Dynamic Change of Left Turn Phase Sequence between Time-Of-Day Patterns – Operational and Safety Impacts

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Abstract

Left turn phase sequences has long been a discussion item for traffic engineers. Every traffic engineer has a preference in the application of the left turn phase sequence at signalized intersections. Leading left turn phasing sequence is the popular application in the country as a whole due to issues related to driver expectancy. Driver expectancy is an essential factor in the decision for the use of such signal phasing operation. Violation to driver expectancy will normally lead to safety implications at signalized intersections. Some agencies as a policy implement leading left turn phase sequence due to this very same reason. Very few agencies mix the application of leading and lagging left turning phase sequence at different intersections within the jurisdiction. The application of lead-lag left turn phasing sequence is surprisingly limited even with well proven improved traffic flow due to improved progression band widths. The primary reason is due to the assumption of violation of driver expectancy. City of Boca Raton has implemented lead-lag left turn phasing at several intersections with dynamic change of left turn phasing sequence by time-of-day from leading left turn sequence during isolated mode to lead-lag phasing sequence during coordinated operation. At some intersections, the lead-lag phasing is reversed by time of day during coordinated operation in that a particular left turn moving as a lag movement at one time will lead at another time of the day. This is primarily implemented to achieve the maximum throughput along the major arterial sections operating at saturated conditions.

This paper includes discussion on the operational impacts of the use of lead-lag left turn phasing and dynamically changing the phasing sequence by time-of-day. The paper includes three aspects to analyze the safety and operational effects of the change in phasing sequence. The response times of the first vehicle in the left turn queue to cross the stop bar from the start of the green interval were compared between lead to lag left turn movements at four study intersections. This comparison is done to verify if there is a difference in the lost time of the first vehicle in queue between leading and lagging left turn movements. The second aspect was geared towards the comparison of arterial flow measures of effectiveness between use of lead-lead left turn phasing sequence to lead-lag left turn phasing sequence. This analysis is performed to simply justify the use of lead-lag left turn phasing and document benefits to the through movements and overall arterial performance with the use of this particular left turn phasing sequence. Simulation analysis was used to compare the arterial flow conditions for two sections of roadways in the city. The measures-of-effectiveness for the comparison included total stop delays, travel speeds and stops per vehicle for through traffic along the arterial, the total stop delay for the left turns along the arterial and the total stop delay for the overall section. The third aspect was to analyze the crash occurrences at the intersections where the phasing sequence changes have been implemented. The paper includes analysis and discussion on the effect of the changes in left turn phasing on the left turn crash patterns. The analysis time period included two years before and after the implementing year.

Introduction

Poor traffic signal timing results in needless vehicle stops and delay, with excess energy consumption, increased operating costs, and detrimental air quality. One of the greatest benefits to tax dollars spent on traffic operations improvements generally come from coordination of adjacent traffic signals to provide smooth traffic flow on that particular section. Continuous flow promotes a traffic engineer's goal to reduce stops, delay, motorist time cost, vehicle operating cost and crash occurrences. It is a proven fact that the appropriate use of phase sequences at signalized intersections saves the motorists many hours of delay and results in fewer crashes.

The goal for coordinated operation of signals is to move as many vehicles possible and minimize stops along the coordinated street while resulting in an overall reduction in delay for the system. Maximizing the bandwidth for the coordinated movements requires the proper selection of several signal-timing options. The controlling factors include the section cycle length, phase splits, type of left turn operation and offsets. Maintaining agencies generally have a specific policy on left turn operation techniques at signalized intersections. This paper discusses the selection and application of left turn operation to achieve maximum throughput along the coordinated street.

Different types of left turn control and sequences are typically used at signalized intersections. The types of left turn control are listed below with a brief description:

- Protected left turn control: Left turns have dedicated right-of-way with a green arrow.
- Permissive left turn control: The left turns do not have dedicated right-of-way with a green arrow and will have to execute turns when an acceptable gap exists in the opposing through movement, under the green ball situation.
- Protected-Permissive left turn control: The left turns have a dedicated right-of-way with green arrow followed by permissive operation under a green ball.
- Permissive-Protected left turn control: The left turns will have permissive operation under a green ball followed by dedicated right-of-way with green arrow.

The lead-lead operation moves both the opposing left turns at the same time with a protected green arrow before the through movements and lag-lag operation moves the opposing left turns at the same time after the through movements while lead-lag operation separates the left turns phasing by direction. Protected-leading and protected-permissive left turn operations are considered as leading operation and protected-lagging and permissive-protected operations are considered lagging operation. Most agencies prefer the use of lead-lead (or standard) left turn phasing since the belief is that driver expectancy weighs heavily in favor of leading left turns. Some agencies use lag-lag left turn phasing when left turns and opposing throughs are light in cases of permissive-protected operation.

