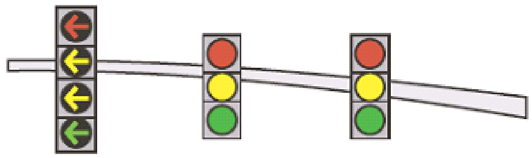
Dynamic Flashing Yellow Arrow (FYA)
A Study on Variable Left Turn Mode Operational and Safety Impacts



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CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	Mega grams (or "metric ton")	Mg (or "t")

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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16. Abstract

Accommodating left turns at signalized intersections has been a challenge for traffic engineers as they seek balance between two conflicting goals; capacity and safety. The use of a four-section head for the left-turn lane only with a flashing yellow arrow indication for permissive left turns has been deemed to be the new standard for signalization. With the advent of this new signal configuration, there was the opportunity to take the protected-permitted left-turn mode to a new level of operation. Although numerous studies have developed warrants and guidelines for selecting left-turn control types, to date there are no clear or uniform standards for the implementation of a variable left-turn mode, changing by time-of-day. Hence, there is a need to develop an interactive and efficient framework to serve as a decision support system (DSS) for the evaluation of left-turn phasing alternative based on intersection conditions. This framework will allow (1) an interactive evaluation of left-turn phasing and ultimately recommend phasing mode by time-of-day and (2) Traffic Management Center (TMC) data to be fed into the DSS so that intersections requiring attention/modification of left-turn mode can be flagged. The current study develops an interactive DSS for assessing the likely benefits of warranting a permitted left-turn phase using custom design approach. The developed DSS is designed to predict these benefits based on multilevel factorial parameters that are practical and applicable to assist TMCs in evaluating the efficiency of a permitted left-turn phase by time of day.

17. Key Word	18. Distribution Statement
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EXECUTIVE SUMMARY

Accommodating and addressing left-turning traffic has been a challenge for traffic engineers as they seek balance between intersection capacity and safety; these are two conflicting goals in the operation of a signalized intersection that are mitigated through signal phasing techniques. Exclusive left-turn lanes and protected left-turn phases are commonly used to minimize the impact of left-turning traffic. Cycle lengths typically have to increase, and the addition of extra time from through phases must be sacrificed. This may contribute to an increase in delay or decrease in operational performance at these intersections. Hence, to increase the left-turn capacity and reduce the delay at the intersections, researchers and traffic engineers found protected/permitted left turn (PPLT) control to be the most effective, thus far.

The traditional PPLT signal head has been a five-section configuration with a circular green (CG) indication for permissive left turns as well as the through traffic. However, the use of a four-section head for the left-turn-only lane with a flashing yellow arrow (FYA) indication for permissive left turns has been deemed to be the new standard for signalization as recommended in the 2009 Manual on Uniform Traffic Control Devices (MUTCD). FYA treatments at intersections are considered new and evolving fast especially in the Central Florida area. With the advent of this new signal configuration, there was the opportunity to take the protected-permitted left-turn mode to a new level of operation. The new all-arrow configuration provides the opportunity to change the operation mode throughout the day from fully protected to completely permissive or combinations of the protected-permitted signal phasing as well.

To date, there are no clear or uniform standards for the selection of left-turn phasing mode or sequence in Florida. Furthermore, there are no clear warrants for the implementation of a variable mode, changing by time of day, for left-turn phasing, and there is no systematic approach that allows for scanning intersections and flagging ones that require attention to left-turn phasing mode. Hence, there is a need to develop an interactive and efficient framework to serve as a decision support system (DSS) for the evaluation of left-turn phasing alternative based on intersection conditions. This framework will allow (1) an interactive evaluation of left-turn phasing and ultimately recommend phasing mode by time-of-day (2) Traffic Management Center (TMC) data to be fed into the decision support system so that intersections requiring attention/modification of left-turn mode can be flagged.

