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16. Abstract

As technology in the traffic controller industry continues to improve, controllers are now more responsive to changing traffic conditions. Taking advantage of the advances in traffic controller technology, the Texas Transportation Institute (TTI) designed an adaptive left turn feature for a signal controller. Automatic Signal / Eagle Signal has introduced this logic internal to their EPAC 300 controller which is capable of deciding and implementing when a separate left turn phase should be provided or when permissive operation is acceptable based on traffic conditions. The adaptive left turn feature was tested for a wide range of left turn volumes and opposing through volumes. MOE's that were examined included cycle length, average stopped delay, total delay, and queue length. It was determined that the adaptive feature activated in the controller typically provided a benefit to the opposing through traffic, some disadvantage to the left turning traffic, but generally a benefit to the overall intersection.

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ADAPTIVE LEFT TURN PHASING

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SUMMARY

A separate left turn phase may decrease delay for left turning traffic, but will ultimately increase delay for other movements at an intersection. The choice of providing a left turn phase and allowing only permissive left turn movements requires a trade-off between maximizing overall efficiency and avoiding excessive delays and queue lengths for any approach.

The choice of left turn operations is one that most traffic engineers make for an intersection based on peak hour traffic. The intersection then operates in that manner throughout the day for several years. However, traffic patterns and conditions are not constant 24 hours a day, 7 days a week. Efficiency is lost if intersection operations are not consistent with current traffic conditions. Data collection by local agencies is time-consuming, expensive, and even time-of-day operations can not always respond effectively to fluctuations in traffic.

As technology in the industry continues to improve, traffic controllers are now able to be more responsive to changing traffic conditions. Because controllers are constantly aware of current traffic conditions at fully actuated intersections due to detector actuations, they are the most capable of making the real-time decisions for the most efficient control of an intersection. Taking advantage of the advances in traffic controller technology, the Texas Transportation Institute (TTI) designed an adaptive left turn feature for a signal controller. Automatic Signal / Eagle Signal has introduced this logic internal to their EPAC 300 controller. The controller is now capable of deciding and implementing when a separate left turn phase should be provided and when permissive operation is acceptable based on traffic conditions.

The basic concept for an adaptive left-turn is for the controller to monitor gaps in the opposing traffic stream. Conceptually, if adequate gaps exist in the opposing traffic stream, activation of the left turn phase (assuming a left turn phase is not required due to geometric or other considerations) may cause excessive delay if more cars are waiting on the opposing through phase. Based on user defined parameters, criteria to select when the protected portion of a protected/permissive phase can be omitted can be established.

The EPAC 300 controller measures the volume of left turning traffic and available gap windows in opposing through traffic by detector actuations to determine whether the left turn operation should be permissive or protected/permissive. The operation is designed to run permissive unless there are not enough acceptable gaps in the opposing through traffic *and* left turning volume is high enough to justify a protected left turn phase.

For this study, a microscopic simulation model, TexSIM, was used. TexSIM is capable of providing detections to a signal controller, reacting to signal indications, and calculating various measures of effectiveness (MOEs) about the system. One benefit of using a traffic simulator is that the intersection could be modeled under the exact same conditions with and without the adaptive left turn feature activated. The left turn and through volumes could also be

varied while the other volumes at the intersection were held constant. This was the best indication of how delay affected all approaches through activation of the adaptive protected/permissive left turn feature during varying left turn and opposing through volumes.

A typical eight-phase quad was chosen as the model intersection. Each movement had one lane except the main street through approaches, which had two lanes. Detectors were placed at the stop bar for each approach. The phase 1 left turning movement and phase 2 opposing through movement were examined in this study. The flow rates for these two movements varied from very low to very high while the rest of the intersection movements were held at a constant flow rate.

The MOEs examined in this study included average stopped delay and total delay for phase 1 and phase 2 approaches and for the total intersection. The percentage of cycles that phase 1 was omitted and average cycle lengths per period were also examined as characteristics of operation of the intersection with and without the activation of the adaptive protected/permissive feature. Maximum queue lengths on phase 1 were measured to determine the effect of omitting the left turn phase on queue length. Each MOEs was provided by TexSIM, and imported to a spreadsheet for analysis. Although TexSIM did not report fuel consumption as a MOE, the number of vehicles, total delay, and number of stops that were reported by TexSIM were imported into a spreadsheet to calculate fuel consumption as a MOE.

In order for the phase 1 omit to be lifted when the adaptive feature was on, an insufficient number of acceptable gaps with a left turning flow rate greater than 120 vehicles per hour (vph) was required, or a vehicle had to activate the left turn detector for more than two minutes. As expected, conditions to lift the phase 1 omit existed mostly in the lower range flow rates. Phase 1 was omitted in some, but not all, cycles in the medium and higher range flow rates. This allowed a protected left turn phase to service left turning traffic when conditions were warranted, without causing excessive queuing or delays on that approach.

The average stopped delay was calculated for the total intersection, phase 1 left turn movement, and phase 2 opposing through approach with and without the adaptive left turn feature functional. Some stopped delay savings were noticed for the total intersection in most, but not all cases. For nearly all cases, the phase 2 opposing through movement experienced less average stopped delay with the adaptive feature active, and the phase 1 left turn movement experienced greater delay with the adaptive feature active. This is because the left turning vehicles were forced to wait for an acceptable gap when the left turn phase was omitted, and opposing through vehicles were not stopped for a protected left turn.

Total delay (in hours) experienced during each 15-minute test period was recorded for the total intersection, phase 1 approach, and phase 2 approach. The adaptive left turn feature provided some delay savings in most of the test cases for the overall intersection. At the higher left turn flow rates, higher total intersection delay was experienced with the adaptive feature on because delays being caused to the left turning vehicles did not offset the delay savings experienced by the rest of the intersection approaches. Phase 2 experienced delays savings in all test cases and phase 1 had higher delays with the adaptive left turn feature activated.