The City of Boca Raton has installed a new distributed-hybrid system for operating and maintaining traffic signals. The system is run with MATS Direct Connect software developed by Peek Traffic Systems and intersections are controlled with Peek Traffic's 3000 controllers and 3000M (master controllers). The 3000 controllers have the ability to program lead-lag left turn phasing under time-of-day control. Lead-lag phasing was implemented to maximize bandwidths along many traffic control sections. This phasing was applied at intersections where the left turns are operated as protected only movements. One of the intersections has a protected phase for the eastbound left turns while the westbound left turns are operated as permissive-protected movements. The intersection is operated with lead-lag phasing with the westbound left turns operated as lag phase i.e., permissive-protected operation. This operation is to avoid yellow trap situation for the westbound permissive left turns.

To clearly explain the left turn trap situation, the above referenced intersection can be used as an example. Assume that the westbound left turns with a horizontal five section display is operated with leading protected-permissive operation and the protected only eastbound left turns are operated as lagging left turns. When the signal cycles around, the westbound left turns get an amber display concurrent with the through movements at the time of the eastbound lagging left turns. The permissive westbound left turns waiting in the intersection are under the assumption that the similar display is shown for the eastbound left turns and through movements as is for leading left turn protected-permissive operation. Under this assumption, the westbound left turn would turn in front of the eastbound throughs resulting in a possible left turn collision. This situation is known as a left turn trap or yellow trap.

The intersections where the lead-lag left turn sequence is used in the city are limited to those with protected only left turn control. This will avoid left turn trap situation as in the case of protected-permissive operation. The left turn phasing is dynamically changed between time-of-day to use lead-lead phasing sequence during isolated free mode and lead-lag phasing sequence under coordinated operation. In addition at some intersections, lead-lag phasing is reversed by time-of-day to achieve maximum bandwidths in differing cycle length scenarios. The selection of lead-lag left turn operation is generally used to improve the progression of traffic for the coordinated street. Traffic signal engineers have, in the past, used discretion with lead-lag left turn phasing. Associated operational problems can be avoided with proper treatment of geometry and traffic control. While use of lead-lag phasing as a means to improve progression is one issue, dynamically changing the operation of left turns between lead-lead to lead-lag and reversing lead-lags between time-of-day (TOD) operation is another item of discussion and with differing policies among maintaining agencies.

Scope

The scope of this paper includes assessment of operational and safety impacts due to the lead-lag left turn phasing sequence at the study intersections. Maintaining agencies in the State of Florida, particularly in South Florida prefer leading left turn sequence as a policy. The areas of concern in using lead-lag left turn phasing sequence include driver expectancy violation, as it is different from the traditional lead-lead phasing sequence used in South Florida. This issue is covered through safety evaluation using crash history at intersections where lead-lag phasing is used and dynamically reversed by time-of-day. The study intersections were limited to those within the City of Boca Raton city limits. The historic crash data at each of the intersections before and after the phasing changes was compared to identify significant changes in crash experience.

Lead-lag left turn phasing sequence is primarily used to achieve increased throughput by maximizing the green bandwidth. Two control sections along major arterials in the city are analyzed using computer simulation to quantify average travel speed, delay and percent stops for the through movements at the intersections in the control sections. The analysis was performed to compare the measures of effectiveness along the study arterial sections with use of lead-lead left turn phasing sequence and lead-lag left turn phasing sequence as two different scenarios. In addition, the response times for the leading and lagging operations are measured during the peak hours and off peak hours. Response time is the lost time of the first car in queue from the start of green interval to the time the car passes the stop bar. The collected data was analyzed to test for difference in the response times between leading and lagging operation of the left turn movements.

Literature Review

Much research has been conducted to measure the operational and safety implications related to leading and lagging left turns. The bulk of the research is geared towards the testing of operational and safety impacts of protected-permissive and permissive-protected phasing sequence. Although protected leading and protected lagging left turns were included in study samples in the test of safety effects of several phasing sequences, they may not have been tested explicitly in the lead-lag operation of left turns at signalized intersections. In addition, the number of agencies using lead-lag left turn sequence and dynamically changing the left turn sequence by time of day are very limited. The summary of literature reviewed prior to the study is as follows.

Hummer, Montgomery and Sinha (1) in the research study, using locations in Indiana, developed guidelines for the use of leading and lagging left turns. The survey conducted by the authors resulted in data that favored leading left turn phase operation. The traffic conflict study conducted as a part of this research indicated significant difference in driver confusion with lagging left turns when compared to leading left turns at suburban intersections. The study further documented that conflicts of left turning vehicles with pedestrians are significantly higher with a leading left turn sequence at intersections in the downtown area. The recommendations listed in the study include the following:

1) use of sequence of left turn phasing should result in maximized bandwidth and consequently throughput;
2) lagging left turns, instead of the leading sequence, should be used at isolated signals serving heavy pedestrian traffic and at isolated diamond interchanges or one-way pairs;

3) where protected only leading or protected only lagging phases are not feasible, the solution to reduce crashes between left turn and oncoming through traffic is to use permissive-protected phasing sequence instead of protected-permissive phasing;
4) Left turn trap situations should be avoided in the cases of lagging phase operation with opposing permissive movements.

