Operational Comparison of Leading and Lagging Left Turns

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Field studies were conducted in the Phoenix and Tucson metropolitan areas for the purpose of comparing the operational differences between leading and lagging left-turn signal phases. Delay studies were conducted in both areas at isolated intersections, and the influence on signal system progression was evaluated at three locations in the Phoenix area. In both areas, the lagging left-turn phases do not utilize overlaps even though phase overlaps were used with the leading left-turn operations. Intersections with protected-only as well as protected-plus-permissive left turns were included. The study involved a before-and-after analysis of the intersection as well as arterial operations. For the individual intersections, the field studies found that the intersection delay is significantly greater with the lagging left-turn operation. This finding was true for both of the metropolitan areas. In terms of the signal system progression, no significant differences were found in progression among the leading, lagging, and mixed operations.

In 1985 the city of Tucson, Arizona, initiated an effort to convert the protected left-turn signal phases from a leading to lagging operation. It was believed that the use of lagging left turns would improve intersection operations and network flows.

In order to provide uniformity in the area, Pima County converted from leading to lagging left-turn operations in 1987. On the basis of the Tucson experience, other jurisdictions in Arizona began to consider changing to the lagging left-turn phasing. Scottsdale, which is in the Phoenix metropolitan area, converted their protected left-turn phasing to a lagging operation in early 1989.

It should be noted that most intersections in Arizona with a protected left-turn phase also have a permitted phase that allows motorists to turn left through gaps in opposing traffic. At intersections with permitted/protected phasing, simultaneous lagging left-turn arrows are used to avoid trapping motorists who have pulled into the intersection while waiting to turn.

The concept of the lagging green left-turn interval is not new. Neither is the question whether leading or lagging left turns are preferable, as shown by the discussion in the 1965 edition of the *Traffic Engineering Handbook* (*1*). It is noted that the use of either leading or lagging green should be approached with extreme caution because a motorist who is receiving the shorter green might not realize it since the driver sees opposing traffic flowing freely. In addition, some authorities believe that the leading green is probably less hazardous than the lagging green because motorists in opposing directions would generally be starting from a stopped position. Nevertheless, other authorities favor the lagging green because they believe that the left-turn capacity is increased.

The potential for the lagging left turn's being more hazardous as mentioned above refers to what is sometimes called the "trap" of lagging left turns.

The simultaneous dual-lag operation is utilized by the city of Tucson, which has had the most experience within the state with lagging left-turn operations. In 1984 Tucson conducted an experiment on 22nd Street from Tucson Boulevard to Kolb Road. In this study, it was found that converting from leading to lagging operation reduced delay, fuel consumption, emissions, and accidents (memorandum from Joel D. Valdez, City Manager, to Mayor and Council, May 10, 1985).

In a study based on a simulation model called TEXAS, Machemehl and Mechler investigated various left-turn sequence patterns at an isolated intersection. They reported no significant difference in delay between leading and lagging turn phases (*2*).

The literature does not support the current phasing practices within the state, particularly the apparent need for standardization of either leading or lagging operation within the various governmental jurisdictions. Conversely, the literature generally recommends that the decision for leading versus lagging operation be based on conditions at the specific intersection and the opportunity to provide the best progression.

In this paper the studies and findings relative to the effect of leading versus lagging left turns on intersection delay and signal system progression are described. Studies were conducted in both the Phoenix area and Pima County. The following studies were performed:

- Phoenix Area Intersection Delay Study
  - Leading versus lagging,
  - Leading versus combination;
- Pima County Signal Operation Analysis
  - Vehicle arrival,
  - Vehicle delay,
  - Cycle length;
- Phoenix Area Travel Time Study
  - Leading versus lagging,
  - Leading versus combination.

At seven intersections in Glendale, Tempe, and Mesa, intersection delay with leading left turns was compared with that with lagging left turns. At the one intersection studied in Mesa, the only after condition involved a leading left turn in

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one direction and a lagging left turn in the opposing direction. The delay in the Phoenix area was obtained by counting the queued vehicles in 15-sec increments. The Pima County intersection delay was obtained using time-lapse photography with both leading and lagging left turns at nine locations.

Signal system progression was evaluated in Glendale, Tempe, and Mesa. Four conditions in Glendale and Tempe were examined: existing timing (all leading), optimized all-leading timing, optimized all-lagging timing, and optimized combination. The signal progression evaluation in Mesa consisted of evaluating the existing leading operation and combination of leading left eastbound and lagging left westbound. A minimum of 2 weeks was provided between the before-and-after delay studies. It was the intent of the researchers to allow enough time for drivers to become familiar with the new phasing but to keep this time short so volume and vehicle mix were not substantially changed. An evaluation of the accidents for leading and lagging operation was also conducted but is not included in this paper.

