Optimization of Left Lane Traffic Signals

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Abstract

The use of detection to activate protected left-turn phasing has developed primarily through empirical trial and error and has been instituted without the supporting scientific theory. This study compares the performance of left-turn phasing to provide quantifiable benefits of one phasing over another. Permitted, protected, and protected/permitted (P/P) phasing are analyzed for a range of left-turn volumes and opposing through traffic in order to develop relational curves. The measure of left, through and overall intersection delay is used to compare the different phasing performances. Specific consideration is given to determining the optimal location of the queue detector for P/P phasing. From the analysis, guidelines are developed for determining the type of left-turn phasing based on left-turn volume, opposing through volume and lane geometry.

The analysis indicates that P/P phasing provides the best method of left-turn phasing signal control. The P/P phasing allows for a wide range of control and is better able to accommodate the changing volumes throughout the day. The optimal queue detector location for P/P varies based on opposing volume and geometry. UDOT typically has placed the queue detector location at the third vehicle. This is based on permitted phasing to accommodate two sneakers per cycle. Therefore the third vehicle location triggers the protected phasing so that all left-turning vehicles can be accommodated. However, this assumes that no gaps exist in the oncoming traffic to provide capacity for left turns and that the opposing traffic is operating near capacity. Based on this assumption, delay comparisons indicate that geometry and queue locations are related. For a single lane geometry, the third vehicle location is appropriate. However, as the geometry is increased to two or three lanes, the opposing through volume increases and the overall intersection delay is reduced when the detector location is moved to the fourth vehicle location.

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INTRODUCTION

According to the 1983 Traffic Control Devices Handbook (TCD), published by the Federal Highway Administration, the number of phases for a traffic signal cycle should be held to a minimum. As the number of phases increases, the green time available for other phases is reduced. This may decrease intersection efficiency because of starting delays, change (yellow) intervals, longer cycles, and adverse impacts on optimal progression. Through and right-turning vehicles are most efficiently accommodated by a two-phase traffic signal. Left-turn phasing facilitates left-turn traffic; however, this is done at the expense of green time available for through traffic. Therefore, phasing is primarily a left- turn issue.

The purpose of a traffic signal is to provide structure to an intersection and provide for a safe and efficient interaction of vehicles. However, the goals of safety and capacity often conflict. This conflict is most evident with Permitted and Protected left-turn phasing. Protected left-turn phasing describes left-turn movements which can only be made on a green arrow with opposing flow stopped. Permitted left-turns are performed through gaps in the opposing traffic. A combination of Permitted and Protected phasing often is used on a single approach. Under this Permitted/Protected (P/P) situation, the Protected phase is activated by the presence of a vehicle or vehicles in the left-turn lane. The Utah practice of queue detection for activating the protected phase is somewhat atypical as many states simply use a stop-line detector to activate protected phasing with the arrival of only one car.

As left-turning volumes and opposing volumes increase, acceptable gaps in the opposing traffic flow are reduced and left-turning vehicles are increasingly delayed. There is a traffic volume level at which the permitted left is no longer able to adequately provide for the left-turning demand. This can be caused by increases in left-turn movements, opposing traffic flow, or accidents, which can be reduced by installing protected phasing. Once one of the conditions is reached, the question of whether to install Protected or P/P phasing occurs. In Utah, safety rather than capacity is the primary concern in determining the use of

Protected or P/P phasing. The Protected phasing provides for the capacity needed to accommodate the left-turning demand, but guarantees delays to left-turns even if acceptable gaps in opposing traffic are available. The P/P provides protection when the queue length of left-turns reaches a certain defined level and allows for permitted left-turns when gaps in opposing flow present themselves. The queue length at which the Protected phasing is initiated has not been standardized.

Protected phasing also is used for single left-turn lanes when the left-turning vehicles must cross three or more opposing lanes with speeds of 45 mph or greater or when sight distance or alignment is inadequate. This also is a safety issue. Currently, the P/P phasing is the “default” left-turn design used in all other cases.

In a cycle, two alternatives are available for the occurrence of protected left-turn phasing. When left-turn phasing precedes the opposing through movement it is referred to as “lead-left.” When the protected phase follows the opposing through movement, it is referred to as “lag-left.” This lead and lag left can be applied to Protected and P/P left-turn phasing.

This research develops left-turn phasing and traffic relationships. It investigates how Permitted, Protected, and P/P left-turn signal phasing compare in terms of delay for various left-turn and opposing flow conditions. Optimal queue detector location for activating the Protected phase of a P/P phasing also is analyzed using left-turn, through and overall intersection delays.

The left turn phasing affects left-turning, through, and overall delay to the intersection, however not in the same way. A left-turn phasing may decrease delays and be optimal for the left-turn movement, but at the same time it may increase overall intersection delay. This research continues by developing general guidelines on how to select the appropriate type of left-turn phasing.

The goal of the research is met by the following objectives, which are discussed as phases throughout the research process:

1. Phase I - Assess the delay due to Permitted, Protected, and P/P left-turn phasing under various opposing flows, left-turn traffic conditions, and road geometrys.
2. Phase II - Identify where queue detectors should be placed to activate protected left phasing for Protected / Permitted left-turn phasing. By assessing left-turn and overall intersection vehicle delay for different opposing flow conditions and left-turn queue lengths, an optimal queue length is determined. This optimal location will vary based on opposing flow and left-turn queued vehicles.
3. Phase III - Develop guidelines to determine the need for separate left-turn phasing regimes based on conflicting traffic volumes (left turn and opposing through).

While left-turn accidents and the left-turn impacts on signal coordination are not addressed by this study, it does address the type of left-turn phasing most efficient under a given flow condition, when queue lengths should be detected, and general guidelines that will guide future decisions on implementing left-turn phasing.

In Salt Lake City, the method of applying prior trial and error experience to current phasing plans has produced a working system of installing left-turn phasing and the queue detector location. However, the science that supports why the developed system works and if it is truly the optimal condition must be addressed.

LITERATURE REVIEW

A review of current literature shows that University of Utah's study, *Selection of Optimal Left Turn Phasing at Traffic Signals*, (hereafter referred to as the U of U study) is needed and unique. The literature collected and reviewed regarding left-turn movements includes existing published guidelines, physical design elements affecting efficiency, accident history considerations, and various delay minimization and optimization methods. A short discussion and description of the Highway Capacity Software (HCS) program and its applicability and use in this project also is provided.

Existing Published Guidelines

In 1981, the Federal Highway Administration (FHWA) published *Guidelines for Signalized Left-Turn Treatments*. Among other purposes, the guidelines were intended to give general guidance on how to select the most appropriate left-turn treatment at a signalized intersection. The guidelines are based on the experience of more than 200 practicing traffic engineers. The recommendations of the FHWA were based on peak hour left-turn demand-to-capacity (v/c) ratios and accident history. The guidelines are as follows:

- For left-turn v/c ratios less than 0.7, protected phasing is probably not needed.
- For left-turn v/c ratios between 0.7 and 0.9, protected phasing possibly may be needed depending on accident history.
- For v/c ratios of 0.9 and above, protected phasing probably is needed.
- If protected phasing is not needed, permissive-only phasing is suggested and permissive/protected phasing is not considered.

The given v/c values are then compared with accident history and are shown graphically on Figure 2.1. The guidelines provide a basic outline on the use of permitted and protected phasing and do not include discussion of the use of protected-permissive left turn phasing.

The guidelines also include a brief discussion of delay considerations associated with left-turn phasing. A "general rule" for defining a cycle failure is set forth as any cycle in which a left-turning vehicle waits longer than one complete cycle to turn. These failures should not be considered "a problem" until the cycle failure rate reaches 10 percent because of the random nature of arrivals. Excessive delay is defined as being "somewhere around 30 to 35 seconds" per left-turning vehicle.

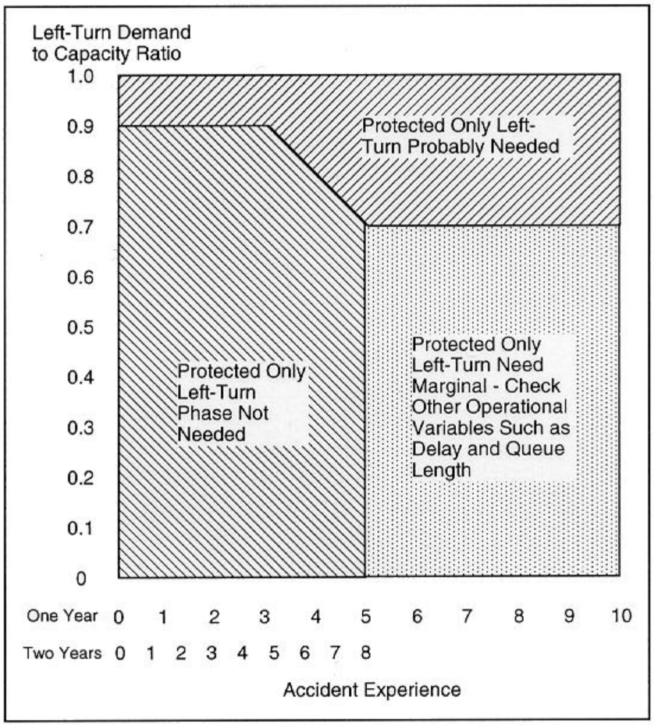

Figure 2.1 Graph of Conditions for Protected Left-Turn Phasing (After FHWA 1981)

Chapter Four, Section C of the 1988 Manual of Uniform Traffic Control Devices (MUTCD) (FHWA 1988) describes 11 conditions that require installing a traffic control signal. The 11 conditions are defined as signal warrants, which range in scope from pedestrian activity, to traffic volume, to vehicle accidents. However, no guidelines are included in the MUTCD on warrants for left-turn phasing.

