehicles that stopped increased from 42.7 percent in the before phase to 70.6 percent in the after phase.

Economic Impact

It has been demonstrated in previous sections of this paper that vehicle delay and the number of vehicles stopping were both greatly increased. These impacts result in greatly increased costs for the roadway user and the public in terms of increased vehicle operating cost, increased travel time, and vehicle emissions. These costs can be estimated based on: (a) the increased number of vehicles that must decelerate and accelerate due to the increased percentage of vehicles that stop; and (b) the increased stopped delay (vehicle hours of idling time). An estimate of these costs is described next.

Costs Due to Additional Number of Stopping Vehicles

An estimate of additional vehicle operating costs was performed by using procedures described in *A Manual on User Benefit Analysis of Highway and Bus Transit Improvements, 1977 (6)*. Unit costs presented in this report were updated to 1985 values, and a correction was made for vehicle fleet fuel consumption improvements.

From the time-lapse photography it was known that during the 8 hr that were filmed the number of vehicles that stopped increased by 6,868 vehicles. Expanding this number to a 24-hr period yielded 9,444 vehicles per day. For simplicity, it was assumed that (a) all of these vehicles were passenger cars; (b) they all underwent a speed change cycle from 40 to 0 to 40 mph; and (c) vehicles that did not stop did not go through a speed change cycle at all. These assumptions caused the actual increase in costs to be understated.

The additional vehicle operating cost due to a speed change cycle from 40 to 0 to 40 mph (updated to a 1985 value) is $31.74 per 1,000 speed change cycles. Therefore, the additional vehicle operating cost on 44th Street was

$$\$31.74/1{,}000 \text{ vehicles} \times 9{,}444 \text{ vehicles} = \$299.77/\text{day}$$

This equals $109,416/year.

The value of time is related to the activity pursued and the length of time involved. It is difficult to quantify such a subjective cost. Previous studies have assigned values to low, medium, and high time savings, which should logically be applicable to losses of time as well *(6)*. The medium time savings value per traveler-hour for average trips was chosen as a reasonable estimate. This was $1.80/hr at 1975 prices *(6)*. Updated to 1985, the value is $3.66/hr per person.

Average vehicle occupancy was assumed to be 1.56. This is the same value used in 1977 after an FHWA survey indicated it to have held true since the late 1960s *(7)*. This increases the cost to $5.71/hr per vehicle.

Travel time losses were calculated from a base value of 4.42 hr/1,000 speed change cycles *(8)*. Multiplied by 9,444 additional vehicles stopping, the result was 41.74 additional hours of travel time per day. At $5.71/hr, this amounts to a travel time cost of $238.34/day or $86,992.98/year.

Data on increased vehicle emissions due to speed change cycles are provided by Dale *(8)*. Unit costs of the pollutants are also available *(9)*.

An additional 46 lb of carbon monoxide, 2.1 lb of hydrocarbons, and 2.4 lb of nitrogen oxide are generated for every 1,000 stopping vehicles. By applying the unit costs and multiplying by 9,444 vehicles, the additional emission costs were calculated to be $6.60/day or $2,408.60/year. The increased costs due to the additional number of stopping vehicles are summarized in Table 10.

TABLE 10 ADDITIONAL COST FOR THE ROADWAY USER AND THE PUBLIC

	Additional Cost per Day Due to Additional No. of Stopping Vehicles ($)	Additional Cost per Day Due to Increased Stopped Delay ($)	Total Additional Cost per Day ($)	Total Additional Cost per Year ($)
Vehicle operating cost	299.77	43.12	342.89	125,155
Travel time cost	238.34	501.91	740.25	270,191
Emission cost	6.60	2.28	8.88	3,241
Total	544.71	547.31	1,092.02	398,587

Costs Due to Increased Stopped Delay

A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements (6) was also used to estimate these additional vehicle operating costs. Once again, unit costs were updated to 1985 values and a correction was made for improved fuel economy. The 1985 rate was $490.60 per 1,000 vehicle-hours of idling. Multiplied by the additional 87.9 vehicle-hours of stopped delay, this yielded an increased vehicle operating cost of $43.12/day.

The value of a person's time is the largest component of the costs due to stopped delay. Using the 87.9 additional vehicle-hours of delay per day and a value of $5.71/hr per vehicle yields a daily travel time cost of $501.91.