The maximum queue length during each 15-minute test period was recorded by the simulation model. The adaptive feature appeared to have the greatest effect on queue lengths at the medium and higher left turn flow rates with the medium opposing through flow rates. At these flow rates, the adaptive feature continued to frequently omit the left turn phase, but there were fewer available gaps for the left turning vehicles. Most other tested flow rate combinations experienced an increase of one to two vehicles in the max queue length.

Total travel, total delay, and number of stops were used to calculate fuel consumption for each test cases with and without the adaptive left turn feature activated. Fuel was saved over the entire system for the lower left turn flow rates. Higher left turn flow rates experienced fuel savings in some cases but not in others due to higher number of stops and/or higher delays experienced by the left turning vehicles.

Although a left turn phase may be skipped at a normal fully actuated intersection if no vehicles are present, a left turn may also be activated unnecessarily for only one or two vehicles even when adequate gaps in the opposing traffic stream exist. This report reveals that by omitting the left turn phase and forcing left turning vehicles to use a permissive phase, delay to opposing through traffic and possibly the rest of the intersection approaches may be reduced. Left turning vehicles may experience higher delays and/or longer queues. As long as these delays are not excessive, the overall intersection should benefit by omission of the left turn phase for left turning flow rates less than 150 vph. For left turning flow rates of 150 vph or greater, this study reveals that the omission of the left turning phase during some cycles will cause a disadvantage to the left turning vehicles that is greater than the benefit to the opposing through vehicles thereby degrading the overall operation of the intersection.

1.0 INTRODUCTION

1.1 INTRODUCTION

The treatment of left turning traffic at a signalized intersection greatly effects the capacity and safety of the intersection. Many research reports address provisions for a separate left turn phase, without providing a definite agreement on what conditions warrant a separate phase. A separate left turn phase may decrease delay to the left turning traffic, but will ultimately increase delay for the other movements at the intersection. The choice of providing a left turn phase and only allowing permissive left turn movements requires a trade-off between maximizing overall efficiency and avoiding excessive delays and queue lengths for any approach *(1)*.

The choice of left turn operation is one that most traffic engineers make one time for an intersection based on peak hour traffic. The intersection is then allowed to operate in that manner throughout the day for several years. Traffic patterns are not constant 24 hours a day, 7 days a week and efficiency is lost if the operation of an intersection is not consistent with current traffic conditions. Data collection by local agencies is time-consuming and expensive and even time-of-day operations can not always respond effectively to fluctuations in traffic.

As technology in the traffic controller industry continues to improve, controllers are now able to be more responsive to changing traffic conditions. Because controllers are constantly aware of current traffic conditions at fully actuated intersections due to detector actuations, they are the most capable of making real-time decisions concerning the most efficient control of the intersection. Taking advantage of the advances in traffic controller technology, TTI designed an adaptive left turn feature for a signal controller. Automatic Signal / Eagle Signal introduced this logic internal to their EPAC 300 controller which is capable of deciding and implementing when a separate left turn phase should be provided or when permissive operation is acceptable based on traffic conditions.

1.2 OBJECTIVES

The objectives of this research were to design, implement, and test an adaptive left turn feature for a traffic signal controller. The feature was designed by TTI and implemented by Automatic Signal/Eagle Signal in a NEMA controller. A literature review was performed to determine acceptable values for providing a separate left turn phase for use as input to the controller. The Adaptive Protected/Permissive feature on the Automatic Signal/Eagle Signal EPAC 300 signal controller was evaluated for reducing delay at fully actuated intersections by providing and implementing real-time decisions on whether the left turn phase should operate permissive or protected/permissive based on current traffic conditions *(2)*.

2.0 BACKGROUND

2.1 LEFT TURN SIGNAL PHASING

Left turn phasing at signalized intersection falls into one of three basic categories *(3)*:

• *Permissive Phasing* - Permissive left turn phasing occurs when no protected phase for left turning vehicles is provided. Vehicles turning left utilize gaps in the opposing traffic flow to make their turn. A green ball signal indication is provided during the permissive phase.

• *Protected Only Phasing* - For protected only phasing, a separate phase is provided during the cycle to accommodate left turning vehicles while opposing through vehicles are stopped. Left turns are prohibited during the rest of the cycle. A green arrow is provided during the protected left turn phase.

• *Protected/Permissive Phasing* - Signalized intersections with protected/permissive left turn phasing provide a separate protected left turn phase during one part of the cycle but allow unprotected left turns across opposing through traffic during another part of the cycle. A green arrow is provided for left turning vehicles during the protected phase and a green ball is provided during the permissive part of the cycle.

2.2 SEPARATE LEFT TURN WARRANT

In recent years several studies addressed the topic of when to provide a separate left turn phase at a signalized intersection. The subject of providing a separate left turn phase involves both safety and efficiency issues. Many intersection characteristics and variables were examined in previous studies including: left turn volume, adjacent through volume, opposing volume, number of available gaps, number of lanes, number of left turn related accidents, number of conflicts, vehicle speed, geometric characteristics, and sight distance. Most studies suggesting guidelines for providing a left turn phase, though, are based on left turn and opposing volumes, left turn delay, and accident experience.

Not providing a necessary left turn phase may contribute to excessive left turn delay, long queues, and even accidents if vehicles have trouble turning safely against opposing through traffic. However, providing a separate left turn phase if it is not necessary decreases the efficiency of the intersection. If the cycle length is increased to provide a left turn phase, other approaches are delayed. In coordinated systems, green time may be lost on higher volume phases in order to provide the separate left turn phase.

Due to the efficiency considerations, a separate left turn phase should only be provided when certain guidelines are met. Although most agencies have some warrants or guidelines detailing when to provide a protected left turn phase, these warrants are generally not consistent from agency to agency *(4)*.