PHOENIX AREA INTERSECTION DELAY STUDY

Intersection stopped-time delay studies were conducted to evaluate the difference in performance between leading and lagging left-turn arrow operation. One intersection was studied to evaluate the difference between leading and combination-leading-and-lagging operation.

Leading Versus Lagging Operation

A paired comparison was made between the average delay per vehicle in the leading condition and the average delay per vehicle in the lagging condition. Six intersections were used in the analysis, and manual stopped-time delay studies were conducted at each intersection before any signal timing changes associated with this research were made. In the before condition, each of the six intersections operated with leading left turns. Five of the six intersections operated with protected/permissive left-turn phasing and third-car actuation on all approaches. The intersection of 48th Street and Broadway operated with protected-only left turns and first-car actuation on the northbound and southbound approaches and protected/permissive left-turn phasing with third-car actuation on the eastbound and westbound approaches.

Manual stopped-time delay studies were conducted at each intersection with lagging operation. All approaches that were protected/permissive in the leading condition were permissive/protected in the lagging condition. The two protected-only approaches remained protected only in the lagging operation.

Results

A before-and-after difference in the average stopped-time delay per approach vehicle was calculated for each intersection. A difference was calculated for left-turn vehicles, through or right-turn vehicles, and total intersection approach vehicles. The percent change in delay from the before to the after condition was also calculated. The results of the Phoenix area intersection analysis of leading versus lagging left-turn operation are presented in Table 1.

Average stopped-time delay per left-turn approach vehicle increased in the after condition at four of the six intersections studied. The largest change occurred at 51st Avenue and Northern, where delay increased by 139 percent for left-turn vehicles. The intersection of 48th Street and Southern measured essentially no change for left-turn vehicle delay with the conversion to lagging left turns, whereas the intersection of 48th Street and Broadway registered a 5 percent decrease in delay for left-turn vehicles in the after condition.

Average delay per through or right-turn approach vehicle increased at five of the six intersections studied. The largest increase occurred at 48th Street and Southern, with 129 percent more delay for through or right-turn vehicles in the after condition. The intersection of 51st Avenue and Northern was the only one that registered a decrease in delay for through or right-turn vehicles in the after condition. Delay decreased approximately 16 percent at this location.

Average delay per total approach vehicles also showed increases in the after condition at the same five intersections, though the changes were not as drastic when total intersection approach vehicles were considered. The large increase in through or right-turn delay at 48th Street and Southern was partially offset by no change in left-turn delay. However, this intersection still registered the largest increase (85 percent) in total intersection delay with the conversion to a lagging operation. The intersection of 51st Avenue and Northern was the only location that registered an overall improvement in the after condition, with a decrease in total intersection delay of approximately 4 percent.

Three statistical tests were performed: difference by intersection left-turn movements, difference by intersection through or right-turn movements, and difference by total intersection delay. In each case, the statistical test performed was a paired t-test using the difference for each pair as one observed value. A mean of the difference was then calculated. The null hypothesis for the each test was that the difference between the before and after conditions is equal to zero. A two-tail test was performed at a 95 percent level of confidence.

The results of the paired data analysis are also presented in Table 1. On the basis of this analysis, it is concluded that left-turn delay and total intersection delay are significantly greater for the lagging left-turn operation.

Leading Versus Combination Operation

Two delay studies were performed at the intersection of Southern Avenue and Stewart in Mesa to compare the difference in delay for a leading operation and a combination-leading-and-lagging operation. Southern Avenue is an east-west arterial street and Stewart is a local collector street. The signal operated in a five phase mode in the before condition with protected-only phasing on the east and west approaches. The combination phasing operated with leading left turns in the eastbound direction and lagging left turns in the westbound direction. The signal was also operated in the protected-only mode in the after condition.