As mentioned above, the objectives of this research are two-fold. First an interactive evaluation framework will be developed and tested; second, based on this framework a simplified and systematic decision support system will be designed to flag intersections requiring attention. The guidelines would provide traffic engineers with the tools to utilize the efficiency of a permitted left turn at peak and off-peak times and reduce the delay at approaches when there are low volumes on the roadways.

From the literature, the majority of the developed warrants and guidelines was based on either operational efficiency or safety aspects. In studies that accounted for both operational efficiency and safety, similar methodology was implemented either in terms of benefit/cost analysis or before/after study. Although the developed guidelines are applicable, they are not considered practical to be implemented in the field. Prior information is needed for before and after study conditions. For left-turn volume warrants, almost all studies were consistent in applying the cross product methodology of left-turn and opposing through volumes as the main warrant. A cross product is generally accepted as one of the signal warrants but cannot be applied to all intersections as the main warrant. Furthermore, a more comprehensive approach is necessary to continue the advancement of understanding how other parameters affect and interact with each other to provide a more balanced and efficient operation while maintaining safety. Combining the two aspects is rarely achieved.

A list of candidate parameters was developed to determine the operational and safety impact measures of effectiveness (MOEs) for left turns. These parameters represented the basis of the interactive framework to evaluate the suitable left-turn mode under different time-of-day volume levels. The process for obtaining the left-turn parameters required several different methods of collection. There were several factors that required no field work and others that were obtained through databases or live data capture in the field. The research requirements demanded intersections having either a five-section signal head where the protected-permitted phase was used or a flashing yellow arrow signal already installed and operational. Because of the wide spectrum of intersection types available in Central Florida, the goal for these intersections was to be scattered around the area to obtain a fair sampling of sites. Thirteen intersections were selected for data collection, ranging from small minor roads and ramp terminals to major arterials.

The data extraction process began with identifying the left-turn approach that would be analyzed. The left-turn parameters related to the volume during the permitted green time and the extents of these periods were extracted in the laboratory by watching the videos second-by-second. Subject left turns were also timed from start to finish on the selected approaches by hand along with the calculation of the critical gap. Conversely, total turning movement counts and gap analysis were processed at the intersections using automated video detections. Across all of the intersections, 23 left turn approaches were analyzed totaling 229 hours of video data processed including off-peak and peak conditions. Video data extraction was an essential process in constructing and analyzing the design of the experiment and eventually developing the new thresholds for the determination of left-turn modes by time of day.

Standard experimental designs either using full factorial or fractional factorial did not fit the research requirements, and therefore optimal custom designs were selected as the recommended design approach. Also, choosing an optimality criterion to select the design points to be run was another requirement. JMP statistical software was used to generate the custom design for this experiment. The custom design approach in JMP (statistical software created by SAS) generates designs using a mathematical optimality criterion. Optimal designs are computer-generated designs that aim at solving a specific research problem to optimize the respective criterion.

Preliminary DOE analysis was conducted for 139 hours of processed data using JMP's forward stepwise regression approach with all main effects and interactions as candidate effects. Stepwise regression is a very basic way of handling variable inclusion issues when there are large numbers of variables. This step-by-step iterative construction of the regression model involved automatic selection of independent significant variables. However, the resulting simple linear regression model showed all main effects in the first-degree order only while not showing some of the main factors as significant. Although the coefficient of determination was shown as 97%, the domain was found to be constrained and very limited. That's why it was imperative to investigate other model types, specifically Generalized Linear Models (GLM).