The *Manual on Uniform Traffic Control Devices (10)* provides no warrants for left turn signal phasing. The *Traffic Control Devices Handbook (11)* has suggested the following guidelines based on volumes, delay, and accident experience:

- *Volumes* - Consider further studies for separate left turn phasing when the product of left turning vehicles and opposing volumes during peak hours exceeds 100,000 on a four-lane street or 50,000 on a two lane street and the left turn volume is greater that two vehicles per cycle.

- *Delay* - Install separate left turn phasing if a left turn delay of 2.0 vehicle-hours or more occurs on a critical approach during a peak hour, and the left turn volume is greater that two vehicles per cycle with an average delay per left turning vehicle of at least 35 seconds.

- *Accident experience* - Install left turn phasing if the critical number of left turn accidents has occurred. For one approach, the critical number is four left turn accidents in 1 year or six in 2 years. For both approaches, the critical number is six left turn accidents in 1 year or ten in 2 years.

A survey of 45 states performed by Agent *(4)* revealed that criteria for providing a separate left turn phase differs from agency to agency. Guidelines from each of the surveyed agencies are summarized below according to two of the categories defined in the *Traffic Control Devices Handbook.*

Volumes - Provide a separate left turn phase if *(4):*

1. At a pretimed signal, LT volume of >2 veh per approach per cycle during peak hour
2. LT volume >100 vehicles during peak hour
3. More than 90 vph are making a left turn
4. The number of LT vehicles is about 2 per cycle
5. 120 LT vehicles during design hour
6. LT volume >100 vph
7. LT volume of 90-120 vehicles in peak hour
8. LT volume must be >50 vph and LT volume * opposing through volume = 100,000

Delay - Provide a separate left turn phase if *(4)*:

1. Delay to left turn vehicles is in excess of 2 cycles
2. 1 left turn vehicle is delayed 1 cycle

Another survey discussed by Agent asked engineers for their opinion of what constituted the maximum tolerable delay for a vehicle controlled by a traffic signal. The mean maximum tolerable delay was found to be 73 seconds *(4)*.

Due to accidents that can be caused by an unsafe left turning situation, safety is also a concern when deciding on a left turn phasing type. A study done by Upchurch *(6)* listed criteria suggested by several agencies of when a protected only left turn phase should be used instead of protected/permissive or permissive phasing. It should be remembered that the safety of left turning vehicles at individual intersections depends on the specific geometry of the intersection and the characteristics of the drivers that travel through the intersection.

The Upchurch study found that a protected only left turn phase should be provided for safety reasons if *(6)*:

1. Left turning traffic must cross three or more lanes of opposing through traffic.
2. The speed limit of opposing traffic is greater than 72 km/hr (45 mph.) At high speeds it is more difficult for left-turning motorists to judge acceptable gaps. It should be noted, though, that a study by Cottrell *(7)* found no safety problems with speed limits greater than 72 km/hr (45 mph.)
3. There is restricted sight distance due to roadway geometry or opposing left-turning vehicles. Sight distance should be greater than 76.2 m (250 ft) for speeds of 56.3 km/hr (35 mph) and 121.9 m (400 ft) for speeds greater than 56.3 km/hr (35 mph.)

Cottrell *(7)* found the angle of the intersecting roadways may also contribute to safety problems of vehicles turning left on a permissive phase. When the need for additional time is not perceived, a turning driver may accept an inadequate gap thereby creating a hazardous situation.

Gap acceptance is an important factor in permissive phasing. There must be an adequate number of acceptable gaps in the opposing through traffic flow that allows left turning vehicles to complete their maneuver. Only one study, by Benham *(9)*, was found that actually used gap availability as a specific variable for determining if protected left turns are needed. Gap availability has a direct relationship to the volume of opposing through traffic. When there are higher volumes, there will be fewer acceptable gaps. Because volumes are easier to measure and are also used for other applications, volumes have been generally preferred as a variable in determining the need for a separate left turn phase.

2.3 DELAY EFFECTS OF LEFT TURN PHASING TYPE

Upchurch *(6)* compared each of the three left turn phasing types to delay experienced on the left turn approach and the opposing through approach. The study determined that at low volume levels permissive phasing works very effectively. Changing to protected/ permissive phasing at these low volumes results in very little reduction in left turn delay. At higher volume levels, left-turn delay increases rapidly when permissive phasing is used and protected/ permissive phasing results in a significant reduction in left turn delay. Protected only phasing resulted in higher left turn delays at all volume levels except high volumes. For high volume traffic there was no significant difference in delay between protected/permissive and protected only because there were very few adequate gaps for vehicles to turn during the permissive phase.

For the opposing through approach, delay was negligible for permissive phasing. Delay was higher for the opposing approach with protected/permissive phasing but less than with protected only. The magnitude of the delay experienced by through traffic increased as the volume levels increased *(6)*.

Lin *(1)* performed a simulation model study to attempt to establish guidelines concerning the choice between permissive phasing and protected/permissive phasing. Factors used in the model were: effective length of left turn bay, left turn volume, adjacent through volume, opposing through volume, number of opposing lanes, and cross-street volume. Some assumptions made in this study were: left turn drivers have a 5 second critical gap, there is a 15 percent chance that the first left turn vehicle in queue will turn in front of the first opposing vehicle immediately after the light turns green, and vehicles approach the intersection randomly at an average speed of 48 km/hr (30 mph.)

Lin (*1*) found that overall delay was more sensitive to left turning volume for permissive phasing and that protected/permissive phasing provides more equitable services to the vehicles in every lane, especially at higher volumes. The study also indicated that permissive left turns provides shorter left turn delays and overall delays, when the left turn volume is small. As the left turn volume increases, protected/permissive phasing easily provides better service to the left turn vehicles, although permissive phasing may still yield less overall delays. When the left turn volume is high, protected/permissive phasing reduces not only left turn delay but also overall delay.