An additional 434 lb of carbon monoxide, 14.1 lb of hydrocarbons, and 4.4 lb of nitrogen oxides are generated by 87.9 vehicle-hours of idling. The emission cost of these pollutants is $2.28/day.

All additional costs due to idling and stopping are given in Table 10 in terms of cost per day and cost per year. It is emphasized that the values in Table 10 are the increased costs for vehicles on 44th Street only. If increased costs for Thomas Road were also considered, the costs would be much higher.

CONCLUSIONS

1. Volumes of both left-turn and through movements for north and south approaches increased in the after phase. The increase in left-turn volumes was found to be statistically significant; the increase in through volumes was not.
2. The increase in southbound left-turn volume, expressed as a percentage of total southbound volume, was significant at the 95 percent level of confidence.
3. The increase in northbound left-turn volume was not significant when expressed as a percentage of total northbound volume.
4. Average delay to southbound through vehicles more than quadrupled in the after phase. Average delay to northbound through vehicles more than tripled in the after phase.
5. Average delays to left-turn vehicles decreased to 82 percent of the before values. The decrease was not found to be statistically significant. Delay decreased even though left-turn volume increased.
6. There was a minimum net increase in total delay (on the north and south approaches) of 87.9 vehicle-hours per day. The net decreases in left-turn delay were only a fraction of the net increases in through delay.
7. The increased vehicle operating, travel time, and emission costs due to the net increase in delay were at least $547/day or $199,655/year. Additional costs due to the increased number of stopping vehicles were $545/day or $198,819/year. The combined costs were $1,092/day and $398,587/year.
8. The percentage of through vehicles that stopped on 44th Street increased significantly (from 35 to 66 percent).
9. Longer cycle lengths and inefficient use of green time increased the number of stopping vehicles and vehicle delay.
10. The loss of progression contributed to the problem of inefficient use of through-green time.
11. The efficiency of through movement operations was impaired by the addition of the exclusive phase. The improvements in processing left-turn vehicles were obtained at the expense of inconveniencing the through movement.

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DISCUSSION

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Left-turn control strategies have important impacts on the signal capacity, traffic operations, and safety design of signalized intersections. Selecting the proper left-turn signal phasing can improve the level of service, decrease intersection delay, and reduce left-turn-related accidents. Various jurisdictions frequently have to determine which left-turn treatments are more effective for daily traffic operations. Three left-turn signal phasings are commonly used with the green arrow or circular green indications. These control strategies include the "permissive or permitted," "exclusive or protected," and "exclusive/permissive or protected/permitted" phases for different signalized left-turn treatments. However, there are currently no standard guidelines in the United States for determining which left-turn phasing treatment is best at a particular intersection.

Permissive versus exclusive phasings have been discussed in many past studies. However, few studies have examined permissive versus exclusive/permissive treatment. Many practicing traffic engineers have been reluctant to convert from permissive to exclusive/permissive phasings for three reasons. First, they are likely to reduce arterial through-green times for progression. Second, the possible delay increase may reduce total intersection capacity. Third, no good signal timing methods are currently available to calculate exclusive/permissive green splits and provide capacity evaluation. Despite these potential disbenefits, the uses of exclusive phases and alternative phase sequences have been proved to be successful in many signalized locations. Overall, implementation of the exclusive left-turn treatment can significantly reduce the possibility of severe left-turn accidents when a large percentage of left-turn traffic exists at a signalized intersection.

Described in this paper is a field experiment study that investigated the conversion from permissive to exclusive/per-

missive operation. The study compared two signal treatments and evaluated the before-and-after performance. A signalized intersection in Phoenix, Arizona, was converted from pretimed to semi-actuated operation. Traffic volume and delay data were obtained and processed manually through time-lapse photography. Stopped delay and traffic characteristics were identified for the arterial left-turn and through movements. Finally, performance evaluations were summarized for the specific study intervals. In this study

1. A statistically significant amount of volume increase in left-turn movements was observed in the "after" study.
2. A significant increase in average arterial through delay was noted when the signal control changed from the "before" permissive left turn to the "after" exclusive/permissive left-turn treatment.
3. A decrease in left-turn delay in the after study was observed even though the overall volume had increased. However, the net increases in arterial through delay were far greater than the net decreases in left-turn delay after the exclusive/permissive phase was implemented.