The safety analysis in the study did not specifically indicate the type of left turn phasing (i.e., protected or protected-permissive operation) used in the comparison of leading to lagging operation. The simulation analysis in the research concluded that protected only leading left turns result in less overall delay than lagging left turns while permissive-protected left turns experienced less delay than protected-permissive left turns. The authors developed a flow chart to facilitate the decision making process for left turn phase sequence selection.

Fambro, Gaston and Hoff in a research study funded by the Texas State Department of Highways (2) tested the operational efficiency of Dallas protected-permissive phasing sequence and the standard protected-permissive phasing with signal displays allowed by MUTCD. The Dallas phasing is a special type of lead-lag operation developed and implemented by traffic engineers in the cities of Dallas and Richardson, Texas. The phasing eliminates the possibility of a left turn trap situation that was explained earlier in the case of lead-lag sequence with protected-permissive and permissive-protected left turns. The results of the study indicated that the Dallas phasing results in less delay for both the left-turning and through movements when compared to phasing with MUTCD left turn signal displays. The study also documented that at intersections along high volume coordinated arterials; the Dallas phasing offers significant operational benefits. The study, however, did not appear to measure and compare the safety impacts of the Dallas phasing versus the phasing allowed per MUTCD signal displays.

Parsonson, in a synthesis on signal timing improvement practices funded by NCHRP (3) indicated that in many cases leading left turn phasing is the normal sequence of operation, which in a gap out situation caused by an early release in through movements, can potentially damage progression. It should be noted that this situation could also be caused by an early release due to a cross street gap out situation. The synthesis further discusses the applicability of lagging left turn sequences under tight storage length situations and qualifies the safety implications that may result due to left turn trap situations. The responses to a survey in the synthesis qualify that driver expectancy weighs heavily in favor of leading left turns. The respondents indicated that lagging left turns were used only when necessary and safe. One respondent indicated that the driver-expectancy problem might exist when phase sequencing is changed by time-of-day to obtain a better bandwidth. This paper includes investigation of this particular issue.

Buckholz, (4) indicated that one of the major pitfalls of coordinated signal timing is the reluctance by traffic engineers to use lead-lag left turn phasing to improve progression, due to possible violation of driver expectancy. He further indicated that experience has shown that where drivers become used to traffic signal phasing variations, the lead-lag left turn phasing can have positive effects on the arterial flow. The ITE Traffic Signal Handbook (5) has a table that summarizes the benefits and disbenefits of leading and lagging left turn schemes.

A study performed by the City of Tucson (6) showed that changing left turn phasing from leading to lagging operation resulted in positive synchronization results. An after study of the arterial signal conversion documented decreases of 38.3% in fuel consumption, 43.1% in air pollutants, 40.0% in traffic collision rate, and 42.2% in vehicle delay. A study performed by Lee, Wortman, Houk, and Poppe (7) in 1991 documented by field measurements that higher delays resulted with lagging left turn operations. The study stated that there was no significant difference in measures of effectiveness, quantifying progression of traffic with leading, lagging and mixed left turn schemes. Motorist surveys indicated that drivers from different cities preferred different sequences of left turns.

Based on these studies, Pline, in the draft NCHRP Synthesis (8) regarding left turn treatments, indicated that phasing sequence selection should be based on analysis on a case by case basis and dependent upon acceptance of drivers using the traffic signal. Bonneson and McCoy (9) evaluated the response time to the leading left-turn indication, considering only the first vehicle in queue. The evaluation was geared towards the left turn displays, but did not evaluate difference in leading to lagging left turn sequence.

Lead-lag left turn sequence is not popular in the South Florida area even with protected only left turn control. The use of lead-lag left turn phasing with protected-permissive and permissive-protected operation for opposing left turns is not used due to safety issues related to left turn trap. Dallas phasing which solves the left turn trap problem is not used in the area due to strict local adherence to MUTCD recommended displays of signal faces for through and left turn phasing.

Traffic Safety Review

The use of lead-lag left turn phasing at signalized intersections to improve the traffic flow raises a valid concern related to impact on traffic safety. This concern is raised due to possible violation of driver expectancy of left turn phasing at the intersections. Motorists in South Florida, as discussed earlier, are used to lead-lead left turn phasing sequence, where both the opposing left turns move together based on vehicle presence in the left turn lanes. The literature review has also indicated that the relative safety of leading and lagging left turn phasing sequences has not been well documented.

A traffic safety review has been performed as a part of this effort to document the effect of use of lead-lag left turn phase sequencing and the dynamic change in left turn phase sequence by time of day on intersection safety. The City of Boca Raton, as mentioned earlier, applies the lead-lag left turn phase sequences with dynamic change in the sequence by time of day at fifteen intersections. The intersections analyzed for safety impacts were selected from these fifteen intersections based on certain qualifications. The study intersections had to be considered typical, meaning a right angle intersection with four approaches of two or three through lanes each, relatively flat grade, 12-foot lane widths, no on street parking, and no additional variables that directly affect the left-turn movement being evaluated. Nine intersections were selected for the safety analysis to document safety impacts of the change in type of phasing sequence. These intersections were selected for the analysis since the before and after conditions reflected similar geometric and signal control for the left turning traffic.