In the case of the GLM, the database was expanded to include all the 229 hours. The developed Poisson regression model provided better prediction profiles and showed the relationship between the significant parameters to a third-degree polynomial equation with coefficient of determination (R^2=84%). JMP has an interactive capability of fitting a separate prediction equation for each dependent variable, such as volume or speed, to the observed response (PT LT Volume). This enables prediction of all combinations of parameters on the dependent variable at the same time. The analysis of the experiment produced an interactive decision support system for left-turn mode. Based on the predicted number of left turns during the permitted phase, the analyst can decide whether the permitted left-turn phase is feasible or not. Three (3) criteria were developed for this particular decision. Two of which are related to operational aspects while the third one relates to safety. Specific thresholds were also determined for these criteria. The model of the decision support system was also coded in Visual Basic language. The purpose of the system is to dynamically determine the mode of the left turn for the particular intersection using the mentioned criteria and thresholds.

The developed guidelines would provide traffic engineers with the tools to utilize the efficiency of the permitted left-turn phase at both peak and off-peak times and reduce the delay at approaches with low volumes. Furthermore, Traffic Management Center (TMC) data can be fed into the decision support system so that intersections requiring attention/modification of left-turn mode can be flagged.

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CHAPTER 1: INTRODUCTION

1.1 Background

The most critical aspect of signal design and timing at an intersection is the development of an appropriate phase plan, which is mainly driven by left turn treatments. Accommodating and addressing left-turn vehicles has been a high concern for traffic engineers as they seek a balance between intersection capacity and safety through signal phasing techniques. Exclusive left-turn lanes and protected left-turn phases are commonly used to minimize the impact of left-turning traffic. However, to accommodate left-turning vehicles and to account for safety, cycle length has to be sufficient, or extra time has to be provided from the through phases. This may contribute to an increase in delay or decrease in operational performance at intersections. Hence, to increase the left-turn capacity and reduce the delay at the intersections, researchers and traffic engineers found protected/permitted left turn control (PPLT) to be the most effective (Noyce et al., 2007). In the design of left-turn signal phasing, traffic engineers face three critical decisions; mode, sequence, and display. To date, there are no clear and uniform standards for the selection of left turn phasing mode or sequence in Florida. Furthermore, there are no clear warrants for the implementation of a variable mode (changing by time of day) for left turn phasing. Additionally, there is no systematic method that allows for scanning intersections and flagging ones that require attention to left-turn phasing mode.

The MUTCD defines four modes of left-turn control: permissive, protected, protected/permissive, and variable left turn. *Permissive* or *Permitted* (PT) left-turn control typically is used at locations without left-turn signals. Under permissive operation, the MUTCD does not require an exclusive signal indication or signal face for left turns. Consequently, one signal display can be used for all traffic movements on a single approach and the circular green indication permits left turns to be made after drivers yield to oncoming traffic and pedestrians. *Protected* (PO) left-turn control is used where there is an exclusive display for left-turn movements. With this type of traffic control, left turns may be made only when a green arrow indication is displayed.

Permissive/protected (PPLT) control protects left-turning traffic from oncoming traffic during the protected interval. In another part of the cycle, during which the circular green indication is typically displayed, left-turn movements may be made after drivers yield to oncoming traffic and pedestrians. *Variable* left-turn mode describes a situation in which the operating mode changes among the protected-only mode, the permissive-only mode, and/or the protected/permissive mode during different periods of the day.

Phase sequence is the order in which a controller cycles through all phases. The three main types of sequences are: (1) Lead-Lead Left Turn, (2) Lag-Lag left Turn, (3) Lead-Lag Left Turn. Lead-Lead Left Turn, also called dual leading left turns, indicates a phase sequence in which two left-turn movements from opposite directions of a roadway are both served by leading protected phases. Lead-Lag Left-Turn signifies a phase sequence in which one left-turn movement is served by a leading protected phase, and the other left-turn movement (from the opposite direction of the same street) is served by a lagging protected phase. Lag-Lag Left-Turn is a phase sequence in which two left-turn movements from opposite directions of a street are both served by lagging protected phases.