2.4 DEVELOPMENT OF ADAPTIVE PROTECTED/PERMISSIVE LEFT TURN PHASING

As previously discussed, each agency follows it's own guidelines when determining which left turn phasing strategy to implement at a signalized intersection. Studies also found that choosing the wrong phasing strategy can result in safety problems, as well as decreasing the efficiency of the intersection and causing excessive delays. What these reports did not address was that variables used in selecting a control strategy change throughout the day.

Most agencies examine only peak hour volumes when determining a control strategy. That strategy is then implemented around the clock. Only a few agencies attempt to change the left turn phasing by time-of-day. Lin *(1)* found that in terms of overall delay, the control efficiencies may deteriorate by more than 30 percent when an improper phasing arrangement is implemented. To achieve maximum efficiency throughout the day without causing excessive delays, the control strategy should based on current traffic conditions.

The signal controller at a fully-actuated intersection is aware of traffic conditions 24 hours a day, 7 days a week due to detector actuations. Therefore, the signal controller is the most logical candidate for determining when a left turn phase can be permissive or when a protected phase is needed to serve left turning vehicles. This logic was developed by the TTI and incorporated into the Automatic Signal/Eagle Signal EPAC 300 NEMA controller.

The basic concept for an adaptive left-turn has the controller monitoring gaps in the opposing traffic stream. Conceptually, if adequate gaps exist in the opposing traffic stream, activation of the left turn phase (assuming a left turn phase is not required due to geometric or other considerations) may cause excessive delay if more cars are waiting on the opposing through phase. Based on user defined parameters, criteria can be established to select when the protected portion of a protected/permissive phase can be omitted.

2.5 ADAPTIVE PROTECTED/PERMISSIVE LEFT TURN FEATURE

The EPAC 300 controller measures the volume of left turning traffic and the available gap windows in opposing through traffic by detector actuations. This determines whether the left turn operation should be permissive or protected/permissive. Left turn operation is designed to run permissive unless there are not enough acceptable gaps in the opposing through traffic *and* left turning volume is high enough to justify a protected left turn phase.

There are four user set variables that apply to two detector inputs for each left turn/opposing through traffic combination. The user enters which detector is the left turn detector and the phase with which it is associated. The user also enters which detector input is the opposing through traffic and the phase with which it is associated. The user set variables are described as follows *(2)*:

- *Minimum Turn Volume* - This variable represents the minimum volume of left turning traffic necessary to consider running protected operation. The controller accepts values between 0-999 vph for this variable.

- *Minimum Vehicle Gap* - This variable represents the minimum gap between opposing through detector calls during the opposing through green needed to accommodate a permissive turn vehicle. The controller accepts values of 0-999 seconds for this variable.

• *Gap Percentage* - This variable represents the percentage of through gap windows that will be utilized by left turning vehicles. The controller accepts values of 0-999% for this variable.

• *Maximum Constant Call* - This variable represents the maximum time a constant call on the turn detector can exist before this routine will discontinue calling for permissive operation. The controller accepts values between 0-999 minutes for this variable.

Using detector actuations, the controller calculates Smoothed Turn Volumes based on a rolling average for a smoothed averaging time of 5 minutes. The controller also calculates Smoothed Gap Windows based on a rolling average for the same smoothed averaging time of 5 minutes. The controller uses the calculated Smoothed Turn Volumes and Smoothed Gap Windows to decide if a protected phase is needed or if the left turn can operate efficiently as permissive *(2)*.

The logic in the controller decides if the Smoothed Turn Volume is less than the Minimum Turn Volume. If the Smoothed Turn Volume is less, the routine calls for permissive operation; in other words, the protected left turn phase is omitted. If the Smoothed Gap Windows multiplied by the Gap Percentage exceeds the Smoothed Turn Volume, the routine also omits the protected phase. If there has been a constant left turn detector call longer than the Maximum Constant Call, the routine will not omit the protected phase *(2)*.

2.6 TexSIM 2.0 TRAFFIC SIMULATION MODEL

TexSIM 2.0 (12), was developed by the TTI to facilitate testing advanced signal phasing strategies to determine their safety and effectiveness before field implementation *(13)*. TexSIM can handle up to 1000 intersections, each with up to 16 approaches. TexSIM supports permitted phasing, protected phasing, stop control, and yield control on any of eight possible approaches and turning movements. This model offers such advanced features as variable lane-assignments, lane changing, incident simulation, and rail simulation (12).

TexSIM 2.0 also offers several features not currently available in many traffic simulation models. The simulator can interact with a traffic signal controller in real-time and has an animated graphical display that provides vehicle, detector, and system information in real-time. The simulator generates a variety of measure of effectiveness (MOE) data and can simulate nearly any control strategy (12).

TexSIM's ability to interact in real-time with a traffic controller during simulations made it possible to test the adaptive protective/permissive feature of the Eagle Signal EPAC 300 controller in a laboratory environment. The controller receives the detector information generated by TexSIM for each approach. Splits are allocated by the controller and monitored by TexSIM. While operating in this mode, all simulator internal controller logic is switched off.

The signal indications on the simulator are updated by directly reading the signal status from the controller output fed into a National Instruments PC-DIO-96 card *(12)*.

3.0 STUDY DESIGN

3.1 ADAPTIVE PROTECTED/PERMISSIVE VARIABLES

A literature review was conducted to determine acceptable values for the Minimum Turn Volume and Maximum Constant Call variables. As previously stated, the left turn volume for warranting a separate left turn phase varied anywhere between 90 vph to 120 vph. A value of 120 vph was determined to be acceptable for calling for a separate left turn phase in this study. As stated in the literature, the maximum acceptable delay to left turning vehicles varied between one cycle and two cycles with 73 seconds being an acceptable mean maximum *(4)*. Because this variable had to be entered in whole minutes in the controller, a value of 2 minutes was chosen as the Maximum Constant Call.