The results of the before-and-after study are presented in Table 2. Delay per intersection left-turn approach vehicle

TABLE 1 Intersection Delay for Leading Versus Lagging Left-Turn Operation, Phoenix Area

		Delay per Approach Vehicle (sec/veh)		
Intersection		Left Turn	Thru/Right	Total
1. 51st Ave./Glendale	Before	25.70	22.55	22.95
	After	57.79	34.34	37.66
	Difference	32.09	11.79	14.71
	Change	125%	52%	64%
2. 51st Ave./Northern	Before	23.51	44.57	41.57
	After	56.24	37.32	39.80
	Difference	32.73	-7.25	-1.77
	Change	139%	-16%	-4%
3. 51st Ave./Olive	Before	27.50	21.58	22.41
	After	45.30	27.65	30.19
	Difference	17.80	6.07	7.78
	Change	65%	28%	35%
4. 51st Ave./Peoria	Before	42.03	20.07	22.88
	After	65.64	33.83	38.00
	Difference	23.61	13.76	15.12
	Change	56%	69%	66%
5. 48th St./Southern	Before	54.95	21.56	27.23
	After	54.92	49.28	50.30
	Difference	-0.03	27.72	23.07
	Change	-0%	129%	85%
6. 48th St./Broadway	Before	63.39	39.27	44.51
	After	60.14	43.97	47.91
	Difference	-3.25	4.70	3.40
	Change	-5%	12%	8%
Analysis				
Sample Size		6	6	6
Mean of Difference		17.16	9.47	10.38
Overall Change		63.30%	45.54%	42.17%
Sample Standard Deviation		15.62	11.58	9.00
Test Statistic (t)		2.691	2.002	2.825
Significant @ 95%?		yes (p=.04)	no (p=.10)	yes (p=.04)

Before Condition: Leading Operation
After Condition: Lagging Operation

TABLE 2 Intersection Delay for Leading Versus Combination Operation, Phoenix Area

		Delay per Approach Vehicle (sec/veh)		
Intersection		Left Turn	Thru/Right	Total
Southern/Stewart	Before	37.86	10.76	14.34
	After	33.25	9.63	13.02
	Difference	-4.61	-1.13	-1.32
	Change	-12%	-11%	-9%

Before Condition: Leading Operation
After Condition: Combination (leading EB/lagging WB)

decreased by 4.61 sec, or approximately 12 percent, in the after condition. The decrease was 1.13 sec per vehicle for the through or right-turn movements. This represents a change of approximately 11 percent. Total intersection delay decreased by 1.32 sec per approach vehicle in the after period. Total intersection delay decreased by approximately 9 percent with the conversion to a combination-leading-and-lagging operation.

PIMA COUNTY SIGNAL OPERATION ANALYSIS

The conversion from leading to lagging left-turn signals by Pima County in 1987 represented a unique opportunity to examine the effect of the operational change. With the cooperation of the Pima County Department of Transportation and the Arizona Department of Transportation, a before-and-after data collection effort was undertaken at selected intersections.

Selection of Intersections

The conversion program in Pima County involved a total of 37 signalized intersections in the Tucson area. At some of these intersections, various modifications to the signal operations were made in addition to the conversion of the left-turn phasing. At a limited number of intersections, the only planned change was to switch from the leading to the lagging left-turn operation; thus these intersections were selected for the before-and-after data collection. The intersections studied are given in Table 3.

Ultimately, the intersection of First Avenue and Ina Road underwent other changes in signal phasing as well as modifications in lane use that significantly changed the operation of the intersection. For this reason, the intersection was eliminated from the comparative analysis, although field data were collected at the site. In addition, the initiation of construction in the area of Ina Road and Thornydale Road significantly changed the traffic at that location before there had been an opportunity to collect the after data.

Signal Phasing

Pima County uses actuated control for traffic signals; thus all of the intersections in the study utilized full actuated control. In addition, each of the intersections operated on an isolated basis with no interconnection among adjacent signals. Table 3 identifies the operation of the left-turn signal phasings at each of the study locations.

It should be noted that phase overlaps were used for the leading left-turn conditions; however, the overlaps were not used with the lagging left-turn operations. At a limited number of intersections that utilized the protected-only left turns, a phase overlap condition would occur with the lagging left-turn operation. For example, one intersection had very low westbound approach volumes. For some cycles, the eastbound through and left-turn movements would occur at the same time.

With respect to the actual signal timing, the study utilized the signal settings employed by Pima County for the before and after conditions. There was no attempt by the research team to evaluate the signal timing settings used at the intersections.