(FHWA 1983) describes left-turn phasing warrants from a survey of 45 states, each with unique methods of warranting left-turn phasing. Based on the survey responses, the TCD handbook suggests guidelines that form an aggregate of all responses. However, they are intended to be used as a general guide for all 50 states where traffic conditions can vary greatly. The criteria for left-turn phasing suggested by Chapter Four, Page 18 of the TCD based on volume, delay, and accidents are:

Volume

- the product of left turning vehicles and conflicting through vehicles during the peak hour is greater than 100,000
- as above, with the product greater than 50,000
- left-turn volume greater than 100 (or 90) vehicles during the peak hour
- left-turn peak period volumes greater than two vehicles per cycle per approach still waiting at the end of green (for pre-timed signals)
- left-turn volumes greater than 50 vehicles per peak period when through traffic speed exceeds 45 mph

Delay

- delay to left turn vehicles is greater than two cycles
- one left-turning vehicle delayed one cycle or more during one hour

Accidents

- five or more left-turn accidents in a 12-month period
- the TCD also provides general suggestions for when P/P may be used
- Where left-turn phasing has been determined to be warranted on a volume basis, consider the use of P/P left-turn phasing before protected only left-turn phasing is implemented.
- When using leading P/P phasing, consider the use of left-turn queue detection to improve overall intersection operating efficiency.

The criteria offer no coherent structure to guide traffic engineers in the implementation of left-turn phasing strategies. The U of U study investigates the TCD handbook recommendations to define a more focused set of guidelines appropriate for the State of Utah.

The [NCHRP 1996] synthesized available literature on left-turn treatments. The synthesis includes all aspects of the issue including design, signs and markings, signal appearance, phase timings, and performance measures. It provides a complete discussion of the possible signal face combinations associated with the permitted, protected, and permitted/protected phasing arrangements. A discussion of the criteria for a protected left-turn phase correctly observes that, "The requirement for separate left-turn traffic signal phasing at an intersection is based on the left-turning volumes, vehicle delay, visibility, and safety of the intersection." The discussion also states that, "while a separate phase may reduce delay for left-turning traffic, it could result in more overall intersection delay because it takes traffic signal green time away from the heavier intersection movements." It is of consequence to the U of U study that the synthesis does not give any definitive suggestions regarding the phasing choice that would minimize delay. Representative examples of current values used by agencies to justify a protected phase are as follows:

- "The product of left-turning vehicles and conflicting through vehicles during the peak hour is greater than 100,000 (or 50,000).
- "Left-turn volumes greater than 100 (or 90) vehicles during the peak hour.
- "Left turn peak period volumes greater than two vehicles per cycle per approach still waiting at the end of green (for pre-timed signals)."

It is not stated in the article when to use 100,000 or 50,000 (in the first bullet) or whether this simply represents two or four approaches. The synthesis includes suggested guidelines for selecting phasing type are reproduced from (Upchurch 1986) which will be reviewed later in this report.

Geometric Considerations with Left-Turn Treatments

One of the objectives of the U of U study is to suggest guidelines on choosing a type of left-turn phasing — permitted, protected, permitted/protected. Therefore, It is assumed throughout the project that a separate single left-turn lane already exists. The U of U study does not attempt to give guidelines that suggest when to increase the number of left-turn lanes. Literature is available which estimates the capacity of dual or triple left-turn lanes and when to convert a shared left-turn lane to a separate left-turn lane. Although the research contained in the literature is helpful in deciding when to increase the number of left-turn lanes in an intersection, the question could be addressed more specifically with regard to cost, safety, and efficiency in the scope of another study. A brief summary of the available literature regarding the number of left-turn lanes is given here.

A study by Oppenlander and Bianchi, 1990, gives suggested guidelines for the use and installation of an exclusive left-turn lane. The guidelines were developed with a Monte Carlo simulation model and determine the design lengths for left-turn lanes with separate phasing. The guidelines are given in terms of intersection type (signalized and unsignalized, divided and undivided), number of opposing lanes, demand volumes, number of phases, and accident history.

Pethe 1994, employs "existing analytical techniques combined with statistical regression models to predict the capacity of a shared left-turn lane with permissive phasing." Because the HCM tool is iterative in nature, this paper defines a new, non-iterative equation for single and multiple lane models to predict the capacity of a shared left-turn lane. He also showed the effects of increasing opposing volumes and the number of opposing lanes on capacity. While the U of U study does not address shared left-turn lanes, it will be implementing an increasing opposing volume and opposing number of lanes in its investigation.

The overall operating efficiency of dual left-turn lanes is explored by Shaik and Graham, 1996. The analysis consisted of actual data taken from several intersections, which was used as input for a TRAF-NETSIM model to determine and compare several measures of efficiency. The conclusion of the study is that upon the change from a single left-turn lane to a dual left-turn lane, the decrease in overall intersection delay ranged from six to 37 percent with a mean of 23 percent.

The ITE Technical Council 5P-5A gave a preliminary informational report on the capacities of triple left-turn lanes. The report concluded that the saturation flow is estimated to be 1830 pcphgpl (passenger cars per hour green per lane). This is within 5 percent of the value reported by the ITE Technical Council 5P-5 for double left-turn lanes. It also suggests that the results for the triple left-turn lane indicate that the left-turn adjustment factor (f_{LT}) used should be approximately 1.00 (ITE 1995).

Safety Considerations

Accident history is an important factor in the choice of left-turn phasing because each of the phasings in question has a different level of safety associated with it. Protected phasing typically has a lower accident history than permitted/protected phasing. At the same time, protected phasing may not be as efficient as permitted/protected phasing. Many times a trade-off between safety and efficiency exists. As a result, there have been several recent studies that examine the safety of each phasing type. Although the U of U study will describe optimality in terms of efficiency only, safety considerations are incorporated into the proposed guidelines by examining guidelines from other studies and incorporating those that follow closely the requirements from UDOT operations of safety and left-turn phasing.

Upchurch, 1991, compared accident rates for different types of left-turn phasing arrangements. With 523 intersection approache samples he developed the accident statistics. Each of the sample approaches had a dedicated left-turn lane. Results are given according to left-turn volume and opposing volumes. A summary of the results is shown in Table 2.1

Table 2.1 Accident Rates for different Left-Turn Phasing Types (after Upchurch, 1991)

	Leading Protected/	Lagging Protected/	Leading	Lagging

		Permitted	Permitted	Permitted	Protected	Protected
2	M	2.62	2.71	3.02	1.02	2.09
Opposing Lanes	N	162	62	44	57	4
3	M	3.83	4.54	2.65	1.33	0.55
Opposing Lanes	N	25	52	35	80	2

M=Mean Left Turn Accident Rate (accidents per million left turning vehicles).
N=Number of Approaches in the Sample

Shebeeb, 1995, examines trade-offs between safety and efficiency for several left-turn phasing arrangements. The arrangement schemes inspected were permissive only, lead and lag permitted/protected, protected, and Dallas phasing. The delay was measured in terms of left-turn delay only without consideration to through delays. The study concluded a trade-off exists between safety and efficiency. Shebeeb reports that the order from safest to least safe left-turn phasing is lead protected, lag protected, lead protected/permitted, lag protected/permitted, Dallas, and permitted only. This order also is the order of least efficient to most efficient. It was determined that there is no statistically significant difference in the efficiency or safety of lead and lag protected operations. Although the report seems to indicate to the contrary, the left-turn delay for all intersections does not necessarily follow the order described. It is reasonable to imagine that an intersection with a high opposing volume and permitted phasing will have a higher left-turn delay than if the phasing included a protected left-turn.

Delay by Left-Turn Phasing Scheme

A number of studies have examined the manner in which left-turn phasing should be chosen to reduce left-turn and overall delay. The studies range from rigorous mathematical optimization models to collecting and analyzing field data. None of the research to date employs the approach used by the U of U study and as a result, none contain the broad range of results obtained by this study. Each of the works are described below.

Guidelines for selection of left-turn phasing were developed by Asante, 1993 #729. The study is based on field studies of 108 intersections located in several Texas counties. The study encompassed phasing schemes of permitted, permitted/protected, protected, and Dallas phasing. It studied each type of intersection for one, two, and three opposing lanes, each with varying approach speeds, and for one and two left-turn lanes. Each intersection was videotaped for one hour during peak flows. A measurement important to this study is the correlation of measured delays vs. calculated using the 1985 HCM delay model. The results of this portion of the study are included in Table 2.2. They are a basis for the assumption that the HCM model produces valid delay estimates to compare the three left-turn phasing types for modeling purposes. The results of the study are linear relationships between left volume and opposing speed limit that suggest either permitted only phasing or Òsome protectionÓ for one, two, and three opposing lanes. The suggested guidelines presented by this study favor the permitted phasing unless geometry and traffic require more restrictive control.