In the TexSIM simulation model the gap size utilized by left turning vehicles is not a variable. Although an acceptable gap size can be set in the program, a left turning vehicle will always accept anything greater than the preset acceptable gap size during a permissive phase. Therefore, the Minimum Vehicle Gap was set for 5 seconds at the controller and the Gap Percentage (percent of vehicles that will accept the minimum gap) was set to 100 percent. For field implementation of this feature, a critical gap study should be performed and the Minimum Vehicle Gap should be set to the observed critical gap with a Gap Percentage of 50 percent.

3.2 "BEFORE AND AFTER" STUDY

One benefit of using a traffic simulator is that the intersection could be modeled under the exact same conditions with and without the adaptive protected/permissive feature activated. Left turn and through volumes could also be varied while other volumes at the intersection were held constant. This was postulated as the best indication of how delay for all approached was affected by activation of the adaptive protected/permissive left turn feature during varying left turn and opposing through volumes.

3.3 INTERSECTION CHARACTERISTICS

A typical eight-phase quad was chosen as the modeled intersection. Each movement had one lane with the exception of the main street through approaches, which had two lanes. Detectors were placed at the stop bar for each approach.

A standard NEMA ring structure with leading left turns was programmed into the controller. Figure 3-1 depicts the phasing for the intersection. Phases 1 and 2 were chosen as the left turn and opposing through phases to be studied. The controller phase settings selected are shown in Table 3-1. The flow rate for each movement was held constant, with the exception of the movements for phases 1 and 2. The flow rates for phases 3 through 8 are also shown in Table 3-1. Flow rates for phase 1 varied between 50 vph and 300 vph in increments of 50 vph.

The flow rates for phase 2 varied between 500 vph and 1750 vph in increments of 250 vph. Six flow rates for phase 1 ranging from very low to very high and six flow rates for phase 2 ranging from very low to very high were tested. Therefore, 36 different combinations of left turn and opposing through flow rates were tested while the flow rates for each of the other phases were held constant.

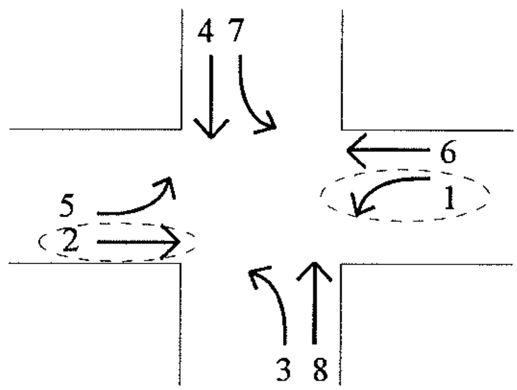

Figure 3-1. Phasing Structure for Modeled Intersection

Table 3-1. Controller Phase Settings and Movement Flow Rates

	Phases							
	Ph 1	**Ph 2**	**Ph 3**	**Ph 4**	**Ph 5**	**Ph 6**	**Ph 7**	**Ph 8**
Min Green	10	10	10	10	10	10	10	10
Passage	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Max Green	20	70	15	25	20	70	15	25
Yellow	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Red Cl.	1.0	1.0	1.0	1.0	1.0	1.0.	1.0	1.0
Flow Rate (vph)	variable	variable	150	250	200	1200	150	250

3.4 TexSIM SIMULATION RUNS

Each of the 36 combinations of left turn and opposing through flow rates were tested in 15 minute increments using TexSIM. Five simulation runs for each of the 36 combinations were conducted both with and without the adaptive protective/permissive feature active, for a total of ten simulation runs for each combination. A different random number seed was used for each set of combinations. The five adaptive-feature-on runs were averaged and the five adaptive-feature-off runs were averaged for comparison. All analysis was performed with the average values.

3.5 MEASURES OF EFFECTIVENESS

The MOEs examined in this study included: average stopped delay, total delay for both the phase 1 and phase 2 approaches, and total delay for the whole intersection. The percentage of cycles that the phase 1 was omitted and the average cycle lengths per period were examined as characteristics of operation of the intersection both with and without the adaptive protected/permissive feature activated. Maximum queue lengths for phase 1 were also measured to determine the effect of omitting the left turn phase on queue length. The TexSIM output for each MOE was imported to a spreadsheet for analysis.

Average stopped delay was calculated by TexSIM by dividing the total number of seconds that vehicles were queued by the number of vehicles discharged during each fifteen minute period. Average stopped delay is reported in seconds per vehicle. The stopped delay value for phase 1 was calculated using only the left turn lane designated for phase 1. The average stopped delay value for phase 2 was calculated by averaging the stopped delay for the two opposing through lanes designated as phase 2. The average stopped delay value for the total intersection was calculated by averaging the stopped delay for each of the lanes in the intersection.

Total delay calculations are based on the desired speed of the vehicle, as determined on entry to each approach. The delay is the additional travel-time required by traversing the system, as compared to the travel time required if the vehicle was allowed to proceed at the desired speed with no influential interaction from other cars *(12)*. Total delay is reported in vehicle-hours. The total delay value for phase 1 was calculated using only the left turn lane designated for phase 1. The total delay value for phase 2 was calculated by summing the total delay for the two opposing through lanes designated as phase 2. The total delay value for the entire intersection was calculated by summing the total delay for each of the lanes in the intersection.

For each combination of left turn and opposing through flow rates, the number of cycles occurring during the 15 minute test period was compared to the number of times that phase 1 was activated during that period. The number activation times for phase 1 was then divided by the number of cycles to determine the percentage of cycles that phase 1 occurred. This value gives an indication of whether or not the adaptive protected/permissive feature plays a role in the rest of the MOE values.