Data Collection

For the field data collection, two time-lapse super-8-mm movie cameras were used to film the operation of each of the intersections. The filming of each intersection occurred during

TABLE 3 Delay Study Intersections, Pima County

Intersection	Type of Control (a,b)
Ajo Way/Alvernon Way	4 Phase (c)
Alvernon Way/Irvington Rd.	4 Phase (Protected/Permissive)
Campbell Ave./Skyline Rd.	3 Phase (Protected)
First Ave./Ina Rd.	4 Phase (d)
First Ave./Orange Grove Rd.	3 Phase (Protected/Permissive)
First Ave./River Rd.	3 Phase (Protected/Permissive)
Ina Rd./Thornydale Rd.	4 Phase (Protected/Permissive)
Kolb Rd./Valencia Rd.	4 Phase (Protected)
Palo Verde Rd./Valencia Rd.	3 Phase (Protected)

(a) The number of phases reflects the basic operation of the intersection. Phase overlaps were used in situations with opposing leading protected left turns.

(b) In the "after" condition, the "protected/permissive" left turn operation obviously becomes "permitted/protected."

(c) At the intersection of Ajo Way and Alvernon Way, a combination of types of control was used. For example, some approaches had protected left turn operations.

(d) At the intersection of First Avenue and Ina Road, a 4-phase signal operation was used in the before condition with protected/permissive left turns on the northbound and westbound approaches. For the after condition, the northbound and southbound approaches on First were treated as separate phases. In addition, the lane use on the northbound approach was changed.

the period from 3:00 to 6:00 p.m. on weekday afternoons in the before and after periods.

Analysis

Using the film record of the intersections during the before and after periods, data that reflected operational parameters were extracted. These operational data for each intersection were then used for the comparative analysis of the leading and lagging left-turn phasing. The discussion that follows presents the analysis of and results for each of the operational parameters.

Intersection Volume

In the design of the data collection effort, it was recognized that significant changes in volume can have a potential impact on the operational measures of intersection performance. For this reason, a number of precautions were taken in an attempt to minimize the possibility of major changes in volume between the before and after study periods.

Table 4 presents the average approach volumes for each intersection. At most of the study intersections, only minor differences in traffic volumes were observed. Given the relatively short period between the collection of the before and the after data, only small differences would be expected. Two exceptions were noted. There was no explanation for the cause of the significant increase in traffic volume at the intersection of Campbell Avenue and Skyline Road. The before data set was collected in April 1987, and the after data set was taken the following October. Although only 6 months passed between the data collection periods, there was a 21 percent increase in the approach volumes at that intersection. This increase generally occurred on all approaches and throughout the study period. In essence, there was a major increase in the use of the intersection.

In the second exception, there was a 16 percent decrease in the approach volume at the intersection of Kolb and Valencia roads. There had been a major change in employment in the vicinity of this intersection; thus the after condition was influenced by the reduction in employment.

Arrival of Vehicles

The arrival pattern of vehicles for a given intersection was examined by determining the percentage of the approach vehicles that had to stop because of the operation of the traffic signal. Basically, review of the film revealed the approach vehicles that were required to stop as well as those that were able to pass through the intersection without stopping. The percentage of vehicles stopped was then calculated by comparing the number of vehicles that stopped with the total approach volume. Table 5 summarizes this information for each intersection.

At most of the intersections the percentage of stopped vehicles was in the general range of 50 to 55. The main exception was the intersection of Palo Verde and Valencia roads, where the percentage for the before and after conditions was significantly lower than that for other intersections. This lower value can be explained by the presence of a free-flow right-turn lane on one of the approaches.

Vehicle Delay

Table 6 summarizes the results of the delay analysis and indicates the average stopped delay for the stopped vehicles as well as for the approach vehicles. These values reflect the overall delay for an intersection. At all the intersections where delay was actually measured, there were increases in the average delay per vehicle. Even for the intersections where there were decreases in the approach volume, the average vehicle delay increased.

Cycle Length

The average signal cycle lengths for the before and after periods for each intersection are given in Table 7. A general review of the table reveals that the differences in the cycle lengths vary from intersection to intersection, with increases at some of the sites and decreases at others. At intersections where there was a decrease in the cycle length, the permitted/protected left turn was utilized. The increases in cycle length were at intersections where protected-only left turns were

TABLE 4 Intersection Total Approach Volumes, Pima County

		Average Approach Volume (vph)*	
Intersection	Before	After	Difference
Ajo Way/Alvernon Way	3644	3523	-3%
Alvernon Way/Irvington Rd.	2788	2882	3%
Campbell Ave./Skyline Rd.	2527	3070	21%
First Ave./Orange Grove Rd.	2519	2472	-2%
First Ave./River Rd.	3379	3107	-8%
Ina Rd./Thornydale Rd.	3495	**	**
Kolb Rd./Valencia Rd.	7052	5950	-16%
Palo Verde Rd./Valencia Rd.	2560	2472	-3%

* The average approach volumes are for the entire intersection. The value in the table reflects the sum of all approaches.
** After values not available for Ina Rd./Thornydale Rd.