Table 2.2 Parameter Estimates for the Intercepts and Slopes for the Calculated Versus Observed Left-Turn Delays

Phase Sequence	R^2
Protected	0.59
Protected/Permitted	0.86
Permitted	0.76

(After [Asante, 1993 #729])

Suggested warrants for the installation of protected left-turn phase were developed by Agent and Deen, 1978, according to accident experience, delay, volume, and traffic conflicts. It was recommended that protected left-turn phasing seriously should be considered when certain critical values are met as follows. It is a critical value if:

- for one approach, four left-turn accidents occur in one year or six left-turn accidents occur in two years and for both approaches, six left-turn accidents in one year or 10 in two years are the critical values.
- in the left-turn lane with the highest v/c ratio, a left-turn delay of two vehicle-hours or more occurs during the peak hour. This is subject to a minimum of 50 vehicles turning left during the peak hour. The average delay per left-turning vehicle is a minimum of 35 seconds.
- the product of left-turning and opposing vehicles exceeds 100,000 on a four lane street or 50,000 on a two-lane street with a minimum left-turn volume of at least 50 vehicles during the peak-hour.
- an average of 14 or more total left-turn conflicts or 10 or more basic left-turn conflicts occur in the peak hour. (A basic left-turn conflict is defined as the brake or weave of an opposing through vehicle as the result of a left-turning vehicle turning directly in front of it. Secondary conflicts are defined as the braking of a second vehicle (continuation of the basic conflict) or any vehicle turning left on a red light. Total left-turn conflicts are the sum of the basic and secondary left-turn conflicts.)

A new phasing type is examined by Collins, 1988. This phasing type, known as “Dallas phasing,” is shown in Figure 2.2. The concept of the Dallas arrangement increase permitted green time for left-turning vehicles. During a protected left-through phase for the opposing direction, a permitted green is displayed for the left-turn vehicles as shown in Phase A of Figure 2.2. Transition to Phase B provides a typical phase of through and permitted left phasing for both directions. If warranted, the permitted left turn from Phase A becomes a lag protected left as shown in Phase C. It should be clear that Phase A with the lead protected left is intended for the peak direction of travel. Thus, Phase C is only necessary if the off-peak left turns are not accommodated by the permitted phasing. This arrangement — lead protected being provided for the peak direction — allows for an optimal use of green time for the peak direction left-turn.

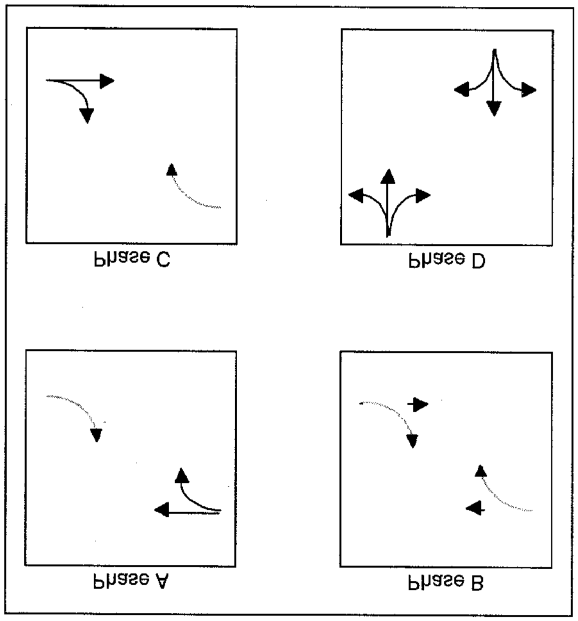

Figure 2.2 Dallas Phasing Diagram (after Collins, 1988)

By providing the permitted phase after the through phase, most of the non-peak flow likely will have cleared the intersection and thus, the permitted left-turn for the peak direction has a high available capacity.

Other articles and investigations of this same arrangement also were performed by (Fambro, Gaston et al. 1991) and (De Camp and Denney Jr. 1992). In this study, computer simulation was employed to obtain and compare the delay associated with Dallas phasing and one other common arrangement that is most similar to Dallas Phasing (shown also in Figure 2.2). Although Dallas phasing is not examined by the U of U study because it is not common in Utah, its feasibility has merit as the subject of another study.

A before and after study of the conversion of a protected to a protected/permitted left-turn phase was performed by Stonex and Upchurch, 1987. It was found that as a result of the conversion, left-turn volume increased in both directions +14.7 percent and the left-turn delay for both directions decreased to 82 percent of the previous value. The overall delay of the combined left-turn and through traffic for both directions increased by 87.9 vehicle hours per day. The net decreases in left-turn delay “were only a fraction of the net increases in through delay." It was also noted that after the conversion, progression on the arterial could no longer be achieved, because of the changes in timing due to longer cycle lengths and inefficient use of through green time. Subsequently, the number of vehicles stopping increased by 65.4 percent. This study demonstrates the need for better procedures and understanding of the delay associated with different phasing types. It should be noted that the intersection spoken of in this study was converted due to engineering judgment and social pressures. The author comments that in this area of Arizona the public has the misinformed perception that permitted/protected or protected only phasing is much more efficient than permitted only phasing.

A sub-committee of the Institute of Transportation Engineers (ITE) in Florida examined the manner in which left-turn phasing should be recommended for various situations (ITE 1982). The committee examined accident statistics at 28 intersections as well as the before-and-after delay statistics from three intersections that were changed from protected only to protected/permissive phasing. Combining the above collected data with the professional opinions of the sub-committee members, the following recommendations were made.

- "Protected/permissive phasing should be provided for all intersection approaches that require a left-turn phase unless there is a compelling reason for using another type of left-turn phasing."
- They note that, "drivers favor this type of phasing because the reduction in delay is very noticeable."
- Protected only phasing should be provided if there dual left-turn lanes exist, geometric warrants (sight distance, non-orthogonality of intersecting streets, roadway curvature, or left turn across three or more opposing lanes), high speed opposing traffic, or high accident history.

The study by the ITE sub-committee demonstrates the need for further studies. The lack of available delay information caused them to resort to public opinion and their own intuition for the final decision. Although this may be a good estimate of the delay situation, it lacks scientific basis.

Rigorous mathematical modeling techniques are employed by Rouphail and Radwan, 1990, in an attempt to optimize signal settings and left-turn treatment simultaneously. The signal settings include the number of phases and signal timing, including protected, protected/permitted, and permitted. The objective function of the model is to minimize the cycle length while setting adequate constraints on the v/c ratios, cycle length, phase split, and other constraints. The model was then tested with the aid of a branch-and-bound solution algorithm (Linear Interactive Discrete Optimizer - LINDO). The solution gives optimum phase lengths and cycle times. It does not directly indicate what type of left-turn phasing to use. It does, however give values that would indicate what the v/c ratios would be with each type of phasing. Then, they could be used to determine delays for each approach. This model does not account for an actuated permitted/protected phase. It could, however be used to give the maximum green time limit on the protected portion of a protected/permitted phase.

Upchurch, 1986, performed a study resulting in suggested guidelines for selecting one of the three common types of left-turn phasing. The guidelines are based on actual data collected from six different intersections in the Phoenix, Ariz., urban area. Two intersections for each type of phasing — protected, protected/permitted, and permitted — were chosen. One of each of the intersections was chosen with two opposing lanes, and the other with three opposing lanes. Several variables were tested to find any "meaningful" relationships. These include: left-turn delay versus opposing volume, left-turn delay versus left-turn volume, through delay versus left-turn volume, and left-turn delay versus volume cross product. The volume cross product is defined as the left-turn volume multiplied by the opposing through volume. The most meaningful relationships found were left-turn delay versus volume cross product, and through delay versus volume cross product.

The study by Upchurch, 1986, hereafter referred to as the Upchurch study, and the U of U study have similar objectives albeit different approaches. The Upchurch study is used as a comparison for the U of U study regarding the similarity in results and recommendations. The differences between the U of U study and the Upchurch study are discussed. The Upchurch study was performed using real data from six intersections in five-minute intervals. While use of actual traffic data is always the ideal way to develop guidelines, certain limitations exist, which often make simulated data more efficient and able to span a wider range of traffic situations. When simulated data is used, existing data also should be checked to validate the guidelines developed. The present study will use simulated data to analyze an increased range of traffic volumes and a larger sample size. Simulated data allows the results of the research provided to give greater insight into the relationships at hand as well as the larger scope of applicability. A disadvantage of using real data is the fact that limited intersections may or may not be representative of a “normal” intersection, causing the sample and the study to be non-representative. The results, therefore, would not be easily applicable to other intersections that have different geometrys.

The use of the volume cross product is a way of considering the left-turn volumes and the opposing volumes; however, the use of the volume cross product assumes that the two variables are equally weighted with respect to delay. It is likely that the different combination of left and through volumes have varying impacts on delay. The use of the volume cross product may, therefore, prohibit the observation of that relationship because it is assumed rather than observed. Among other items, the U of U study will observe the relationship between delay, through volume, and left-turn volume.

The Upchurch study and this research are similar in that they both take into account accident history to aid in the development of guidelines. The Upchurch study states that the references used for this information are “obtained from the review of the warrants, guidelines, and criteria used by others.” The U of U study will develop guidelines based on the operational findings of the study considering the results of the accident study developed by FHWA ,1981, and existing accident criteria used by UDOT.

DATA COLLECTION

Data collection for this study is based on modeling using the Highway Capacity Software (HCS). Due to the many variables influencing the HCS model, field data was collected on the variables and is discussed in detail where applicable in Section 3. These variables are based on video tape data collection of four downtown Salt Lake City intersections during the PM peak period on three weekdays. The intersections of 4th South and State Street, 4th South and Main Street, 3rd South and Main Street, and 3rd South and State Street were monitored during the PM peak, as this represents the most congested period and the time when the optimal signal operation and value of the P/P phasing is most applicable.