The analysis included review of crash data two years before and two years after the sequence change had been implemented at each intersection. The intersection details and the changes in the sequence of left turns with the years of analysis are identified Table 1 below.

The crash types that were analyzed included all the crashes that associate left turning vehicles from the subject left turn movement. The crash types included left turn rear end, left turn head-on, left turn angle, and left turn-pedestrian crashes. The total crash frequency at each intersection was also included in the analysis. Left turn crash rates were generated using the combined daily left turning traffic at the left turn movements at each intersection. The crash rates are calculated to reflect the number of left turn crashes per million entering left turning vehicles. The crash rates for the overall intersection are also calculated for each intersection. The analysis indicated that the number of left turning crashes experienced at each intersection is not high enough to compare statistical significance separately. Since the independent variable is the change in the phasing sequence and signal timing is the only modification implemented at the selected intersections, each intersection is used as a data point for the analysis.

The analysis included comparison of before and after left turn crash rates at the intersections with the application of two-tailed t-test for determination of statistical difference. The crash rates reflecting total crashes at the study intersections was also compared for statistical difference. The null hypothesis assumed for the test is that the mean left turn crash rates and total crash rates at the intersections had not changed with the modification in the left turn phase sequence. The test was performed to test if the null hypothesis is true at the 0.05 level. The t-test is performed using the mean and standard deviation of the difference in the crash rates of each data point. The before and after crash data and the results of the statistical tests are summarized in Table 2 below.

Table 1
Details of Study Intersections

Int. No.	Intersection Name	Left Turn Control	Before Condition	After Condition
1	Federal Highway and Spanish River Boulevard	Both Protected	Lead-Lead Operation	Lead-Lead in isolated mode; Lead-Lag Operation in Coordinated Operation
2	Glades Road and NW 2nd Avenue	Both Protected	Lead-Lead Operation	Lead-Lead in isolated mode; Lead-Lag Operation in Coordinated Operation (reverse between time periods)
3	Glades Road and NW 10th Avenue	Both Protected	Lead-Lead Operation	Lead-Lead in isolated mode; Lead-Lag Operation in Coordinated Operation
4	Yamato Road and Congress Avenue	Both Protected	Lead-Lead Operation	Lead-Lead in isolated mode; Lead-Lag Operation in Coordinated Operation (reverse between time periods)
5	Yamato Road and Jog Road	Both Protected	Lead-Lead Operation	Lead-Lead in isolated mode; Lead-Lag Operation in Coordinated Operation
6	Palmetto Park Road and Dixie Highway	Protected & Permissive-Protected	Lead-Lead Operation	Lead-Lead in isolated mode; Lead-Lag Operation in Coordinated Operation
7	Glades Road and NW 4th Avenue	Both Protected	Lead-Lead Operation	Lead-Lead in isolated mode; Lead-Lag Operation in Coordinated Operation
8	Federal Highway and N. Mizner Boulevard	Both Protected	Lead-Lead Operation	Lead-Lead in isolated mode; Lead-Lag Operation in Coordinated Operation
9	Clint Moore Road and Congress Avenue	Both Protected	Lead-Lead Operation	Lead-Lead in isolated mode; Lead-Lag Operation in Coordinated Operation (reverse between time periods)

Table 2
Crash Data at Study Intersections

Intersection	Left Turn Crashes				Total Crashes			
	Before Conditions		After Conditions		Before Conditions		After Conditions	
	Avg Freq.	Avg Crash Rate	Avg Freq.	Avg Crash Rate	Avg Freq.	Avg Crash Rate	Avg Freq.	Avg Crash Rate
Federal Highway at Spanish River Blvd	4.5	3.14	2	1.78	22.5	1.68	25.5	2.08
Glades Road at NW 2nd Ave	3	1.93	2	1.04	16	1.16	9	0.71
Glades Road at NW 10th Ave	4	1.64	3.5	1.52	34	1.95	28	1.64
Yamato Road at Congress Ave	3	2.23	3	1.80	15.5	1.04	18.6	1.16
Jog Road at Yamato Road	4	2.18	3	1.85	34.5	1.84	37	1.87
Palmetto Park Road at Dixie Highway	3.5	3.79	0.5	1.52	15.5	1.02	16.5	1.59
Glades Road at NW 4th Ave	3	0.98	1.5	1.67	16	1.15	16	1.10
Federal Highway at N. Mizner Boulevard	3.5	3.38	2.5	2.42	21.5	2.50	10.5	1.23
Clint Moore Road at Congress Avenue	1.0	0.60	2.5	1.38	12	0.80	15.5	1.03
Overall Means	**3.28**	**2.21**	**2.28**	**1.67**	**20.81**	**1.46**	**19.62**	**1.38**

The results indicate that the change in sequence of the left turns and use of dynamic change of phase sequence by time of day did not result in change of left turn and total crash experience. The calculated t-value for the before and after left turn crash rates was 1.67. This is within the critical range of t-value at the 0.05 level. The calculated t-value for the before and after total crash rates was 0.734. This is within the critical range of t-value at the 0.05 level. Since the sample size is small, it is suggested that extreme caution should be used before basing generic conclusions from these results and implying for other areas. Since the analysis was limited to intersections within the limits of City of Boca Raton, the results of crash experience could vary by area type. The results, however, should at least provide a comfort level and guide agencies to be less reluctant to the application of lead-lag left turn phasing due to the fear of safety implications.