TABLE 5 Percentage of Approach Vehicles Stopped, Pima County

Intersection	Percent Stopped Before	After
Ajo Way/Alvernon Way	54.1	53.0
Alvernon Way/Irvington Rd.	54.5	53.8
Campbell Ave./Skyline Rd.	50.7	55.6
First Ave./Orange Grove Rd.	55.6	49.5
First Ave./River Rd.	54.4	55.7
Ina Rd./Thornydale Rd.	60.6	*
Kolb Rd./Valencia Rd.	60.1**	70.4**
Palo Verde Rd./Valencia Rd.	31.3	33.3

* After value not available for Ina Rd./Thornydale Rd.

** At the Kolb Rd./Valencia Rd. intersection, the values are for the eastbound and westbound approaches only. For the before condition, the percent vehicles stopped for all approaches was 49.2 percent. The after condition value for all approaches was not available.

TABLE 6 Vehicle Delay Comparison, Pima County

Intersection	Delay Per Stopped Vehicle (Sec)	Delay Per Approach Vehicle (Sec)
Ajo Way/Alvernon Way		
Before	32.68	17.75
After	39.68	21.04
Difference	7.00 (21%)	3.29 (19%)
Alvernon Way/Irvington Rd.		
Before	22.82	12.44
After	32.32	17.39
Difference	9.50 (+42%)	4.95 (+40%)
Campbell Ave./Skyline Rd.		
Before	27.45	13.93
After	31.43	17.47
Difference	3.98 (+14%)	3.54 (+25%)
First Ave./Orange Grove Rd.		
Before	22.88	12.72
After	27.11	13.43
Difference	4.23 (+18%)	0.71 (+6%)
First Ave./River Rd.		
Before	32.15	17.48
After	33.55	18.68
Difference	1.40 (+4%)	1.20 (+6%)
Ina Rd./Thornydale Rd.		
Before	33.03	20.01
After	*	*
Difference		
Kolb Rd./Valencia Rd.		
Before	26.04	12.69
After	*	19.27
Difference		6.58 (+52%)
Palo Verde Rd./Valencia Rd.		
Before	19.25	6.03
After	23.58	7.85
Difference	4.33 (+22%)	1.82 (+30%)
Average Change	+20%	+30%

* After value not available

TABLE 7 Average Cycle Length, Pima County

	Average Cycle Length (Sec)		
Intersection	Before	After	Difference
Ajo Way/Alvernon Way	95.3	114.3	19.0
Alvernon Way/Irvington Rd.	72.6	70.4	-2.2
Campbell Ave./Skyline Rd.	79.9	90.3	10.4
First Ave./Orange Grove Rd.	77.3	71.9	-5.4
First Ave./River Rd.	95.6	90.7	-4.9
Ina Rd./Thornydale Rd.	85.8	*	
Kolb Rd./Valencia Rd.	65.7	76.7	11.0
Palo Verde Rd./Valencia Rd.	62.1	62.6	0.5

* After value not available for Ina Rd./Thornydale Rd.

utilized. Changes in cycle length, therefore, were a function of whether left turns were permitted along with the through movement or not.

The exception to an increase in cycle lengths with protected-only lagging left turns occurred at the intersection of Palo Verde and Valencia roads. At this intersection, the average cycle lengths remained virtually the same even with the protected left-turn operations. Because of the low approach volumes for some movements, this is one of the intersections that resulted in a phase overlap type of operation. Because of this condition, the average cycle length remained the same.

Discussion of Results

In considering the results of the analysis of the Pima County intersections, it must be recognized that

- All of the study locations were operating with actuated control;
- The signals were basically isolated from other intersections, and there was no coordination with adjacent intersections at the time of the data collection;
- The intersections were not operating at what could be considered saturated conditions; and
- Vehicle queues generally cleared during each cycle.

There was some variation in the measured approach volumes at the study intersections; however, major changes occurred at only two intersections. Because the intersections were not operating at saturated conditions, increase in volumes would not necessarily result in significant increases in delay.

Generally, there was little change in the percentage of vehicles stopped. This would suggest that the arrival pattern was random in terms of the signal cycle. For this reason, the effect of platooning should not be a factor with respect to delay calculations and measurements.

It is significant to note that the reduction in cycle length was associated with intersections where permitted left turns were allowed. On the other hand, intersections with protected left turns only had increases in cycle length with the lagging left-turn operation. This result is reasonable because of the fact that the opportunity for phase overlap was lost when the lagging left turn was used.