Highway Capacity Software

The HCS is the principle tool used for simulating the data. Highway Capacity Software Release 2 was selected because of its industry-wide acceptance and for its ability to simulate multiple delay variables. The values modeled by HCS are referred to as the "known" values throughout the study and are used in developing delay relationships for the three left-turn signal phasing schemes addressed in Phase I.

Data Collection Assumptions

The default values of some of the HCS variables are used where exterior data is unavailable. While this is less than optimal, it will adequately serve the purpose of this project, which is to see how the signal phasings perform relative to one another. Table 3.1 shows the default values used in the modeling process.

Table 3.1 HCS Assumptions and Default Values

HCS Assumption	Default Value
Lane Width	12 feet
Lost Time	3 sec
Adjacent Parking	0 Movements / hour
Right on Red	0 movements / hour
Grade	0%
Percent Heavy Vehicles	2%
Peak Hour Factor	0.95
Pedestrian Button	No
Pedestrians	0 Pedestrians / hour
Bus Stops	0 bus stops / hour

The principle intersection delays are due to the left-turning vehicles and the opposing through vehicles. From the HCS, right turning vehicles have little impact on the left, through, and overall delay and are not considered by this study. A minimal right-turning volume has been assumed at 50 vehicles per hour (vph).

The arrival pattern of vehicles ranges from 1 (poorly coordinated) to 6 (well coordinated) with 3 representing random arrivals. Observations of State Street, Main Street and Fourth South for the priority southbound direction indicate that random arrival (arrival type 3) most represents the observations.

No data was collected on “sneakers;” however, it is an accepted practice of assuming 2 per cycle. If permitted phasing is applied to the HCS and the through volume is raised to eliminate any gaps, the capacity of the left-turn movement reflects an assumed HCS ÒsneakerÓ value of 2.07 vehicles per cycle. No literature is available on why the .07 is applied in the HCS, however it is assumed that this is based on an empirical average.

Intersection Geometry

The geometry of the modeled intersections was standardized for all the runs. Because the delay principally is a function of left volume and through opposing volumes, the intersections considered were symmetric. Each approach had an equal number of through lanes, one exclusive left-turn lane, and an exclusive right-turn bay. Having exclusive left- and right-turn lanes prevents the variable increase in delay resulting from the obstruction of through traffic in a shared lane. Delays were calculated for one, two, and three opposing through traffic lanes.

Range of Data

Data is developed for the three phasing types found in the Salt Lake City area: permitted, protected, and permitted/protected (P/P). The ranges for which the volumes are modeled depends on the intersection geometry. Increments of 100 vph for through volume and increments of 25 vph for left-turning volume are used to calculate the associated delays for intersections with a single opposing through volume. Increments of 200 vph for through volumes and 25 vph for left-turn vehicles are used for 2- and 3-lane opposing through geometry. The difference is due to the increases in capacity that multiple lanes provides. The variance in the choice of increments depended on the number of through lanes and rate of change of the delays. For example, if there appears to be a large change in delay from one interval to the next, a mid-range interval is analyzed to assure a complete range of values for a more representative model.

Cycle Length

Two schemes were used for the cycle lengths. The first set of delays were calculated using a fixed cycle time of 80 seconds, which was observed for several signals in downtown Salt Lake City.

A second analysis assumes that most traffic signals are optimized for the peak volumes they carry. Therefore, delays are calculated based on an optimal cycle length. They are determined using the Webster method. Equation 3.1 used here follows (Stewart and Van Aerde 1990):

$$C_{opt} = \frac{1.5L - 5}{i - Y}$$

(Eq 3.1)

Where L = total lost time (amber + all red)

C_{opt} = optimal cycle length (seconds)

Y = sum of the y values

y_i = volume/capacity (v/c) ratio for lane group i

The maximum value for optimal cycle length was 120 seconds. Conventional limits of maximum optimal cycle length are 120 and 150 seconds (Stewart and Van Aerde 1990). In Salt Lake City, 120 is the more common value.

Phase Split

The timings for the phase splits are calculated using the volume to saturation volume ratios as described in equation 3.2.

$$\phi_i = (C - (L + \tau))\left[\frac{\sum\left(\frac{s_i}{V_i}\right)}{\left(\frac{s_i}{V_i}\right)}\right]$$

(Eq 3.2)

Where ϕ_i = phase split for phase i (seconds)

C = cycle length (seconds)

τ = amber time for each phase (assumed to be three seconds for all phases)

V_i = the flow for lane group i (vph)

S_i = saturation flow value for lane group i (vph)

ℓ = loss time for each phase (assumed to be one second for all phases)

Capacity of the through and left-turn traffic is a function of geometry and signal timing. In the permitted left-turn case, the left-turn lane saturation flow is related to the through traffic flows according to the number of available gaps, which is related to the arrival type.

Data

Using the HCS defaults, observed variables, signal cycle lengths, and phasing splits, the delays for each intersection were calculated for the range of left and opposing through volume until the intersection failed. Failure is defined by HCS as any lane group having a volume to capacity ratio (v/c) of 1.2 or more. This HCS or "known" data is available in Appendix A. It is used throughout the analysis process to develop the delay equation relationships in Phase I and the delay comparsions for different queue detector locations in Phase II.

PHASE 1. ANALYSIS

Introduction

The relationship between flow and delay is not represented by a simple linear equation. Delay is influenced by intersection geometry, traffic flow volumes, arrival rate, signal cycle length, and phasing arrangements. Permitted left turns complicate the analysis and rely on a secondary method of determining capacity and delay. Permitted left turn capacity relies on the opposing flow rate, the arrival pattern, and the proportion of green time available to determine the anticipated gaps available for accepting left turns.

A concern with the cross-product flow method introduced by Upchurch (1986) is that it assumes that any combination under a certain threshold is acceptable. This implies that left and through movements are interchangeable with little impact on capacity. However, this is rarely the case, as evidenced by the delay equations from the Highway Capacity Manual (HCM). Assuming, for a permitted phased intersection, that reducing the through flow by 100 will allow 100 more left movements is not realistic.

Phase I describes how the three left-turn phasing types are compared using the HCM software. The analysis examines which type of phasing provides the minimum delay under different flow regimes of left and opposing through volumes. This indicates optimal phasing based solely on delay for different flow regimes. This section continues with the development of general equations that estimate left, through and overall intersection delay as a function of geometry, phasing type, opposing through volume, and left-turn volume.

The purpose for comparing delays of different left-turn phasing arrangements is to examine which phasing increases signal performance, and the limits of the improvements. While always providing protected phasing may benefit left-turning vehicles, adding phasing increases lost time and reduces through green time, which reduces through capacity. In addition, providing protected left-turn phasing is not always the most efficient method of providing left turn green time. Under protected only phasing the left turns are only possible during the protected green time, reducing left-turn capacity and delay if gaps are available during the through green time.

Throughout the analysis process two different timing schemes are addressed: Fixed and Optimal timing. Fixed timing is based on the current 80 second cycle length, which exists in the downtown Salt Lake City area. The Optimal timing is based on the Webster method and determines the cycle length with a maximum 120 second cycle length. The phase timing is based on a weighted average of the volume.

Highway Capacity Analysis

The Highway Capacity Manual Software (HCS) is a widely-implemented transportation engineering tool, which provides the "known" delays for combinations of left and through volumes for this study. The HCS model allows a full range of flow regimes to be examined as opposed to limiting the study to only flows measured in the field. However, the HCS is a model that requires proper input to produce meaningful results. This input is based on assumptions and observations explained in Data Collection, Section 3. All HCS known flows are calculated based on a single left-turn lane, a random arrival pattern, even directional flows, and phasing splits based on the Webster method.

The HCS flows provided the basis for developing delay estimating equations. These equations allow all three types of left-turn phasing to be compared for left, through and overall intersection delay. This facilitates the evaluation of an intersection's performance under the different left-turn signal phasing. These equations are a function of geometry and left and opposing through volume. Using the "known" HCS results, the minimum delay is found from among the three phasing types.

Simple Comparison of Delays

The initial investigation simply compared the HCS “known” flows for the three phasing types by left, through and overall vehicle delay. Comparing the delays of each phasing type, the phasing that minimizes delay is considered the best choice. However, the phasing that minimizes left-turn delay may increase through and overall delay. Therefore, only one of the delays is used as the evaluation delay. Overall delay is selected as it is common practice to use an intersectionÕs overall performance to evaluate its condition.

Table 4.1 shows the overall intersection delay from the HCS analysis for the permitted, protected, and P/P left-turn phasing. This is for two lanes of opposing through traffic under optimal timing conditions for the range of left and through volumes. The difference between the P/P and protected or permitted phasing shows the benefit of P/P. The negative values indicate that P/P delay has less delay than the other phasings. The differences show that P/P always performs with less delay than protected phasing. This is because the permitted portion of the P/P allows for two sneakers each cycle that are not accommodated by the protected phasing only. For low flows, the permitted phasing is shown to provide a reduced delay over P/P. This is due to the P/P sometimes activating a protected phase when the permitted phase could provide adequate capacity with gaps in the opposing flow.