The selection of the left turn mode and sequence is based on thresholds and criteria such as the volume of left turns, the opposing through traffic volume, and the opposing through operating speed. Additional criteria include left turn sight distance restriction, left-turn reported accidents, percentage of heavy vehicles, and acceptable stopped delay. Currently, there exist no uniform methods of applying left-turn signal phasing throughout the state of Florida. Different jurisdictions use different approaches to determine which mode of left-turn phasing should be used. As mentioned previously, the selection of an appropriate left-turn phasing treatment is a rather complicated process in which trade-offs between safety and operational efficiency may be required.

1.2 Objectives

Hence, there is a need to develop an INTERACTIVE and EFFICIENT framework to serve as a decision support system for the evaluation of left turn phasing alternative based on intersection conditions. This framework will allow (1) an interactive evaluation of left turn phasing and ultimately recommend phasing mode by time-of-day (2) Traffic Management Center (TMC) data to be fed into the decision support system so that intersections requiring attention/modification of left turn mode can be flagged.

As mentioned above, the objectives of this research are two-fold. First an interactive evaluation framework will be developed and tested; second, based on this framework a simplified and systematic decision support system will be designed to flag intersections requiring attention.

1.3 Summary of Project Tasks

In order to achieve the research objectives, the following tasks are conducted:

Task 1: Identify literature and practices related to variable left turn modes and sequence
Task 2: Develop framework for interactive evaluation
Task 3: Field data collection and measures of effectiveness (MOE) selection
Task 4: Traffic simulation
Task 5: Develop interactive Decision Support System (DSS)
Task 6: Conclusions and recommendations

CHAPTER 2: LITERATURE REVIEW

2.1 Guidelines and Warrants Practices

A literature review related to practices involving guidelines and warrants for left turn modes and sequence was conducted as follows:

- FDOT Traffic Engineering Manual:
  - A protected/permissive mode 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. If the decision between providing protected/permissive or protected only mode is not obvious, the traffic engineer should initially operate the left turn phase as protected/permissive mode on a trial basis. If satisfactory operations result, the protected/permissive mode should be retained. If unsatisfactory operations result, the protected/permissive mode should be converted to protected-only mode.

  - A permissive/protected mode can be used effectively for some intersection approaches if the traffic engineer feels that the advantage to be gained in better progression, as demonstrated in a traffic signal analysis computer program, is worth the violation of driver expectancy. However, use of this type of left turn phasing should be limited and should be restricted to only the following situations which will not create a left-turn trap:
    (a) T-intersections where opposing U-turns are prohibited.
    (b) Four-way intersections where the opposing approach has prohibited left turns or protected left turn phasing.
    (c) Four-way intersections where the left turn volumes from opposing approaches do not substantially differ throughout the various time periods of a normal day, so that overlap phasing is not beneficial or required.

- SR 436 @ Orange Ave/Riverbend Rd FYA Study:
  - Based on this analysis it is permissible to operate the westbound left turn phase in protected-permissive mode from 9:00 PM to 7:00 AM. However, the evening coordination plan ends at 8:30 pm. The westbound left turn volume between 8:30 and 9:00 pm is 109 vehicles or 218 vph. Since the equivalent hourly westbound left turn volume during this period is less than 240 vph, consideration should be given to beginning protected-permissive phasing to coincide with the end of the evening coordination plan.

  - The criteria set forth in Chapter 3 (Exhibits 3-13 and 3-14) of the Minnesota Department of Transportation (Mn/DOT) Traffic Signal Timing and Coordination Manual (May 2011) was used to determine the allowable time period for westbound left turn phase to operate in protected-permissive mode. The MnDOT criteria was chosen for the analysis, as there is no nationally accepted methodology for analyzing left turn phase operation by time of day.

➢ <u>SR 414 @ I-4 Eastbound FYA Study:</u>

- Based on this analysis it is permissible to operate the eastbound left turn phase in protected – permissive mode from 10:00 PM to 6:00 AM. However, the recommended hours of operation for protected - permissive mode are 11:00 PM to 6:00 AM, as the cross product from 10:00 to 11:00 PM is near 100,000, which is the limiting value for protected-permissive operation.