Response Time

At the beginning of the green interval for each movement, the first several vehicles in a queue experience start-up time losses that result in their movement being less than the saturation flow rate headway. This time lost is referred to as start-up lost time. Start-up lost time is important in evaluating left-turn lane capacity and driver's reaction to the traffic signal indication. This analysis did not include the start-up lost time of the left turn vehicles. However, the response time of the first left turn vehicle in the queue to cross the stop bar was measured. Response time was considered the time from the onset of the protected left-turn phase green arrow indication to the time the first left-turn vehicle in queue crossed the stop bar. The effect of left turn phasing sequence on driver expectancy can be identified with the analysis of the reaction time of the first vehicle in queue.

Response times were measured at four intersections with lead-lag left turn phasing sequence along the arterial approaches. All the four intersections operate with lead-lead left turn phase sequence during free isolated mode while one of the left turns becomes lag movement during coordinated operation. Three of the four intersections have left turn phase sequence that is reversed by time of day during coordinated operation. At least sixty cycles were measured for each left turn movement during the course of the day. The time-periods ranged between 7:30 to 8:30 AM, 12:00 to 1:00 PM and 4:30 to 5:30 PM. Since the left turn movements lead at certain times and lag at certain times, the analysis was concentrated to test the difference of the distribution response times of leading to lagging operations. This analysis was performed for each left turn movement separately at the three intersections where the sequence is reversed by time of day during coordinated operation. The analysis also included test for difference in response times for lagging to leading movements during the course of the day.

Kolmogorov-Smirnov test was used to test to see if there is a difference in the probability distribution of the data sets of leading versus lagging left turn operation at each intersection. The null hypothesis assumed for the test is that the distribution of response times between the two study data sets is similar at 0.05 probability level. The probability distribution of the response times for leading to lagging left turns at the four intersections are depicted in Figures 1 to 4. The details of the data sets are discussed below.

1. EB Left turns at Glades Road and NW 2nd Avenue
   The eastbound left turns are operated as lagging movement during AM and PM dials and as leading movement during mid-day dial. The response times with the movement as leading to lagging operation are compared to see if they represent different distributions.
2. WB Left turns at Glades Road and NW 2nd Avenue
   The westbound left turns are operated as leading movement during AM and PM dials and as lagging movement during mid-day dial. The measured response times with the movement as leading to lagging operation are compared to determine if they represent different distributions.