Table 4.1 provides delay values up to the point that left turn volumes exceed the volume to capacity ratio of 1.2, and HCS no longer provides a delay value. This condition is referred to as intersection failure. The values in Table 4.1 indicate at what flow regime the failure of the intersection occurred under each phasing arrangment. The results show that the P/P phasing allows the intersection to operate under a more congested flow condition than the other two left-turn phasings before failure occurs. Appendix A provides similar comparisons for the different geoemetrys under fixed and optimal timing conditions. Similar trends are observed in these comparisons.

The model results of this investigation showed that under lower flow conditions, permitted phasing provides sufficient gaps to accommodate the left turns. As left and through volumes increase, some protected phasing is required during peak cycles. Further increases to through or left-turn volumes eventually cause protected left-turn phasing to be needed on all cycles. This preliminary investigation supports the concept that P/P phasing allows the flexibility to support a wide range of varying flows, and provides the optimal conditions among the three evaluated phasings.

Modeling

Phase I continues by modeling equations that determine left, through and overall vehicle delay for the intersection based on number of opposing lanes and left and opposing through traffic volumes. The equations are the basis for determining which of the three left turn phasing types provided the minimum delay. The following is an explanation of the theoretical basis on which the model is built, followed by a more detailed explanation of each of the steps and a few exceptions.

Basic Theory

The delay relationship with respect to increasing traffic is best described as a parabola. Figure 4.1 shows the average permitted left-turn delay as left-turn volume increases for a given through volume. The figure shows that as the volumes approach capacity, the delays approach an asymptote.

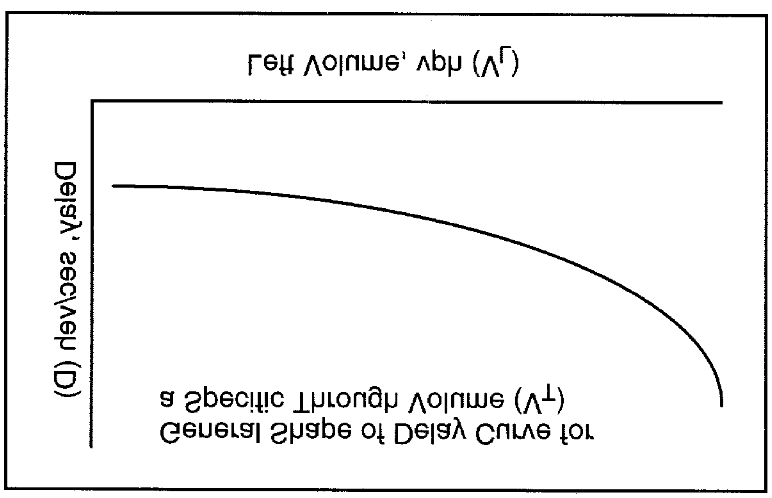

Figure 4.1 General Shape of a Left-Turn Delay Curve for a Specific Through Volume

The mathematical relationship of a parabola is defined as:

$$D = V_L^2 \qquad \textbf{\textit{(Eq 4.1)}}$$

where: D = delay

V_L = left turn volume

Equation 4.1 assumes the curve passes through zero and when $V_L = 0$, $D = 0$. This assumption is invalid for the delay relationships. Figure 4.1 shows that the curve is better represented by a parabola shifted in the positive D direction. This implies an initial delay is associated with only one vehicle attempting a left turn. Translation of the parabola is accomplished by introducing vertical and horizontal shifting variables as shown in equation 4.2.

$$D = (V_L+k)^2 + m \qquad \textbf{\textit{(Eq 4.2)}}$$

where: m = vertical shift in curve

k = horizontal shift in curve

Equation 4.2 represents the delay curve for one particular opposing through volume. For varying through volumes, a set of parabolic curves are formed as shown in Figure 4.2. It is shown that as the through volume is increased, the general slope of the curve is increased and the asymptotic behavior is seen at much lower values of V_L. Similar curves for the protected, permitted and P/P phasing are shown in Appendix B.

If the curves given for the various through volumes could be related to each other, it would be possible to have one general equation for any combination of through and left volume. The most useful set of equations are able to model the delay with left-turning volume and through volume in one equation, such as the following:

$D = f(V_L , V_T)$ ***(Eq 4.3)***

Where: D = delay (seconds/vehicle)

V_L = left-turning volume (veh/hr)

V_T = through volume (veh/hr)

Representing the delay curves with one equation, which is a function of left and through volume, requires manipulation of one of the delay curve equations to estimate the others. This base delay curve equation is referred to as the "goal equation."

K and M Factors

The minimum through volume delay curve represents the goal equation, which is manipulated through the K and M factors to simulate the other delay curves. Therefore, it is necessary to use translation values to shift the equation vertically and horizontally to match the HCS curves. The horizontal translation value K is a function of the through volume. The vertical translation value is M. The translation values are determined by minimizing the delay difference between the delay calculated by the HCS analysis, and the estimated equations for the range of through volumes. Once determined, the M value is kept constant for all through volumes in a specific geometry and phasing arrangement.

One delay curve is chosen as the goal equation to be manipulated to represent the other delay curves. The delay curve for the lowest through volume is most often chosen, with that curve fitted using a fourth order polynomial in most cases. The goal delay is only a function of V_L. The goal delay is then translated using a horizontal value K, which is a function of $V_{T,}$ and a vertical constant M. By doing this, the goal equation is "fit" to the delays found for the other values of V_T. This yields a relationship which for delay is a function of V_L, and the factors $K(V_T)$ and M. In this manner, the delay equation is ultimately a function of V_T and V_L .

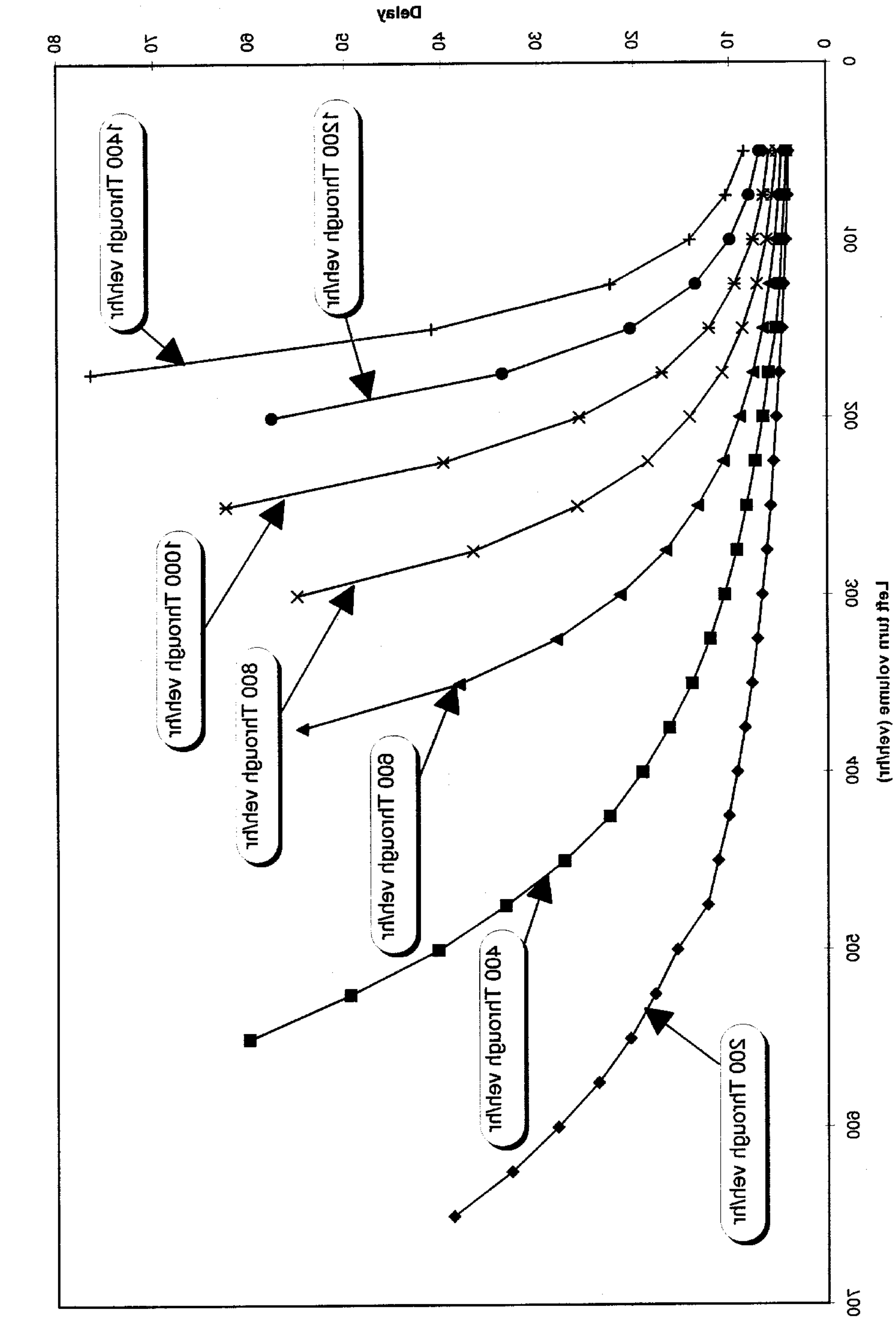

Figure 4.2 Delay Curves Varying by Through Volume.