➢ <u>NCHRP 457:</u>

- Evaluating Intersection Improvements: NCHRP 457 guidance for left turn phasing selection. The left turn phase warrant sheet used is based on recommended guidance from the NCHRP 457 flow chart (Figure 2-1).

- The FHWA Traffic Signal Timing Manual also utilizes a similar flow chart analysis as NCHRP 457 for the determination of a left turn phase. The FHWA criteria include guidance for up to 3 years of crash experience, while NCHRP uses 2 years.

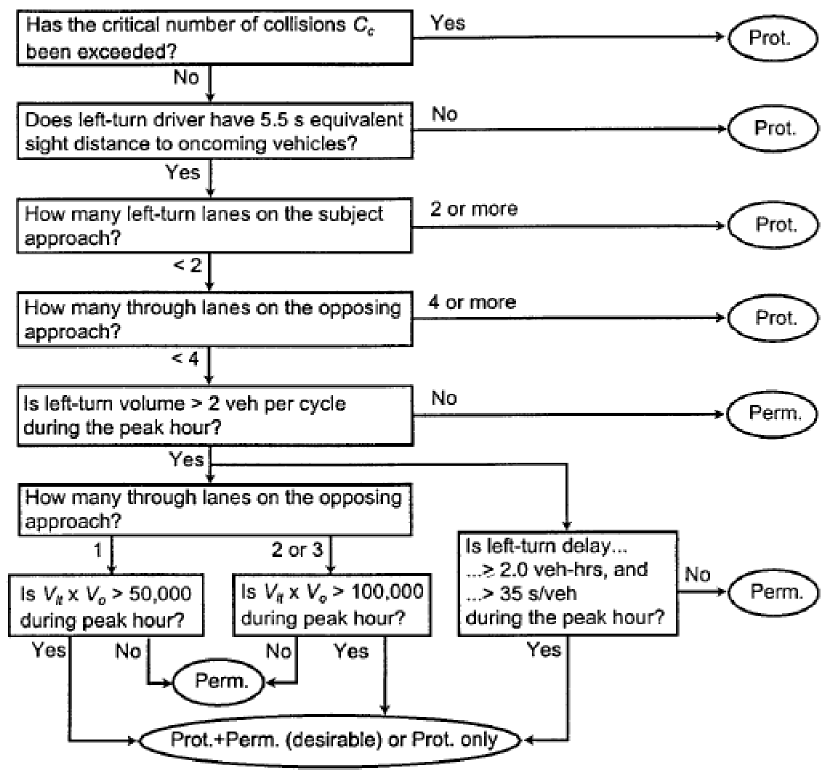


Figure 2-1: NCHRP-457 Guidance for Left Turn Phasing

➢ <u>ITE Member Forum Digest dated May16 "Flashing Yellow Arrow Clearance":</u>

- Kent Kacir was the co-principal investigator for the NCHRP 3-54 study that ultimately made the recommendation to the National Committee to allow the FYA into the MUTCD. The original study began in 1996 and concluded around 2004. So after many years of good discussion, they found the FYA display has become commonly accepted, and in many cases heavily promoted because of the traffic operational and safety benefits over the traditional way of controlling the permissive interval. To date, there are more than 1000 signals in the USA using the FYA display. The now "standard" four-section all-arrow display arrangement is the most commonly used display of the options accepted in the Manual. Most major manufacturers of signal controllers and conflict monitors/MMUs have the FYA as a selectable feature/option; some do it better than others. Workarounds are an issue of the past, but still performed for locations using older model equipment. There have been numerous studies that have documented crash reduction, especially for cases where PPLT was the mode of operation both before and after, just the display is different. There are also many reported implementations that have changed the mode from protected to protected-permitted because of the operational benefits with little to no increase in crashes. So, the display is working for all the right reasons that were identified several years ago. He had a few quick questions for the ITE community that is using the FYA display:

1. A supplemental sign is not required by the Manual. Do you use one anyway? And if so, is it all words?
2. Do you change mode by time of day?
3. Do you use the 4-section display, or 3-section display (bi-modal)?
4. Are you still in the mode of a pilot study, or conversely, moving to a citywide standard/change out?
5. If you are in an urban area with multiple jurisdictions, are you inclined to roll-out the FYA only if all/most neighbors do so in conjunction with you?
6. Do you feel that there is sufficient guidance? For example, did you question the "why" and "how" related to the FYA?