The cycle length was averaged for each 15 minute test period to determine if skipping the left turn phase played a significant role in reducing the cycle length and thereby reducing delay experienced at the intersection. To show the effect that skipping the left turn phase has on queue lengths, the phase 1 maximum queue length for each test period was provided as output from the simulator. TexSIM reported the maximum queue length in vehicles.

3.6 FUEL CONSUMPTION

The effects of adaptive left turn phasing on fuel consumption were not available as output from TexSIM. However fuel consumption effects were calculated in a spreadsheet as a factor of delay and stops that were output from the model. The equation to calculate fuel consumption in both the TRANSYT 7-F and PASSER II-90 was used *(14)*. Equation 1 estimates fuel consumption based on total travel, total delay, total stops and cruise speed of the vehicles traveling through the intersection.

$$\begin{aligned} F &= (A_{11} + A_{12}*V + A_{13}*V^2) * TT \\ &+ (A_{11} + A_{12}*V + A_{13}*V^2) * D \\ &+ (A_{11} + A_{12}*V + A_{13}*V^2) * S \end{aligned} \qquad \textit{Equation 1}$$

where:

F = estimated total system fuel consumption, gal/hr;
TT = total travel, veh-mi/hr;
D = total delay, veh-hr/hr;
S = total stops, stops/hr;
V = cruise speed, mph; and
A_{ij} = regression model beta coefficients, and is given by,

$$A_{ij} = \begin{matrix} 0.75283 & -1.5892\text{ E-3} & 1.50655\text{ E-5} \\ 0.73239 & 0.0 & 0.0 \\ 0.0 & 0.0 & 6.14112\text{ E-6} \end{matrix}$$

The total delay, number of stops, and number of vehicles in each test combination were imported into a spreadsheet. Each of the vehicles traveling through the system was assumed to travel 0.1 miles. To estimate total travel (TT), the number of vehicles in each 15-minute period was multiplied by four to obtain an hourly volume. This value was then multiplied by 0.161 kilometers (0.1 miles) of travel to obtain total travel in veh-km/hr (veh-mi/hr.) Each of total delay and number of stops values were also multiplied by four to obtain delay in veh-km/hr/hr (veh-hr/hr) and total stops in stops/hr. The cruise speed (V) was assumed to be 64.5 km/hr (40 mph) for each approach.

The total system fuel consumption was calculated for each test period in the spreadsheet using Equation 1. The total fuel consumption for each test period with the adaptive left turn feature on was subtracted from the corresponding periods with the adaptive feature was not activated. These values were considered to be the fuel savings experienced when the adaptive left turn feature was activated.

4.0 RESULTS

4.1 PHASE 1 OMITS

The adaptive protected/permissive feature operates by omitting the left turn phase until certain traffic conditions are met. The phase 1 omit is then lifted. Because the modeled intersection was fully actuated, if there were no left turning vehicles present, phase 1 would not be activated even with the adaptive left turn feature off. Table 4-1 shows the percentage of cycles during the test period that phase 1 was not activated with the adaptive left turn feature turned off.

Table 4-2 shows the percentage of cycles that phase 1 was omitted with the adaptive left turn feature turned on. With the adaptive feature on, an insufficient number of acceptable gaps with a left turning flow rate greater than 120 vph was required, or a vehicle must activate the left turn detector for more than two minutes in order for the phase 1 omit to be lifted. As expected, these conditions to lift the phase 1 omit existed mostly in the lower left turn and opposing through flow rates. Phase 1 was omitted in some, but not all, of the cycles in the medium and higher range flow rates. This allowed a protected left turn phase to service the left turning traffic when conditions were warranted, so as not to cause excessive queuing or delays on that approach.

Table 4-1. Percentage of Cycles Phase 1 Was Omitted - Adaptive Feature Off

thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	53%	19%	19%	14%	9%	8%
750	43%	14%	8%	8%	5%	5%
1000	37%	16%	3%	5%	3%	0%
1250	34%	16%	6%	3%	0%	0%
1500	29%	16%	6%	0%	0%	0%
1750	32%	9%	0%	0%	0%	0%

4.2 CYCLE LENGTHS

Cycle lengths were averaged for the five simulation runs over each 15-minute test period. Tables 4-3 and 4-4 show the resulting average cycle lengths when the adaptive left turn feature was on and when it was off. Table 4-5 shows the difference in average cycle lengths for each test scenario. An almost negligible difference in cycle length was experienced. It is expected that a reduction in cycle length was not seen at lower variable flow rates because only one left turn/opposing through combination was tested, and the static approaches controlled the cycle length. At the higher variable flow rates, even though the variable flow rates controlled the cycle length, the adaptive feature was not activated as often, and therefore did not have a significant effect on the cycle length.

Table 4-2. Percentage of Cycles Phase 1 Was Omitted - Adaptive Feature On

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	100%	100%	100%	100%	95%	87%
750	100%	100%	100%	94%	77%	90%
1000	97%	95%	84%	80%	66%	37%
1250	100%	94%	67%	83%	30%	6%
1500	86%	65%	56%	32%	14%	6%
1750	74%	41%	26%	6%	6%	0%

Table 4-3. Average Cycle Length (Sec) - Adaptive Feature On

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	123	121	126	120	123	121
750	122	122	120	126	129	126
1000	126	122	126	130	130	131
1250	124	128	128	130	136	135
1500	129	130	133	141	138	142
1750	130	136	142	143	147	147

Table 4-4. Average Cycle Length (Sec) - Adaptive Feature Off

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	125	124	124	122	125	123
750	126	122	123	121	126	123
1000	125	127	129	123	128	131
1250	132	127	129	131	133	137
1500	132	138	134	140	144	142
1750	135	141	144	147	147	147

Table 4-5. Difference in Average Cycle Lengths (Sec)