The translation factors, K and M, are calibrated for the left, through, and overall estimation equations for each of the three left-turn phasing arrangments under each lane geometry. This produces 27 equations (3 lane configurations x 3 different delay measures x 3 signal phasing types). When both the fixed and optimal timing is considered for the cycle lengths, the number of equations doubles to 54.

A second order equation is appropriate when the curve is a perfect parabola. The delay equations only resemble a parabola, and are more accurately shown as a polynomial with the basic parabola concept. The delay equation is thus more accurately represented by Equation 4.4:

$$D = (V_L + k)^n + (V_L + k)^{n-1} + \ldots + (V_L + k)^2 + (V_L + k)^1 + m \qquad \textbf{\textit{(Eq 4.4)}}$$

where: D = delay in seconds

V_L = left turn volume

m = constant vertical shift

k = horizontal shift as a function of opposing through volume V_T

Special Cases

For the 54 delay estimation equations, there are a few delay ranges that are not well modeled using the typical procedures described above. The special cases are described as follows:

1. left-turn delay for fixed cycle length and permitted phasing
2. through delay for fixed cycle length and permitted phasing
3. through delay for optimal timing and permitted phasing
4. left delay for optimal cycle length and permitted/protected phasing

5. through delay for optimal cycle length and permitted/protected phasing (two and three lanes only).

A discussion of each special case follows.

Special Case 1: Permitted Left-Turn Delay

For left-turn delay, the delay equations are valid for through volumes below a certain limit, depending on the number of lanes. The limits are 500 veh/hr, 800 veh/hr, and 900 veh/hr for one, two, and three lanes respectively. For any through volume greater than the limit, only “sneakers” will be able to make left turns, thus the left turn delay will be constant for a given cycle length. Sneakers are addressed in Phase II.

Special Case 2: Permitted Through Delay (Fixed Cycle Length)

In the permitted phasing, the through traffic delay is not affected by left-turning traffic. Thus, the equation used to model delay is a function of through volume only. There is no need to use the procedures described in sections 4.2.1 and 4.2.2.

Special Case 3: Permitted Through Delay (Optimal Cycle Length)

Similar to Special Case 2, the through delay is not directly dependent on the left-turn traffic. It is, however, dependent on the ratio of allotted green time and total volume — both left and through. Therefore, with increasing volumes, the cycle length and the allotted green time increase, thus affecting the through delay to where the maximum cycle length of 120 seconds is reached. After that point, through delay increase is a function of through volume increase. This divides the delay into two general ranges, which are separated by combinations of through and left volumes that warrant a cycle length of 120 seconds. The area of the ranges is shown for the general case in Figure 4.3.

The cycle length is dependent on the total volume of the intersection. This is a combination of the left and through volumes. The ranges were defined as linear functions of left volume and through volume. “Range A” is defined as the region where the combined volumes are such that the maximum cycle length is

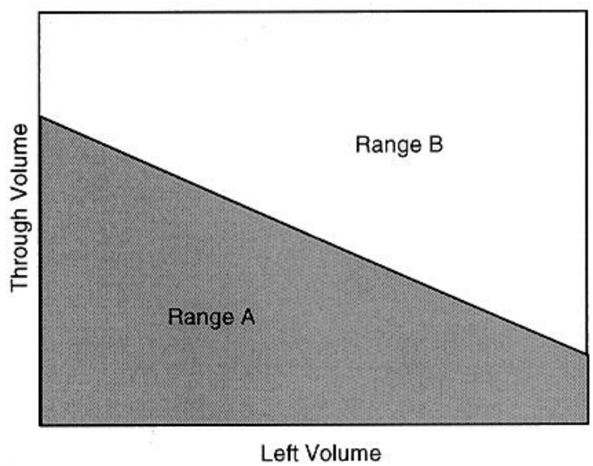

Figure 4.3 General Case of Two Ranges for Delays

not needed, or cycle lengths are less than 120 seconds. Any combinations that require maximum cycle lengths of 120 seconds fall in “Range B”. This approach shall be known as the “Two Range Approach.”

Special Case 4: Protected/Permitted Left Delay (Optimal Timing)

The Permitted/Protected phase did not model well under the three-lane, optimal cycle lengths arrangement when a fixed value for M is applied. Dynamically varying M based on through volume provides an improved equation delay estimation. While it is unclear precisely why the dynamic variation of M for only the P/P, three-lane case improves the estimation, it is likely related to the permitted delay portion of the three-lane geometry. Permitted left turns are more difficult to model for increasing through lanes as the left turn capacity relies on the arrival pattern of opposing through flows and the gaps produced.

In addition, following a protected phase the arrival of left turning vehicles for the permitted phase influences the modeling of the estimated delay.

Special Case 5: Protected/Permitted Through Delay (Optimal Timing)

The permitted/protected phasing with optimal cycle length required the use of the Two Range Approach for two and three lanes. In the two-lane case the goal delay equation was based on the HCS data for 1,000 through vehicles per hour. Using this as the goal equation, Range A is defined as through volumes of less than 1,000 veh/hr, and Range B is defined as through volumes of greater than 1,000 veh/hr. There is one equation for the K value of both ranges, but to make the model more accurate there is a different M value for each range. This goal equation was selected because it is more accurately estimates the higher values of V_T.

The "Two Range Approach" also is used in the three-lane case. The ranges are defined as in Special Case 3 and Figure 4.3. In this case, however, the delay does not become constant after the maximum cycle length has been reached. Rather, the slope of the delay curve has a sudden decrease at the point of maximum cycle length, after which the delay continues to go up as in the fixed cycle length case. The K equation and M value for Range A is based on the goal equation for the 200 through veh/hr curve, and the K equation and M value for Range B is based on the 1,400 through veh/hr curve. The one- and two-lane did not have as drastic a change as the three-lane, thus they did not warrant the same treatment.

Phase 1 Results

Table 4.2 shows the delay estimation equations for the fixed timing evaluation. The optimal timing delay equations are shown in Table 4.3. These tables are available on the following pages. The delay equations are developed for each left-turn phasing type, opposing lane geometry of one, two and three lanes, and the delay parameter (left vehicle, through vehicle, and overall intersection).

The equation performance is tested by comparing the HCS delay and equation estimated delay. The coefficient of determination R^2 is the primary measure of the equation's ability to estimate delay. Table 4.4 shows the R^2 value for the equations. All the delay equations produce R^2 within 90 percent correlation. Most of the equations produce delay estimates within 10 percent of the HCS analysis. The delay equation results for the various left and through combinations under the different geometries and left-turn phasings is available in Appendix C.

Table 4.4 HCS and Equation Comparison (R^2)

R^2 Comparison for Fixed Timing					R^2 Comparison for Optimal Timing				
	Delay	**1ln (%)**	**2ln (%)**	**3ln (%)**		**Delay**	**1ln (%)**	**2ln (%)**	**3ln (%)**
Protecte$	Left	97.75	95.24	97.49	Protected	Left	99.30	94.91	94.91
	Thru	95.01	93.39	92.19		Thru	98.48	94.20	94.19
	Overall	97.79	98.01	96.10		Overall	99.19	98.17	98.17
Permitted	Left	91.15	91.98	93.16	Permitted	Left	94.04	93.46	93.93
	Thru	99.84	99.35	99.27		Thru	99.79	98.68	98.85
	Overall	97.38	97.72	98.28		Overall	99.05	99.09	99.29
Protected	Left	99.35	99.66	99.55	Protected	Left	95.71	90.06	93.54
	Thru	96.08	96.47	93.06		Thru	98.48	98.11	97.21
	Overall	99.36	98.09	96.71		Overall	98.72	99.09	98.63

Phase 1 Discussion

The delay equations are provided in the accompanying spreadsheet. User inputs of through and left volumes apply the equations, and provide a delay value for each of the left-turn phasing and intersection arrangements. The model assumes optimal timing will be used in assessing the left-turn phasing types.

Phase I shows that the prior general relationships developed between flow and left-turn phasing are crude, and that the factors described cause special cases to arise. This makes accurate estimation of delays, and left-turn phasing, much more involved than previously anticipated. The next step in the model development is to incorporate less than optimal signal timing and different counter flows into the equations. This requires a more in-depth investigation.

The results of Phase I support the concept that protected/permitted phasing offers the most flexible left-turn phasing, and can operate throughout the range of permitted only, to P/P, to always protected. The Simple Comparison section 4.3 shows that not only does P/P provide a reduced delay benefit at higher flow regimes, but the flow combination of left and opposing through, which causes the intersection to reach failure is increased. Additional combined left-turn and through volumes can be accommodated under the same phasing because more efficient use of the green time occurs.

Phase II addresses a more detailed investigation into the workings of the protected/permitted phasing, and discusses where the optimal queue detection should be located to trigger the protected phasing.

PHASE II

Introduction

A queue detector provides left turn protected/permitted phasing with a measure for determining the need for left-turn protection. Phase II investigates permitted/protected left-turn phasing and the optimal location of the left-turn queue detector, which is located back from the stop line and informs the controller of vehicle presence. Upon detecting queued vehicles, the controller provides a protected left-turn phase. While the concept already is an applied reality, the optimal location of the detector and impacts of using various queue detector locations still is under discussion.