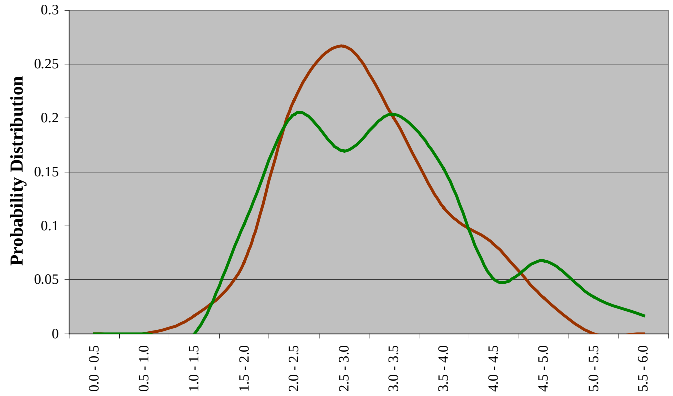

Figure 1. Response Time Intervals
Glades Road at NW 2nd Avenue

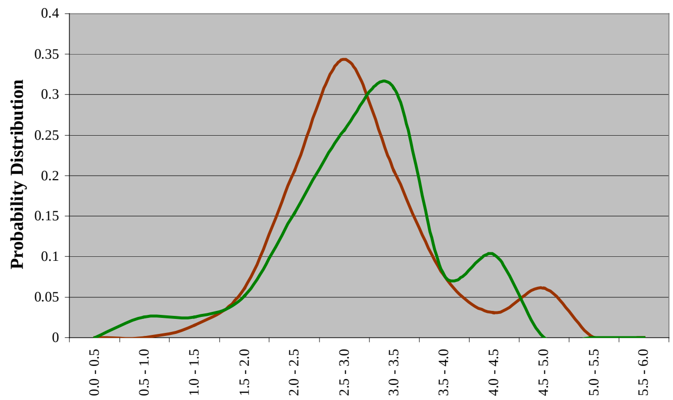

Figure 2. Response Time Intervals
Yamato Road at Congress Avenue

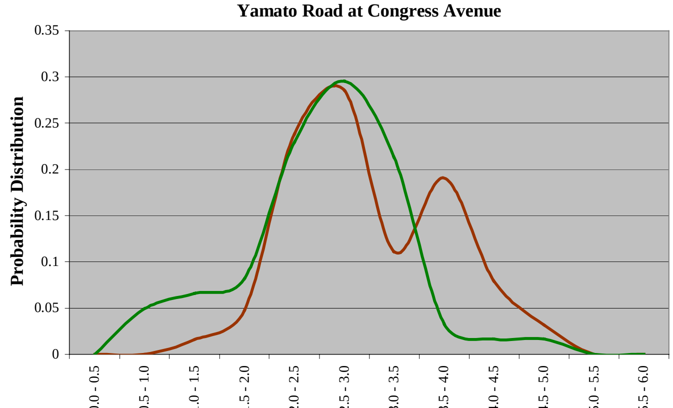

Figure 3. Response Time Intervals
Yamato Road at Military Trail

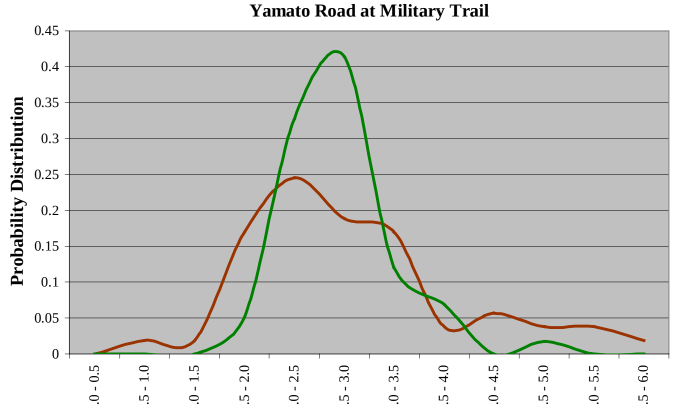

Figure 4. Response Time Intervals
Glades Road at NW 13th Street

3. Eastbound and Westbound left turns at Glades Road and NW 2nd Avenue
   The measured response times with the movements as leading to lagging operation are compared to determine if they represent different distributions.
4. EB left turns at Yamato Road and Congress Avenue
   The eastbound left turns are operated as lagging movement during AM dial and as leading movement during mid-day and PM dials. The measured response times with the movement as leading to lagging operation are compared to determine if they represent different distributions.
5. WB left turns at Yamato Road and Congress Avenue
   The westbound left turns are operated as leading movement during AM dial and as lagging movement during mid-day and PM dials. The measured response times with the movement as leading to lagging operation are compared to determine if they represent different distributions.
6. Eastbound and Westbound left turns at Yamato Road and Congress Avenue
   The measured response times with the movements as leading to lagging operation are compared to determine if they represent different distributions.
7. EB left turns at Yamato Road ad Military Trail
   The eastbound left turns are operated as leading movement during AM and mid-day dials and as lagging movement during PM dial. The measured response times with the movement as leading to lagging operation are compared to determine if they represent different distributions.
8. WB left turns at Yamato Road and Military Trail
   The westbound left turns are operated as lagging movement during AM and mid-day dials and as leading movement during PM dial. The measured response times with the movement as leading to lagging operation are compared to determine if they represent different distributions.
9. Eastbound and Westbound left turns at Yamato Road and Military Trail
   The measured response times with the movements as leading to lagging operation are compared to determine if they represent different distributions.
10. Eastbound and Westbound left turns at Yamato Road and Military Trail
   The eastbound left turns are operated as lagging movement and westbound left turns are operated as leading movement during coordinated operation. The measured response times with the movements as leading to lagging operation are compared to determine if they represent different distributions.

The summary of average response times and the statistical test results are summarized in Table 3 below. The average response times for lagging left turns ranged between 2.55 seconds to 3.69 seconds. The average response times for leading left turns ranged between 2.59 to 3.15 seconds. The results of the Kolmogorov-Smirnov test indicate that the distribution of left turns at all the study intersections are similar when operating as either leading or lagging left turns. The maximum difference in the mean response times for leading and lagging operation of eastbound left turns at Glades Road at NW 2nd Avenue and Military Trail at Yamato Road intersections is 0.55 seconds while the remaining means reflected close values. Glades Road and NW 13th Street was the only intersection which indicated a more dispersed sample between leading and lagging operation. The results clearly indicate that the difference in sequence of the left turn phasing between leading to lagging operation with protected only control did not make any difference in driver reaction time.

Table 3
Response Time Measurements

Intersection	Movement	Average Response Time	No. of Cycles	Maximum Difference in Cumulative Probability D_{max}	Calculated Difference at 0.05 level D_{cal}	Accept Hypothesis @ 0.05 level
Glades Road at NW 2nd Avenue	EB Lead	3.15	40	0.1263	0.3805	Yes
	EB Lag	3.69	18			
	WB Lead	2.76	41	0.1778	0.3860	Yes
	WB Lag	3.07	20			
	Lead	3.02	60	0.0921	0.2494	Yes
	Lag	3.27	59			
Yamato Road at Congress Avenue	EB Lead	2.85	67	0.1060	0.3535	Yes
	EB Lag	2.63	19			
	WB Lead	3.07	64	0.2281	0.3484	Yes
	WB Lag	3.27	20			
	Lead	3.00	131	0.1131	0.2481	Yes
	Lag	2.95	39			
Yamato Road at Military Trail	EB Lead	3.10	45	0.2596	0.3721	Yes
	EB Lag	2.55	19			
	WB Lead	2.59	42	0.0873	0.3831	Yes
	WB Lag	2.84	18			
	Lead	3.02	63	0.2360	0.2442	Yes
	Lag	2.58	61			
Glades Road at NW 13th Street	WB Lead	2.88	58	0.1516	0.2484	Yes
	EB Lag	2.74	53			