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	2	3	-2	3	2	2
750	4	0	3	-5	-3	-3
1000	-1	4	2	-6	-2	0
1250	8	-1	1	1	-3	2
1500	4	8	1	-1	5	1
1750	4	5	2	3	1	0

4.3 AVERAGE STOPPED DELAY

Average stopped delay was calculated for the total intersection, the phase 1 left turn movement, and the phase 2 opposing through approach with and without the adaptive left turn feature functional. Stopped delay savings (adaptive feature on - adaptive feature off) is reported in Tables 4-6, 4-7, and 4-8. The results depicted were for the most part expected. Some stopped delay savings was noted for the total intersection in most but not all cases. In nearly all cases, the phase 2 opposing through experienced less average stopped delay with the adaptive feature active, and the phase 1 left turn experienced greater delay with the adaptive feature active. This is because the left turning vehicles were forced to wait for an acceptable gap when the left turn phase was omitted, and opposing through vehicles were not stopped for a protected left turn phase.

Table 4-6. Average Total Intersection Stopped Delay Savings (Sec/Veh)

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	**100**	**150**	**200**	**250**	**300**
500	0.9	0.4	0.2	1.3	0.5	0.1
750	2.4	2.4	1.1	0.1	0.5	-0.1
1000	1.4	2.6	1.2	0.1	0.3	-1.2
1250	2.5	1.8	-0.3	0.1	0.2	-1.8
1500	1.3	1.8	-2.1	-1.4	0.1	1.1
1750	1.4	1.2	0.8	1.4	0.9	-1.6

Table 4-7. Average Phase 2 Stopped Delay Savings

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	**100**	**150**	**200**	**250**	**300**
500	3.8	5.7	6.2	9.2	5.4	0.4
750	4.2	6.4	8.0	9.3	7.4	9.5
1000	5.1	7.4	5.6	6.5	3.7	1.2
1250	5.3	8.5	5.0	11.3	2.8	-2.9
1500	2.4	5.0	1.5	0.4	0.9	2.5
1750	4.2	2.7	6.7	6.1	8.7	-0.9

Table 4-8. Average Phase 1 Stopped Delay Savings

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	-10.0	-11.3	-12.8	-12.5	-8.7	-3.5
750	-12.5	-12.4	-13.1	-14.2	-10.4	-15.0
1000	-17.2	-13.3	-14.2	-16.6	-6.2	-16.6
1250	-19.0	-25.5	-37.7	-23.8	-3.8	6.3
1500	-21.1	-30.3	-53.1	-40.1	3.5	5.3
1750	-57.6	-21.4	-38.9	-22.7	-10.7	2.4

4.4 TOTAL DELAY

Total delay (in hours) experienced for each of the 15-minute test periods was recorded for total intersection, phase 1 approach, and phase 2 approach. The results are reported in Tables 4-9 through 4-11 and are similar to the results of the stopped delay analysis. The adaptive left turn feature provided some delay savings for most of the test cases for the overall intersection. At the 150 vph and higher left turn flow rates, higher total intersection delay was experienced with the adaptive feature on because the delays being caused to the left turning vehicles did not offset the delay savings experienced by the rest of the intersection approaches. Phase 2 experienced delays savings in all test cases and phase 1 had higher delays with the adaptive left turn feature activated.

Table 4-9. Total Intersection Total Delay Savings (Hrs)

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	0.2	0.2	0.4	0.3	-0.2	0.5
750	0.4	0.4	0.3	-0.3	0.1	0.0
1000	0.4	0.6	0.2	0.2	0.1	-0.3
1250	0.7	0.3	-0.2	-0.1	0.1	-0.5
1500	0.5	0.5	-0.4	-0.3	0.6	0.3
1750	0.1	0.4	0.4	0.1	0.2	-0.8

Table 4-10. Phase 2 Total Delay Savings (Hrs)

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	0.3	0.5	0.2	0.4	0.1	0.1
750	0.5	0.6	0.6	0.7	0.7	0.5
1000	0.8	1.0	0.8	0.8	0.8	0.2
1250	0.9	1.2	0.9	1.4	0.8	0.4
1500	1.2	1.2	0.8	0.8	1.3	0.7
1750	1.3	1.5	2.0	2.0	2.5	1.3

Table 4-11. Phase 1 Total Delay Savings (Hrs)

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	-0.1	0.0	-0.1	-0.1	-0.2	0.0
750	-0.1	-0.1	-0.1	-0.2	-0.2	-0.4
1000	-0.1	-0.1	-0.1	-0.1	0.0	-0.4
1250	-0.1	-0.3	-0.6	-0.5	-0.3	0.3
1500	0.0	-0.1	-0.9	-0.7	0.0	0.1
1750	-0.3	-0.2	-0.9	-0.2	-0.7	-0.5

4.5 LEFT TURN QUEUE LENGTH

The maximum queue length for the left turn lane during each 15-minute test period was recorded by the simulation model. The maximum queue lengths with the adaptive left turn feature on and off are reported in Tables 4-12 and 4-13. The differences in the queue lengths are shown in Table 4-14. The adaptive feature appeared to have the greatest effect on queue lengths at the 150 vph and 200 vph left turn flow rates with the 1250 vph and 1500 vph opposing through flow rates. At these flow rates, the adaptive feature was still omitting the left turn phase frequently, but there were fewer available gaps for the left turning vehicles. Most of the other tested flow rate combinations experienced a one to two vehicle increase in the maximum queue length.