UDOT typically places the queue detector to detect the presence of the third vehicle in the queue. This has been based on historic trial and error, with the third vehicle location logic from the assumption that with permitted phasing, two left turning vehicles pass through the intersection once opposing through traffic has been stopped by the end of the through phase. The vehicles are referred to as “sneakers.” It is an accepted practice in the engineering field to assume that the sneakers exist during permitted phases and is why all red time often is provided in signal timing to allow the intersection to clear.

Locating the queue detector at the third vehicle infers that if only two vehicles are present, they both can be accommodated by left-turn sneaker capacity. If a third vehicle is present, that vehicle may not make it through the intersection and therefore requires a protected phase. This assumption by UDOT to place the detector at the third vehicle infers a worst case traffic situation in that no gaps exist in opposing through traffic to accommodate additional left-turn capacity during the permitted green phasing, implying the opposing through volume is operating at or near capacity.

Theory

While introducing a protected left phase benefits left-turn vehicles, it causes additional delay of opposing through traffic. Introducing a protected phase requires that green time from the through movement be taken and increases in lost time occur. This means that green time is being taken from the opposing through movement, which is operating at or near capacity, increasing the congestion level of the opposing through vehicles.

For a permitted left turn to be accepted across opposing through traffic, adequate gap size must be provided. Acceptable gap size is a behavioral issue, which is related to opposing traffic speed, with typical gap acceptance ranging from 3.5 to 6.5 seconds. This need for gaps to provide permitted capacity is why the arrival type is important. The arrival type is a measure of the platooning of the vehicles. In well-coordinated corridors, the platoon is tightly packed such that vehicles arrive with relatively small gaps and in a short time span. Therefore the permitted left-turn capacity is a function of the acceptable gap, the arrival pattern, and the amount of green time.

With tight platooning, the vehicles have small spaces between them which does not allow for permitted left-turn capacity. However, tightly packed platoons mean more vehicles can be accommodated with less green time, and spare green time at the end of the phase provides left turn capacity. Therefore the platooning of vehicles eliminates the permitted left-turn capacity within the opposing through traffic, and relies on the green time after the platoon has passed through the intersection to provide permitted left turns. As the arrival type moves toward random arrivals, the spacing of the vehicles is more spread and the platoon is not as tightly packed. This reduces the probability of having unopposed green time at the end of the phase for left turns, but it also implies that arriving through vehicles will be spaced further apart, creating the potential for left-turn gaps in the opposing flow.

Consider the following example, which shows the arrival pattern’s influence on permitted left-turn capacity. The example assumes a single lane of opposing through with a 60-second phase length. Under a permitted phasing, the opposing through movement effects the left turn capacity. By holding all variables constant and only allowing the arrival type to vary from 1 (poorly coordinated) through 6 (well coordinated) as defined by the HCM and the opposing through volume, the impacts of through volume and arrival type on permitted left-turn capacity is shown in Table 5.1.

Table 5.1 Effects of Arrival Type and Through Volume on Permitted Left Turn Capacity

Arrival Type*	Left Turn Capacity	Left Turn Capacity	Left Turn Capacity	Left Turn Capacity	Left Turn Capacity	Left Turn Capacity
Through Volume	200	300	400	500	600**	700**
1	423	287	189	108	62	62
2	440	305	205	120	62	62
3	458	325	224	134	72	62
4	478	349	247	154	86	62
5	500	376	278	181	108	62
6	506	398	314	221	146	84

*Arrival Type as defined by the HCM
** Under the 600 and 700 through volumes, no gaps are available under the less coordinated arrival patterns and the 62 left-turn capacity indicates the capacity only when sneakers are accommodated.

Table 5.1 shows that improving the arrival type to promote coordination leads to higher left-turn capacity. Further, the arrival type becomes much more important in terms of increasing the percentage of left turn capacity for higher through volumes..

Analysis

While traffic volumes will vary throughout the day, the analysis of determining the optimal queue location is a function of the amount of gaps in the opposing through traffic. The gaps provided for left-turn capacity are governed by the arrival type, which is a measure of the platooning and coordination of traffic signals. In developing a general recommendation, it is not possible to estimate the flow condition and arrival pattern throughout the day; this must be analyzed on an intersection by intersection basis. For this analysis, the worst case condition of the opposing through volume not providing any additional gaps is assumed. This is the same assumption used in UDOT logic and assumes only sneakers are accommodated each cycle. Therefore, the analysis addresses whether UDOT's detector location at the third vehicle is appropriate and optimal.

Some basic assumptions are inferred in determining optimal queue detector location.

- No gaps exist in the opposing flow, therefore only sneakers are accommodated by permitted phasing. This is the same assumption UDOT uses.
- The arrival of the opposing and left-turning vehicles is random.
- Opposing through volume operates at a v/c less than, but approaching 1.0.
- No left turn vehicle should wait more than two cycles, regardless of impact to through traffic.

Vehicle presence over a detector creates a new left protected phase, reducing the through green time and thus capacity, and increases delay to the opposing through traffic. The optimal queue detector location requires balancing the benefits of protected phasing for left-turn delay against the increased through delay an additional phase adds. From arrival pattern, cycle length, and queue detector location, delay estimates for the opposing through and left turns are found.

Assuming a 120 second permitted phasing cycle length and an even phase split between directions, Table 5.2 shows the capacity of the through movement by the number of lanes. A 120 second cycle length produces 30 cycles an hour, which represents a worst case situation as it minimizes the amount of left turn capacity provided for sneakers. Assuming the random arrival, which has been observed at downtown Salt Lake City intersections, half of the through vehicles arrive during the green time and half during the red. Those arriving during the red time are referred to as "waiting vehicles."

Table 5.2 Waiting Through Vehicles per Cycle

Lanes	Capacity (V/C = 1.0) (Veh/hr)	Through Vehicles per cycle	Waiting Vehicles per Cycle
1	885	30	15
2	1769	59	30
3	2654	89	45

Multiplying the number of waiting through vehicles and the average delay provides the through delay. To justify providing a protected left phase based on delay, the left-turn delay should exceed the through delay.

Increases in average through vehicle delay occur when the green phase is reduced and a protected phase is provided. If we continue to assume a 120 second cycle length with an even direction split in phasing, then each direction of the two phase signal receives 55 seconds of green and five seconds of yellow and all red. If a protected left-turn phase of only 5.5 seconds were introduced, the capacity of the through movement is reduced by approximately 10 percent. Because this reduces the green time in the cycle, the random arrival pattern will produce a 10 percent increase in waiting vehicles. Now this assumes a constant queue dissipation rate, which simplfies the problem and may be better modeled if field observations are available.

For this analysis, we have assumed that the performance of the through movement is always accommodated by the green timing. This implies that the through volume may operate close to capacity but does not exceed it. It ensures that the reduction in green time for a protected left-turn phase does not force a failure of the intersection and an increasing queue length that is unable to be cleared. This implies that this analysis is primarily concerned with a downtown urban or other area where signal spacing is fairly close and uniform.

Results and Discussion

Using the UDOT assumption that there are two sneakers per cycle, a comparison of the delays to the through volume and left-turn volume identify the queue location which minimizes average intersection delay. Queue locations of three, four, and five vehicles from the stop bar are assessed for the one-, two-, and three-lane geometrys. Because the third vehicle detection currently is applied, this represents the baseline from which to compare the fourth and fifth vehicle location detection. Table 5.3 shows the difference between through and left-turn average delay for the detector location of third, fourth or fifth vehicle.

Table 5.3 Detector Location Delay Comparison

Lanes	Capacity (Veh/hr)	Delay to Through if Protected Phase	3 Left	4 Left	5 Left
1	885	82.5 sec	0	+120	+240
2	1769	165.0 sec	0	+120	+240
3	2654	247.5 sec	0	+120	+240

This assumes a 120 second cycle and 60 second phase length for permitted.
This assumes that a protected phase only takes five seconds from the through green time.

Table 5.3 indicates that for a single opposing lane, delay to the left-turn vehicle is greater than delay increased to the through delay, therefore, the queue detector should be located at vehicle location three. This means with a queue detector location at the third vehicle, all vehicles should clear the intersection each cycle.

Under two-lane geometry, the delay is minimized when the detector location is placed at vehicle four. This means that if no gaps exist in oncoming through traffic, one left-turn vehicle may not clear during the cycle. By definition this means that the left turn will fail, but in terms of overall delay, the benefits to the through volume traffic are greater than the delay increase for the one stranded left turn vehicle.

For three-lane opposing geometry, a queue detector located at the fifth vehicle location provides a small advantage over the fourth vehicle location; however, this implies that during peak times, two vehicles may be stranded each cycle. While the delay is reduced by the fifth vehicle location, it is recommended that the fourth location be used based on the geometry constraints on queue stacking distance which often occurs in left turn lanes.

While a 120 second cycle with 60 second phase splits for the permitted phasing is used to demonstrate the vehicle queue detector location, which reduces intersection delays, increasing left-turn time and decreasing opposing through green time will indicate the same queue location still applies, as the analysis has been based on a per cycle basis. However, it is important that the through traffic be below saturation volumes. Providing left-turn phasing green time, which causes through volume to fail, and thus continue to build a through queue at the intersection, is not recommended and will cause a much larger impact to network wide performance than the failure of the left-turn movement.

The results indicate that if it is assumed that no gaps exist in the opposing through traffic, delay to left-turn vehicles under the permitted phasing must exceed the increased delay to through vehicles if protected phasing is added. This is based entirely on the delay aspect of signal operations. In reality, only the peak hours typically have consistent volumes that eliminate any left-turn gaps in opposing through traffic. Therefore, the queue location is primarily based on the peak hour traffic volume. The location of the queue is likely less than optimal during the remainder of the day, when opposing through traffic gaps are available.