A reply by Don Bennett, PE (City Traffic Engineer, Wilmington, NC, 910-341-4696, don.bennett@wilmingtonnc.gov):

1. A supplemental sign is not required by the Manual. Do you use one anyway? And if, so is it all words?
No signs - no issues to date, short of the aforementioned overlap issues when running protected permitted and the RTOR.

2. Do you change mode by time of day?
All locations are programmed with the proper sequence pages (2070 running Econ Oasis) and logic steps to do so, has not been needed to date.

3. Do you use the 4-section display, or 3-section display (bi-modal)?
4-section - we have some permitted only locations where we use a three section FYA where the green arrow has been replaced with the FYA.

4. Are you still in the mode of a pilot study, or conversely, moving to a citywide standard/change out?
New installs are FYA standard, others are upgraded as progression analysis shows need for lead lag and protected permitted installed for peak hours only. All locations ID'd for FYA had Aux files installed during system upgrade project.

5. If you are in an urban area with multiple jurisdictions, are you inclined to roll-out the FYA only if all/most neighbors do so in conjunction with you?
We were the lead in our area, but in the time since, it has become the standard.
6. Do you feel that there is sufficient guidance? For example, did you question the "why" and "how" related to the FYA?

Based on the research that was available from the NCHRP it appeared that this was an intuitive display since drivers' education programs teach anything that is yellow and flashing means use caution. Drawing on the experience of our elder members, what was the reaction when we switched to the 5-section "doghouse" display from whatever existed before then?

Another reply by Thomas Udell P.E., PTOE (Traffic Services Manager, CH2M Hill, Johns Creek GA, tudell@ch2m.com):

1. *A supplemental sign is not required by the Manual. Do you use one anyway?* and if so is it all words? Yes; "left turn yield on flashing yellow arrow" We intend to relocate the signs as we install new locations. Essentially, we plan to use them for education.

2. *Do you change mode by time of day?* Not yet, although we are looking at the needs of specific locations and will decide. I am interested in what Lexington, KY is doing by lagging the lefts. There appears to be a potential for some operational improvements.

3. *Do you use the 4-section display, or 3-section display (bi-modal)?* We use the four section heads. Our concern was the FYA was a big enough change in itself. Where we had low signals our crews tightened the spans to meet clearance.

4. *Are you still in the mode of a pilot study, or conversely, moving to a citywide standard/change out?* We intend to change out the rest of the signals on local streets. The State DOT has not adopted the FYA yet.

5. *If you are in an urban area with multiple jurisdictions, are you inclined to roll-out the FYA only if all/most neighbors do so in conjunction with you?* No, we were the first in the area.

6. *Do you feel that there is sufficient guidance? For example, did you question the "why" and "how" related to the FYA?* There is plenty of guidance as to the benefits and reasons to use the FYA. Our only issues came with the initial implementation and public outreach. Again, there were several members that helped a great deal by sharing their successes and pitfalls.

Another discussion related to doubling the clearance interval for FYA signal started by Robert Rausch P.E., Vice President, TransCore, Norcross GA, robert.rausch@transcore.com:

Our community has deployed FYA for a major roadway. The roadway is 2 travel lanes each direction with an additional left turn pocket. They installed a FYA for the left turn, but when they clear the traffic to allow the cross street, there is a full yellow clearance on the thru lanes while the FYA continues to flash. Then we get a red to the through traffic and then the FYA transitions to a steady yellow and a red - which is essentially doubling the clearance interval for the through movement before allowing the cross street. Is this required or normal? Or is this an artifact of the traffic control equipment not being able to support the FYA as a concurrent phase.