An interesting result of the analysis is that vehicle delay increased at all study intersections. There was an average increase of 20 percent in the delay per stopped vehicle and an average increase of 30 percent in the delay per approach vehicle. Even when there was a decrease in approach volumes, there were increases in delay. Delay might be expected to increase with longer cycle lengths; however, it also increased at intersections with reductions in average cycle lengths.

PHOENIX AREA TRAVEL TIME STUDY

As part of this research, alternative phasing sequences were tested using travel time data along five routes in Glendale, four routes in Tempe, and one route in Mesa.

In order to obtain a true comparison between leading and lagging left turns, it was necessary to use signal timing patterns developed by a common optimization program. Because of the ease of operation and the numerous runs that would be required as part of the combination portion of the study, FORCAST was utilized to optimize the signals.

Once the timing plans were implemented on the street, travel time runs were performed using the "floating car" method with the TIMELAPSE Travelog data collection computer.

Six travel time runs were performed for each route in each direction for three time periods: a.m. peak, p.m. peak, and off-peak. One driver collected all the data in Glendale and another driver collected the travel time data for Tempe. The same driver was used for all runs in each city in order to eliminate the variability of different drivers.

The six runs were averaged for each route to determine the average stops, delay time, and travel time for each route. Each of the estimates for the routes was multiplied by its respective volume to produce a weighted point estimate based on the route volume. A paired Student's *t*-test was then performed between each sample. The following comparisons were made:

- Existing leading minus FORCAST optimized leading,
- Existing leading minus FORCAST optimized lagging,
- Existing leading minus FORCAST optimized combination,
- FORCAST leading minus FORCAST lagging,
- FORCAST leading minus FORCAST combination, and
- FORCAST lagging minus FORCAST combination.

Because FORCAST develops timing plans that weight the benefit of reduced stops with reduced delay and travel time, a representative cost for each timing plan was developed using the information in *A Manual on User Benefit Analysis of Highway and Bus Transit Improvements* (*3*). These values have been updated to 1988 dollars by using the transportation portion of the consumer price index.

ANALYSIS

Glendale Travel Time Study

In the Glendale study area, all the major arterial–major arterial intersections were operating in a protected-permissive leading left-turn mode in the before condition. All the signals within the study area were optimized using the FORCAST signal timing program, but only the signals along 51st Avenue had the phasing patterns changed during the course of the study. The five routes chosen for the Glendale study were 51st Avenue, 59th Avenue, Peoria Avenue, Olive Avenue, and Northern Avenue.

The comparison was made among (*a*) existing leading, (*b*) FORCAST-optimized leading, (*c*) FORCAST-optimized lagging, and (*d*) FORCAST-optimized combination, with the results in shown in Table 8. Figure 1 shows the equivalent motorists' cost based on stopped-time delay, travel time, and stops.

As the data in Table 8 suggest, there is a significant difference in travel time and delay between both the FORCAST leading–FORCAST lagging and the FORCAST leading–FORCAST combination plans. If the cost parameters are viewed separately, it appears that the existing leading timing plan works best for the a.m. peak, the combination plan works best for the midday and p.m. peak, and the lagging plan works best for the off-peak period. In the a.m. peak, the lagging plan also works better than the FORCAST leading or the combination plan. It appears, at least from this information, that lagging left turns work best in situations such as an off-peak period in which left-turn volumes are relatively light.

Tempe Travel Time Study

In the Tempe area, all major arterial–major arterial intersections were operating in protected-permissive leading left-turn operation with the exception of the north and south approaches at 48th Street and Broadway. Because of the dual left turns, these approaches operate in a protected-only leading left-turn mode. FORCAST was used to create timing plans for all signals within the study area; however, alternative phasings were implemented only at 48th Street and Broadway and 48th Street and Southern.

As shown in Table 9, only one result is significant in the Tempe travel time data. FORCAST leading had significantly fewer stops than FORCAST lagging.

From Figure 2, it may be noted that lagging has a higher cost than FORCAST leading or combination in the midday and p.m. peak, but the FORCAST combination has a higher cost in the a.m. peak. The cost difference between leading and lagging is least in the a.m. peak and greatest in the p.m. peak. At the two intersections in Tempe where lagging left turns were implemented, there is a great directional split between left turns in the p.m. peak. Forcing these two movements together has greatly increased the motorists' cost in the p.m. peak.