However, issues other than delay must be considered when determining a queue location and protected phasing activation policy. Increasing delay to permitted left-turn vehicles may have negative effects on behavior. For example, increasing delays may encourage left-turn drivers to accept smaller gaps than would normally be accepted and lead to increased incidents. Another potential is for the number of sneakers to increase from two to three, which seems to be a growing trend throughout the Salt Lake Valley. Current practice is to design all red time into signal timing to allow the sneakers to clear. Increasing sneakers will require more all red clearance time, which increases the lost time and reduces the effective green time and capacity of the intersection.

Expert System

For true optimization of left-turn queue detector location, an expert system should be developed that measures the demand of left turns in the queue and the approaching opposing through volumes. A real-time analysis would then determine if adequate gaps are likely to be available to clear the left queue. If not, a protected left phase would be initiated. An alternative is to detect the left-turn queue. If the queue is not cleared by available gaps, then lagging left-turn phasing could be triggered. This lagging left alternative has more potential during off-peak times when coordination and the green time assigned to the through traffic are not such critical factors. Technology does exist to implement either system, but detection of left-turn queue and measurement of opposing through gaps requires implementing more advanced detection technologies than currently exist, as well as the development of the controlling algorithms.

PHASE III. GENERAL GUIDELINES FOR LEFT TURN PHASING

From the results of Phase I and Phase II, general guidelines are developed to help in planning and implementing left-turn phasing. Combining the delay analysis with other research regarding safety factors, such as opposing lane geometry and roadway speed, Figure 6.1 provides a general method of determining the left-turn phasing type based on the left-turn volume and opposing through volume. If protected/permitted phasing is the optimal choice then the queue detector location for activation of the protected phase is identified. A spreadsheet accompanies the paper, which incorporates the developed delay equations, and allows the user to compare the three phasing types against each other under the anticipated traffic levels. The influence of accidents on left-turn phasing has been included in the guidelines; however, they are from other existing studies and are referenced where appropriate.

CONCLUSIONS

Phase I indicates that protected/permitted phasing always should be installed unless safety concerns warrant a protected only phasing. When left-turn demand is low, the P/P signal operates as a two-phase intersection. With high left-turn volumes on a consistent cycle basis, the signal operates with protected left-turn phasing. Under varying or medium flow left-turn volumes, the protected/permitted phasing provides a decision process for determining the need for protected phasing on a cycle by cycle basis. How this decision process is implemented raises questions and has been discussed in Phase II of this study. The benefits of the different left-turn phasing types and quantifying the benefits was the focus of Phase I with specific comparisons between the left, through, and overall intersection delay. Equations are developed to estimate the delays under different flow levels of opposing and left-turn traffic. Phase III then summarizes and interprets the results of Phase I and Phase II into general recommended guidelines for implementing left-turn phasing alternatives.

The recommendations of the study support:

- Protected/permitted phasing should be installed at all intersection unless
    - Left turn demand averages two or less vehicles per cycle
    - Safety requirements warrant a Protected phase including:
        1. Geometric site distance restrictions: less than 250 feet for speeds 35 mph or less, and less than 400 feet for speeds 40 mph and greater.
        2. Opposing speed greater than 45 mph.
        3. Opposing number of lanes greater than three.
        4. Historical Accident of five per year or eight in two years, which could have been prevented by a protected left-turn phase.
- Once protected/permitted phasing is implemented, the optimal queue location will vary based on the opposing through volume demand and number of lanes.

- With one opposing lane, the third vehicle is the optimal queue detector location.
- With two opposing lanes, the fourth vehicle is the optimal queue detector location.
- With three opposing lanes, the fifth vehicle is the optimal queue detector location; however, the small benefit of the fourth location and engineering judgment has recommended the fourth queue location be used.
- A flowchart of left-turn phasing use based on accident, lane geometry, sight distance and demand is provided to guide traffic engineers.

FUTURE RESEARCH

Many assumptions have been used throughout the analysis and to develop the guidelines. The assumptions, and the developed equations should be tested through field observations to validate the theories presented. They include:

1. Test the location of the detector. Typically a 20- to 25-foot vehicle length is used for analysis purposes. However, vehicles have changed size over the years and if the queue detector is being placed based on the location of the third or fourth vehicles, then it is important that the location be accurately known.
2. Field data to validate theoretical evaluation. Evaluation of the theories and results using modeling techniques, such as those implemented by this study, must always be validated through field studies. This includes measurement of delays, the saturation point at which through vehicles eliminate left-turn gaps, and the range of gap acceptance for left-turn vehicles.
3. Incorporate signal timing impacts. For this preliminary study, optimal timing based on Webster's method and a fixed cycle length of 80 seconds — currently being used in downtown Salt Lake City — are examined. Further, it is assumed for developing the relationships that each approach accommodates the same volumes. This is not often the case, and two- and four-phase cycles that are modeled become six- and eight-phase in real-world applications. While it is anticipated that the results and relationships will remain the same as modeled, only field data will allow a more detailed evaluation of the changes that cycle and direction traffic variations have on the left-turn phasing schemes.
4. Dynamic queue activation for P/P. The Expert Systems section discussed how a dynamic system could be developed to determine if protected phasing is needed, based on the combined measurement of left-turn demand and opposing through volume. An algorithm would determine if

sufficient gaps were available to accommodate the left-turn demand. This could be a valuable tool, particularly for real-time, on-line systems which currently have difficulties in determining left-turn demand.

5. Examine sneaker trends throughout the day. While the typically assumed sneaker value of two is used, there may exist trends indicating increased sneaker use and number during different times throughout the day. An evaluation of the average number of sneakers by time of day can lead to understanding driver behavior and the potential impacts on sneakers if queue detector location is moved from the third to fourth vehicle.

6. Compare intersection performance while implementing the new left-turn phasing types throughout the city. Some UDOT and Salt Lake City intersection have the queue detector located at different locations. A comprehensive study could determine if the detector location has an impact on accidents, and field analysis could compare delays between the various queue detector locations.

During this research the CORSIM model has been unavailable. Some of the above validation for the conclusions reached by this report should first be tested on the CORSIM model, which will likely be less expensive than comparing it to large amounts of collected field data.

REFERENCES

Agent, K. R. and R. C. Deen (1978). Warrants for Left Turn Signal Phasing. Lexington, KY, Division of Research, Bureau of Highways, Kentucky Department of Transportation Research.

Collins, R. (1988). A Comparative Analysis of Left Turn Delay Associated with Two Different Lead/Lag Phasing Arrangements. Austin, University of Texas at Austin.

De Camp, G. and R. W. Denney Jr. (1992). "Improved Protected-Permitted left-Turn Signal Displays -- The Texas Approach." ITE Journal(October 1992): 21-24.

Fambro, D. B., D. G. Gaston, et al. (1991). Comparison of Two Protected/Permitted Lead/Lag Left Turn Phasing Arrangements. College Station, Texas Transportation Institute.

FHWA (1981). Guidelines for Signalized Left-Turn Treatment, Implementation Package. Washington D.C., Federal Highway Administration.

FHWA (1983). Traffic Control Devices Handbook (TCD, 1983).

FHWA (1988). Manual on Uniform Traffic Control Devices (MUTCD, 1988). Washington, D.C., Federal Highways Administration.

ITE (1982). "Left Turn Phase Design in Florida." ITE Journal(September, 1982): 28-35.

ITE, T. C. C. P.-s. (1995). "In Informational Report: Capacities of Triple Left-Turn Lanes." ITE Journal(May 1995): 37.

Oppenlander, J. C. and J. C. Bianchi (1990). Guidelines for Left-Turn Lanes. Institute of Transportation Engineers 60th Annual Meeting, Orlando, Florida, Institute of Transportation Engineers.

Pethe, M. (1994). "A Model to Predict the Capacity of Shared-Permissive Left-Turn Lanes for Signal Timing Design." ITE Journal **64**(2): 22.

Rouphail, N. M. and A. E. Radwan (1990). "Simultaneous Optimization of Signal Settings and Left-Turn Treatments." Transportation Research Record **1287**: 1-10.

Shaik, R. A. and J. R. Graham (1996). "Efficiency of Dual Left-Turn Lane Intersections In Charlotte: A Study Using TRAF-NETSIM." ITE Journal **66**(4): 26.

Shebeeb, O. (1995). "Safety and Efficiency for Exclusive Left-Turn Lanes at Signalized Intersections." ITE Journal **65**(7): 52.

Stewart, J. A. and M. Van Aerde (1990). New Methodologies for Determining Optimum Phase Split and Cycle Length for Signalized Intersections. Compendium of Technical Papers - 60th Annual Meeting of Institute of Transportation Engineers, Orlando, Florida, Institute of Transportation Engineers.

Stonex, A. and J. Upchurch (1987). Conversion from Permissive to Exclusive/Permissive Left Turn Phasing: A Before and After Evaluation. Washington, D.C., National Research Council.

Upchurch, J. E. (1986). Guidelines for Selecting Type of Left-Turn Phasing. Washington, D.C., National Research Council.

Upchurch, J. E. (1991). "Comparison of Left-Turn Accident Rates for Different Types of Left-Turn Phasing." Transportation Research Record No. 1324: 33-40.