A reply was posted by Ray Starr P.E., PTOE, Assistant State Traffic Engineer-ITS, Minnesota Dept. of Transp., Roseville MN, ray.starr@state.mn.us:

When Minnesota first piloted a flashing yellow arrow, we used the "double clearance' operation you describe. The reasoning was that until the advent of the flashing yellow arrow, a solid yellow arrow was always clearing a protected movement. A left turner seeing the solid yellow arrow would know that the opposing traffic was stopped. If the opposing traffic were to have a yellow ball clearing a green ball when the left turner had a solid yellow arrow clearing a flashing yellow arrow, the solid yellow arrow would no longer be a protected movement. The left turner may wrongly think the opposing traffic has a red ball. When the MUTCD came out with the rules for the flashing yellow arrow, it did not require this double clearance. It allows the solid yellow arrow to be clearing a flashing yellow arrow for the left turner while the opposing traffic has a yellow ball clearing a green ball. Locations that have used the MUTCD method have not had crash issues. Left turners seem to understand that since the solid yellow arrow is clearing a permissive movement, the solid yellow arrow does not imply that opposing traffic is stopped. Minnesota removed our double clearance installation and has since been using flashing yellow arrows without the double clearance. Although flashing yellow arrow is still fairly new, we have not, as of now, seen any problems with the MUTCD approach.

Another reply was posted by Thomas Udell P.E., PTOE, Traffic Services Manager, CH2M Hill, Johns Creek GA, tudell@ch2m.com:

I can answer both of your questions with "Yes". When the City of Johns Creek installed the Flashing Yellow Arrows (FYA), we had a conflict when the yellow clearance came up for 1&2 and 5&6. This is the result of the "Compact Mode" FYA we are using. The ASC-3 software will reassign the unused yellow from the ped load switches to flash the turn arrows. The EDI 2010 ECL looks for these outputs on phases 9-12. Georgia cabinets are wired with peds on 13-16. The controller reassigns the outputs to phases the monitor isn't looking for. The quick solution was to delay the clearance for the lefts by the through clearance time plus 1/10th of a second. After watching the operation we noticed what Mr. Starr mentioned, the left turns, especially in Atlanta, needed the extra couple of seconds to clear the intersection. We had considered purchasing programmable conflict monitors, but the double clearance seems to be working well.

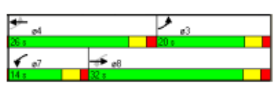
2.2 Previous Studies

Several references were examined in the process of determining the background information and motivation for this research. Numerous past studies have been conducted to develop guidelines or warrants for determining left turn signal control at signalized intersections which are often presented in a sequence format such as flowcharts or a step-by-step process using a ranking score. These studies examined various traffic parameters that have an effect on the signal operation such as traffic volume, delay, geometry, crash data, speed and many other related factors. Furthermore, studies related to FYA focused mainly either on driver's comprehension of the FYA indication or its safety performance.