Mesa Travel Time Study

The city of Mesa changed the phasing at Southern and Stewart avenues from leading east-west to leading east and lagging west. Lee Engineering collected travel time data along Southern Avenue in the a.m., midday, and p.m. peak time periods to determine the effect of this changeover. The results of this change are shown in Table 10.

Although they are not significant, substantial reductions are shown in delay, stops, and travel time because of the change from an all-leading phasing pattern to a combination leading-lagging phasing pattern.

TABLE 8 Travel Time Study Comparisons, City of Glendale

Comparison	Least Delay	Level of Significance (p)	Least Travel Time	Level of Significance (p)	Least Stops	Level of Significance (p)
Existing Leading-FORCAST leading	Existing Leading	.07	Existing Leading	.16	FORCAST Leading	.27
Existing Leading-FORCAST lagging	Existing Leading	.08	FORCAST Lagging	.34	Existing Leading	.73
Existing Leading-FORCAST Combination	FORCAST Combination	.86	FORCAST Combination	.27	FORCAST Combination	.26
FORCAST Leading-FORCAST lagging	FORCAST Lagging	.03	FORCAST Lagging	.01	FORCAST Leading	.43
FORCAST Leading-FORCAST Combination	FORCAST Combination	.02	FORCAST Combination	.01	FORCAST Combination	.87
FORCAST Lagging-FORCAST Combination	FORCAST Combination	.47	FORCAST Combination	.58	FORCAST Combination	.29

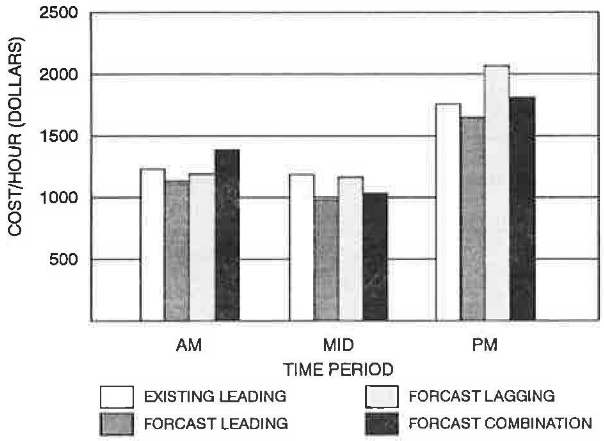

FIGURE 1 Travel time study cost per hour for city of Glendale.

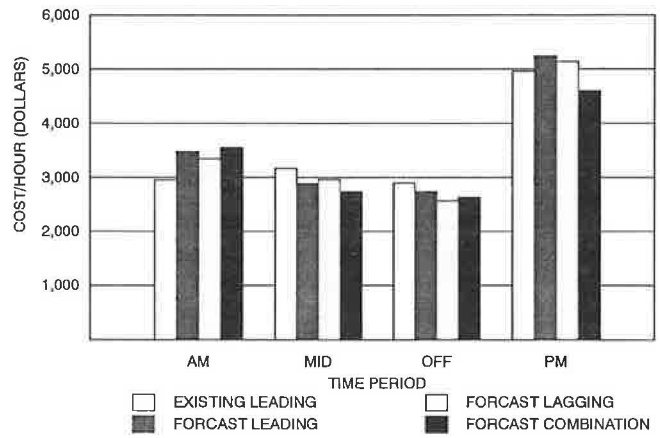

FIGURE 2 Travel time study cost per hour for city of Tempe.

Discussion of Results

It is difficult to determine if either leading or lagging left turns result in better operation for a given situation. Although the difference is not statistically significant, lagging left turns appeared to operate better for three time periods in Glendale (on the basis of FORCAST plans).

The combination timing plan worked better than leading or lagging in Glendale for only midday and the p.m. peak. In Tempe the combination was never the lowest-cost plan. This was surprising, for it was believed that the opportunity for leading or lagging at a particular intersection would help improve progression. It should be stressed again that the FORCAST timing plan must overcome two obstacles in order to choose lagging left turns for intersection phasing. Because it does not recognize left turns made in the permissive period, it does not determine the true best combination plan.

The combination timing plan fared best in Mesa, where stops, delay, and travel time were all reduced substantially. This type of combination phasing is different from those tested in either Glendale or Tempe. The Mesa combination plan was leading eastbound and lagging westbound. In Tempe the phasing tested was leading north-south and lagging east-west. It would appear that there is no substantial reduction in motorists' cost with the Tempe type of phasing, but there is with the Mesa phasing. It is important to realize that to implement the Mesa phasing, it is necessary to have either protected-only operation or programmed-visibility traffic signal heads as are currently being used in Texas.