The intent of this study was to evaluate the differences in operational performance between permissive and exclusive/permissive operations. However, there are three major concerns about the results of this field evaluation. First, because the study team was not able to control the development of traffic signal timing plans for after comparisons, the results may not be suitable for drawing general conclusions among the permissive, exclusive, or exclusive/permissive arterial operations. Second, because the researchers were not able to design desirable signal timing plans to account for the possible effects, some of the observed findings may actually originate from the fact that these signal timing parameters may not be set properly for exclusive/permissive operations. Third, the statements concerning the loss of progression as a result of the use of the exclusive phase are somewhat misleading.

Because of the preceding concerns, three additional comments are recommended:

1. To use the exclusive or exclusive/permissive left turn effectively, the signal timing plans, and especially the arterial phase sequences, have to be provided properly in order to allow maximum arterial progression and yet maintain minimum stops and total delay.
2. The timing design of exclusive/permissive or permissive/exclusive phasings relies primarily on how to provide short but sufficient green time for the required protected left-turn phase movements.
3. Effective signal system operation requires efficient coordination between arterial capacity analysis and signal timing optimization.

When designed and implemented properly, exclusive or exclusive/permissive phases can effectively clear the arterial left-turn traffic in advance of the arriving progression traffic, thereby increasing effective signal capacity and improving operational safety. Therefore, two operational considerations are needed for a fair before-and-after comparison. First, the revised arterial timing design is needed to generate effective, coordinated progression offsets for exclusive/permissive signal operations. Second, accurate signal capacity analyses are also required to calculate efficient amounts of green splits for the exclusive portion of the total left-turn phase. Essentially, three basic design questions have to be answered:

1. What amount of effective green time can be allocated for the protected portion of the left-turn phase without having to take the opposing through green needed for coordinated arterial progression?
2. How should the permitted left-turn saturation flow be accounted for in the permitted left-turn phase to reflect the equivalent added signal capacity in the arterial directions because of the increased arterial through-green time in the permissive phase?
3. How much should the arterial traffic be adjusted to consider the increased arrival traffic in the arterial directions due to the "platooned" traffic from the arterial signal progression effects?

This study confirmed that signal timing design for exclusive/permissive or permissive/exclusive left-turn operations is an important yet complicated process. Field performance measurements are extremely susceptible to the way signal timing plans are implemented and perceived by motorists. Normally, arterial travel time and stopped delay can be reduced by carefully timing traffic signal systems for efficient progression operations. Each of the permissive, exclusive, or exclusive/permissive left-turn signal treatments may introduce operational problems to the arterial system if they have not been timed properly for coordinated system operation. Therefore, the impacts of timing plans on signalized intersection delay should be thoroughly examined before any field implementation can be proved to be successful. Simulation studies or field experiments should not only be performed at individual intersections, but the resultant arterial progression should also be carefully investigated. In this way, more comparative before-and-after study results can be used to examine different traffic signal control strategies before implementing signal timing plans.

AUTHORS' CLOSURE

Chang's comments are greatly appreciated; they stimulate much needed discussion on this important topic.

As indicated in the paper, the study team did not have control over the signal timing plans used in the "after" portion of the study period. Timing plans such as cycle length and G/C ratio for each movement were factors that the study team simply had to accept. Whether or not the signal timing parameters in the after phase were good or poor is simply conjecture at this point.

We generally agree with the following comments made by Chang.

1. To use the exclusive or exclusive/permissive left turn effectively, the signal timing plans, and especially the arterial phase sequences, have to be provided properly in order to allow maximum arterial progression and yet maintain minimum stops and total delay.
2. The timing design of exclusive/permissive or permissive/

exclusive phasings relies primarily on how to provide short but sufficient green time for the required protected left-turn phase movements.

3. Effective signal system operation requires efficient coordination between arterial capacity analysis and signal timing optimization.

Chang states: "When designed and implemented properly, exclusive or exclusive/permissive phases can effectively clear the arterial left-turn traffic in advance of the arriving progression traffic, thereby increasing effective signal capacity and improving operational safety." This is fairly easy to accomplish on a single arterial street. However, it is more difficult to accomplish in a connected network of arterial streets. As Chang points out, "Each of the permissive, exclusive, or exclusive/permissive left-turn signal treatments may introduce operational problems to the arterial system if they have not been timed properly for coordinated system operation." We agree.

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