Simulation Analysis

Simulation analysis was used to compare the operational efficiency of control sections along two major arterials with different left turn phasing sequences. The analysis was performed using the latest version of Synchro and Simtraffic models. Synchro was used to input traffic volumes, geometry and signal timing parameters. The analysis compared the arterial operating conditions between two scenarios. The scenarios included analysis of the sections using the currently implemented timing data with lead-lag left turn phasing sequence and analysis of the sections using lead-lead left turn phasing sequence. The timing data for the intersections with lead-lead left turn phasing sequence was developed using optimization techniques in Synchro. Simtraffic was used to simulate the traffic flow along these arterial sections for the two differing scenarios. Two sections of arterials that included intersections with lead-lag left turn phasing sequence were analyzed with Simtraffic. Sixty-minute simulation runs of traffic flow along these sections of arterials were studied. The time periods analyzed included AM peak hour and PM peak hour. These time periods were selected for the analysis due to the readily available turning movement data at intersections along the study arterials and the critical nature of these periods. The study sections details are listed below:

Section 1: Glades Road from NW 2nd Avenue to NW 10th Avenue

Glades Road is a six-lane divided roadway with 45 mph posted speed limit. The section consists of four signalized intersections. The left turns at all the intersections are operated with lead-lag left turn phasing sequence during coordination and lead-lead left turn phasing sequence during free isolated mode of operation. At one intersection, the lead-lag left turn phase sequence is reversed by time-of-day during coordination. The section experiences heavy traffic flow during AM and PM peak hours. Eastbound Glades Road is the peak direction during AM peak hour and westbound Glades Road is the peak direction of flow during PM peak hour. The peak directions experience over 2,000 vehicles per hour of traffic volumes while the off peak directions experience close to 1,300 vehicles per hour of traffic volumes.

Section 2: Yamato Road from Military Trail to Congress Avenue

Yamato Road is a four-lane divided roadway with 45 mph posted speed limit. The section consists of four signalized intersections. The left turns at two intersections are operated with lead-lag left turn phasing during coordination and lead-lead left turn phasing sequence during free isolated mode of operation. At these two intersections, the left turn phase sequence of lead-lag is reversed by time-of-day during coordination. The section is over-saturated under current conditions and experiences heavy traffic flow during AM and PM peak hours. Eastbound Yamato Road is the peak direction during AM peak hour and westbound Yamato Road is the peak direction of flow during PM peak hour. The peak directions experience over 2,000 vehicles per hour of traffic volumes while the off peak directions experience close to 1,200 vehicles per hour of traffic volumes.

The results of the simulation analysis are summarized in Table 4 below. The analyzed measures of effectiveness are average travel speed, stops per vehicle, stop delay for the arterial through movements and overall stop delay for the complete section. The results indicate that use of lead-lag phasing results in improved traffic flow along the arterials and improves the overall operating conditions of the arterial sections as well. The results of the analysis for each section are described below. The results described below indicate improvements from lead-lead sequence scenario to lead-lag sequence scenario.

Table 4
Simulation Analysis Results

Arterial Section	Measure of Effectiveness	Dir. of Travel	AM Peak Hour			PM Peak Hour		
			Lead-Lead	Lead-Lag	% Diff.	Lead-Lead	Lead-Lag	% Diff.
Glades Road from NW 2nd Avenue to NW 10th Avenue	Average Travel Speed, mph	EBT	27.72	26.82	-3.25%	28.09	28.37	1.0%
		WBT	25.99	27.82	7.05%	28.0	29.37	4.89%
		Both	26.86	27.32	1.72%	28.05	28.87	2.92%
	Stops per vehicle (thru mvmts along arterial)	EBT	0.39	0.46	-17.9%	0.50	0.43	14.0%
		WBT	0.66	0.58	12.1%	0.44	0.38	15.8%
		Both	0.52	0.52	0%	0.47	0.41	12.8%
	Total Stop Delay, veh-hr (thru mvmts along arterial)	EBT	6.88	8.02	-16.0%	6.03	5.23	13.3%
		WBT	9.7	5.90	39.2%	7.40	2.28	43.8%
		Both	8.29	6.96	16.1%	6.72	3.76	44.1%
	Total stop delay, veh-hr (left turn mvmts along arterial)	EBL	7.0	7.68	-9.72%	5.3	5.05	4.72%
		WBL	1.9	1.48	22.1%	2.63	5.33	103%
		Both	4.45	4.58	-2.92%	3.97	5.19	30.7%
	Overall Stop Delay, veh-hr for all movements	All	128.5	117.5	8.6%	146.2	125.8	16.2%
Yamato Road from Military Trail to Congress Avenue	Average Travel Speed, mph	EBT	26.85	26.0	-3.26%	27.17	27.17	0%
		WBT	24.71	26.0	5.22%	16.83	24.5	45.6%
		Both	25.78	26.0	1.0%	22.0	25.84	17.5%
	Stops per vehicle (thru mvmts along arterial)	EBT	0.93	0.96	-3.22%	0.48	0.45	6.67%
		WBT	0.51	0.39	30.8%	0.92	0.73	26.0%
		Both	0.72	0.68	5.88%	0.70	0.59	18.6%
	Total Stop Delay, veh-hr (thru mvmts along arterial)	EBT	25.6	20.1	21.5%	6.8	5.45	24.8%
		WBT	6.95	4.9	29.5%	38.45	27.5	39.8%
		Both	16.28	12.5	30.2%	22.63	16.48	27.2%
	Total stop delay, veh-hr (left turn mvmts along arterial)	EBL	6.28	6.75	-7.48%	2.32	2.83	-21.9%
		WBL	2.48	2.95	-18.9%	17.1	11.53	48.3%
		Both	4.38	4.85	-10.7%	9.71	7.18	35.2%
	Overall Stop Delay, veh-hr for all movements	All	243.0	184.2	31.9%	345.9	264.3	30.9%