In conclusion, the following points should be mentioned:

- One of the greatest benefits of lagging left turns is decreased need for a protected left-turn phase. In order for a timing program to implement the best phasing, it is necessary

TABLE 9 Travel Time Study Comparisons, City of Tempe

Comparison	Least Delay	Level of Significance (p)	Least Travel Time	Level of Significance (p)	Least Stops	Level of Significance (p)
Existing Leading-FORCAST leading	Existing Leading	.59	FORCAST Leading	.86	FORCAST Leading	.08
Existing Leading-FORCAST lagging	Existing Leading	.16	Existing Leading	.41	FORCAST lagging	.99
Existing Leading-FORCAST Combination	Existing Leading	.69	FORCAST Combination	.43	FORCAST Combination	.35
FORCAST Leading-FORCAST lagging	FORCAST Leading	.47	FORCAST Leading	.37	FORCAST Leading	.05
FORCAST Leading-FORCAST Combination	FORCAST Combination	.78	FORCAST Combination	.56	FORCAST Leading	.13
FORCAST Lagging-FORCAST Combination	FORCAST Combination	.26	FORCAST Combination	.12	FORCAST Combination	.23

TABLE 10 Travel Time Studies for All-Leading Minus Combination Leading-Lagging Signal Phasing, City of Mesa

		Weighted Delay (Vehicle-hours)			Weighted Travel Time (Vehicle-hours)			Weighted Stops (Thousand Vehicle Stops)		
Route	Time	Leading	Lagging	Difference	Leading	Lagging	Difference	Leading	Lagging	Difference
Southern Ave. EB	AM	5	0	5	27	22	6	0.8	0.0	0.8
Southern Ave. EB	MID	52	1	51	129	71	58	5.2	0.0	5.2
Southern Ave. EB	PM	41	8	33	132	90	42	5.9	2.9	2.9
Southern Ave. EB	AM	10	3	8	68	60	8	2.1	2.1	0.0
Southern Ave. EB	MID	5	5	0	76	74	2	2.4	2.4	0.0
Southern Ave. EB	PM	0	5	-5	74	66	8	0.0	2.5	-2.5
Total		113	21		506	382		16.4	10.0	
		Sample Size		6	Sample Size		6	Sample Size		6
		Mean Difference		15.197	Mean Difference		20.579	Mean Difference		1.069
		Std Deviation		21.871	Std Deviation		23.436	Std Deviation		2.675
		Test Stat.		1.702	Test Stat.		2.151	Test Stat.		0.979
		Significant		N	Significant		N	Significant		N
		Level of Significance(p)		.15	Level of Significance (p)		.09	Level of Significance (p)		.37

for that program to evaluate the left-turn movement in conjunction with gaps in the opposing traffic stream. Since FORCAST does not do this, it is not a good program for optimizing combination phasing.

- Combination timing seems to work best when leading and lagging are implemented for opposing directions, for example, leading eastbound and lagging westbound.
- In locations like Tempe, where there is a high directionality with opposing left-turn volumes, substantial delay is associated with lagging operation because of the loss of phase overlap.

RESULTS AND CONCLUSIONS

On the basis of the field studies, it was found that intersection delay is significantly greater with lagging left-turn operation. Many factors potentially affect delay, such as loss of phase overlap. In addition, no significant differences were found in progression between the leading, lagging, and mixed operations.

More specifically, the following results were found:

1. Significantly greater delay per approach vehicle occurs with lagging operation than with leading operation for the intersections and time periods tested. It is important to note that the time period tested was generally the p.m. peak hour. During this period it would not be as likely to have sufficiently low left-turn and through volumes to eliminate many protected left-turn phases in the lagging condition.
2. There were no statistically significant differences in stops, delay, or travel time with the different operating conditions. The requirement that the Glendale and Tempe "mixed" operation be limited to either both leading or both lagging on the same street in order to avoid the "trap" restricted potential progression benefit.

The most promise for benefit from lagging or mixed operation was found in the Mesa study, in which leading left-turn operation was utilized for eastbound traffic and lagging for westbound traffic in the after condition. This mixed operation was possible without the trap condition because of the use of protected-only left turns.

The field studies provided valuable insight into the understanding of the many variables that influence left-turn operations. A number of variables have an impact on the effectiveness of left-turn alternatives at a specific site. These variables fall into the general categories of signal control, network considerations, traffic characteristics, and driver perception.

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