Table 4-12. Average Max Queue Length (Veh) - Adaptive Feature On

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	3.4	4.6	5.4	7.4	8.4	9.2
750	3.2	4.2	6.4	7.4	9.6	11.0
1000	4.2	5.4	6.0	8.8	9.6	13.8
1250	3.0	7.0	11.2	12.8	11.4	11.2
1500	3.8	7.8	15.0	17.2	11.8	16.8
1750	6.2	9.4	16.0	15.2	17.4	19.2

Table 4-13. Average Max Queue Length (Veh) - Adaptive Feature Off

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	1.8	4.0	5.6	6.4	6.6	7.4
750	2.8	3.4	6.4	6.2	7.4	8.4
1000	2.6	3.8	5.0	6.2	10.0	10.2
1250	2.8	4.6	5.6	10.0	8.8	12.2
1500	3.8	6.4	7.8	9.0	11.2	18.0
1750	3.4	7.0	9.0	10.2	13.0	17.8

4.6 FUEL CONSUMPTION

Total travel, total delay, and the number of stops were used to calculate fuel consumption for each of the test cases both with and without the adaptive left turn feature activated. The fuel savings experienced by using the adaptive left turn feature for each of the cases is reported in Table 4-15. The greatest benefit in fuel savings was seen consistently for left turn flow rates of less than 150 vph. For flow rates of 150 vph and greater, fuel savings was noted in some cases but not in others due to higher number of stops and/or higher delays experienced by the left turning vehicles.

Table 4-14. Difference in Max Queue Lengths (Veh) - On-Off

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	1.6	0.6	-0.2	1.0	1.8	1.8
750	0.4	0.8	0.0	1.2	2.2	2.6
1000	1.6	1.6	1.0	2.6	-0.4	3.6
1250	0.2	2.4	5.6	2.8	2.6	-1.0
1500	0.0	1.4	7.2	8.2	0.6	-1.2
1750	2.8	2.4	7.0	5.0	4.4	1.4

Table 4-15. Total System Fuel Consumption (Gal/Hr) - Adaptive Feature On

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	288.8	293.0	303.7	305.2	318.2	316.1
750	311.6	314.9	315.4	333.4	335.5	341.0
1000	335.1	342.7	350.6	355.6	362.2	378.1
1250	360.3	370.4	381.4	386.9	392.1	398.5
1500	384.4	393.7	405.6	412.0	416.9	434.4
1750	416.8	426.4	438.4	446.3	460.1	466.1

Table 4-16. Total Fuel Consumption (Gal/Hr) - Adaptive Feature Off

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	290.0	293.7	302.1	306.0	317.3	318.3
750	314.9	316.5	318.5	330.3	334.6	338.2
1000	339.6	344.1	351.4	361.8	365.3	372.3
1250	366.0	371.1	376.7	382.3	393.0	394.2
1500	388.1	399.4	402.7	413.9	420.8	433.9
1750	419.9	427.3	435.0	442.2	456.2	466.3

Table 4-17. Total System Fuel Savings (Gal/Hr)

Thru flow rate (vph)	Left turn flow rate (vph)					
	50	100	150	200	250	300
500	1.2	0.7	-1.6	0.8	-0.9	2.3
750	3.2	1.7	3.2	-3.1	-0.9	-2.8
1000	4.5	1.4	0.8	6.2	3.1	-5.8
1250	5.7	0.7	-4.7	-4.5	1.0	-4.4
1500	3.7	5.7	-2.8	1.9	3.8	-0.5
1750	3.2	0.9	-3.4	-4.1	-3.9	0.2

5.0 CONCLUSIONS

TTI has taken the idea of adaptive control one step further in the development of an adaptive protected/permissive left turn feature for a NEMA controller. With advances in signal controller hardware and software, some control choices should be made by the signal controller which is aware of the current traffic conditions, and therefore, the best candidate for choosing an appropriate control strategy. However, the traffic engineer or signal technician must choose the proper operating parameters under which the control choices are made.

Although a left turn phase may be skipped at a normal fully actuated intersection if no vehicles are present, a left turn is also likely to be cycled unnecessarily for only one or two vehicles even though adequate gaps in the opposing traffic stream exist. This report shows that by omitting the left turn phase and forcing left turning vehicles to use a permissive phase, delay to opposing through traffic and possibly the rest of the intersection approaches can be reduced. It was also found that the adaptive left turn feature provided the most benefit to the entire intersection under lower left turn flow rates. Although benefits were noticed for the opposing through volume for all conditions, at higher left turn flow rates, the delay to left turning vehicles sometimes exceeded the benefit to the opposing through vehicles.

For left turning volumes less than 150 vph, the adaptive left turn feature is beneficial in that a left turn phase is only provided when a left turning vehicle waits a designated period of time and a sufficient gap in the opposing traffic stream cannot be found. This saves time during the cycle because a protected phase is not provided to vehicles that find an acceptable gap within a reasonable amount of time.

For left turning flow rates of 150 vph or greater, this study demonstrates that omitting the left turning phase during some cycles will cause a hindrance to left turning vehicles that is greater than the benefit to the opposing through vehicles, thereby degrading the overall operation of the intersection. The literature review revealed that most traffic departments implement a protected phase for left turning volumes somewhere between 90 vph to 120 vph. It was substantiated in this report that a protected phase is needed to service left turning volumes of 150 vph or greater so as not to degrade the intersection operation.

The adaptive left turn feature can be activated and deactivated by time-of-day within the controller. If the feature is providing some benefit during certain times of day but a disadvantage during others, it can be deactivated during that time and the signal will function under normal operation. It is recommended at this time that the adaptive left feature be deactivated during times of day with higher left turn flow rates.

The parameters in the EPAC controller should be set so as not to allow excessive delay and queues on the left turn. The phase 1 omit is lifted when these conditions are present and the intersection will operate with normal protected/permissive left turn phasing as long as the conditions are warranted. The values set in the controller are different for each intersection depending on geometry and drivers at the intersection. Some of the parameters discussed are guidelines suggested by several agencies for left turn delay and volumes required for a protected phase. Adjusting the adaptive left turn parameters in the controller adjusts the delay and queuing experienced by the left turning vehicles. The traffic engineer must decide for each intersection the amount of delay and queuing that is acceptable and adjust the parameters accordingly.

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