Section 1: Glades Road from NW 2nd Avenue to NW 10th Avenue

The benefits due to the implementation of the lead-lag phasing are primarily gained by the off-peak direction in this control section. The average travel speeds along Glades Road are found similar for the section during AM peak hour and PM peak hour. The stops per vehicle for the through movements during AM peak hour did not show any difference between the two scenarios. During PM peak hour, the stops per vehicle had an improvement of 13% with the majority of the benefit attributed from the off peak direction traffic. The total stop delay for the through movements had an improvement of 16% (with 39% improvement for the off peak direction) during the AM peak hour and had an improvement of 44% during the PM peak hour. The left turn movements along the arterial had an improvement of 30% during PM peak hour. The overall stop delay along the arterial section improved by 9% during AM peak hour and 16% during PM peak hour.

Section 2: Yamato Road from Military Trail to Congress Avenue

The average travel speeds along Yamato Road are found to be similar for the section during AM peak hour while the speeds improved by 17% during PM peak hour (with 46% improvement for the off peak direction). The stops per vehicle for the through movements during AM peak hour did not show any difference between the two scenarios, however, the off peak direction had an improvement by 30%. During PM peak hour, the stops per vehicle indicated an improvement of 18% with the majority of the benefit attributed from the off peak direction traffic. The total stop delay for the through movements had an improvement of 30% during the AM peak hour and had an improvement of 27% during the PM peak hour. The left turn movements along the arterial indicated an improvement of 35% during PM peak hour. The overall stop delay along the arterial section improved by 32% during AM peak hour and 31% during PM peak hour.

Conclusions and Recommendations

The objective of this paper was to analyze the operational and safety impacts of the application of lead-lag left turn phasing and dynamically changing the phasing sequence by time-of-day. The safety and operational effects of the change in phasing helped determine if, in fact, the violation of driver expectancy has adverse effects on the operation of the intersections. The analysis results indicated that the crash experience at the study locations did not change with the modification of phasing sequence. The mean crash rates of the left turn related crashes and the total intersection crashes before and after the change in phasing sequence did not show any statistically significant difference. The operational effects were analyzed using measurement of the response time of the first vehicle in the left turn queue to determine if violation to driver expectancy results in higher response times. The collected response data indicated that the probability distribution of the response times when a particular left turn is operating as a leading left turn or lagging left turn is similar. While the results of the crash data analysis indicated that the change in sequence of the left turns and dynamic change of left turn sequence by time of day did not have any impact on the safety at the intersections, the response times measured at the intersections indicated that drivers become used to traffic signal phasing variations and the operation of the intersection is not affected.

Simulation analysis was performed to document that the use of lead-lag left turn phasing does have benefits related to improved traffic flow at the intersections along the arterial sections in the city. The results indicated that one section had similar operational impacts with either lead-lead left turn phasing or lead-lag left turn phasing for the peak direction but the use of lead-lag phasing improved the off-peak direction thus improving the overall conditions of the arterial. The other section had improvements along both the directions with significant improvements along the arterial.

The application of the lead-lag left turn phase sequence in the City of Boca Raton was limited to intersections with protected-only left turn control. The application of any phasing sequence should be analyzed on a case by case basis and proper analysis should be performed before deciding which type of left turn phasing to use. Application of the left turn phasing should not be a default decision to a leading or lagging operation as every phasing sequence has benefits and disbenefits. The use of lead-lag left turn sequence can result in improved green bandwidths. Care should be taken to avoid situations resulting in left turn trap when applying lead-lag phase sequence at intersections with permissive left turn movements. The City of Boca Raton's application of lead-lag left turn phasing and dynamically changing the phasing sequence by time-of-day has resulted in improved progression with no adverse safety or operational impacts. Traffic engineering agencies should be open to consider lead-lag left turn phasing, particularly where the characteristics of the arterial being considered are such that significant improved progression can result.

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