- **Brehmer et al. (2003)** reported in the NCHRP Report 493, that PPLT provide an additional opportunity for left-turn traffic to turn and traverse through the intersection during the permitted phase based on acceptable gaps in the opposing traffic flow. The protected left-turn phase in case of PPLT can either lead or lag the opposing signal phase. The key concern with PPLT control is the "yellow trap" which occurs during the change from the permitted left-turns in both directions to a lagging protected left-turn in one direction. To avoid the yellow trap, most agencies use "Dallas display". This operation improves safety, but, cannot be applied at all intersections.
- **Qi et al. (2012)** conducted a study and demonstrated that the majority of drivers showed very good understanding of FYA indication, and FYA did not present safety issues at most of the field study intersections. However, they observed that FYA signals may result in more traffic conflicts between left-turn and opposing vehicles at the intersections with high left-turn and opposing volumes.
- **Yi (2012)** investigated the safety issues in the implementation of the FYA at signals with PPLT control mode. For this purpose, historical crash data were collected at 17 intersections with FYA signals installed, and the EB was used to analyze the crash data. Their results indicated that, in most cases, the use of the FYA signal indication did not have adverse effect on traffic safety at intersections.
- **Pulugurtha et al. (2011)** evaluated the effectiveness of the FYA signal through the use of Empirical Bayes (EB) method considering data for 6 signalized intersections and found that the number of crashes would have increased had FYA not been installed at these intersections.
- **J. Deskins (Deskins, 2008),** City of Kennewick traffic engineer**,** explained that the FYA display eliminates the yellow trap, allows lead-lag phasing with PPLT, and allows time of day selection of protected-only or permitted-only phasing. He described operational and efficiency benefits of the Flashing Yellow Arrow display and how they are achieved by selection of specific phasing, timing elements, and modified detection methods. He discussed detection strategies from simple to complex that can greatly improve the efficiency of the FYA and included a description of a "perceived" yellow trap that can occur in some circumstances with the FYA and how to recognize when it may be a problem as shown in Table 2-1.
- **Noyce et al. (2001)** showed in the NCHRP 3-54(2), that the flashing yellow arrow permissive indication was equally understood (measured in terms of correct responses to questions presented) as the circular green indication. But, the data demonstrated that drivers understanding of the flashing yellow arrow display increased with exposure and FYA Display showed a higher fail-safe response compared to the circular green indication. So, one can conclude that FYA display can improve the safety of the PPLT.
- **Chen et al. (2012)** evaluated the safety impacts of changing left-turn signal phasing from permissive to protected/permissive or protected-only at 68 intersections in New York City using a rigorous quasi-experimental design accompanied with regression modeling. Changes in police-reported crashes, including total crashes, multiple-vehicle crashes, and left-turn crashes, were compared between before period and after period for treatment group and comparison group by means of negative binomial regression using a Generalized Estimating Equations (GEE) technique. Confounding factors such as the built environment

characteristics that were not controlled in comparison group selection are accounted for by this approach. The change of permissive left-turn signal phasing to protected/permissive or protected-only signal phasing does not result in a significant reduction in intersection crashes. Though the protected-only signal phasing does reduce the left-turn crashes, this reduction was offset by the possible increase in over-taking crashes. These results suggest that left-turn phasing should not be treated as a universal solution that is always better than the permissive control for left-turn vehicles. The selection and implementation of left-turn signal phasing need to done carefully, considering the trade-offs between safety and delay, and many other factors such as geometry, traffic flows and operations.

Table 2-1: Detection Strategies for FYA (Deskins, 2008)

Phasing	Schematic	Lagging Left Detection	Leading Left Detection
Coordinated Street Lead-Lead		Stop bar detection zones call odd phase and switch to last coordinated phase to terminate. Advance left-turn detection zones call odd phase and switch to the last coordinated phase to terminate. If queue detection is desired, have stop bar zones call last coordinated phase to terminate only. If lead-lag sequence changes by time of day, it may be better to have detection switch to opposing through phase, though this would defeat actuated coordination in the ring that has the lagging left. Other option is to switch detector assignments by plan.	Stop bar detection zones call odd phase and switch to opposing through call opposing through. Advance left-turn detectors call odd phase and switch to the opposing through phase. If queue detection is desired, have stop bar zones call last coordinated phase to terminate only.
Coordinated Street Lead-Lag			
Coordinated Street Lag-lag			
Non-Coordinated Street Lead-Lead		Stop bar & advance detection zones call both *odd phase & opposing even phase* by assigning the zones to two different outputs (or detectors in the controller). Optional zone in front of (or straddling) stop bar can hold opposing through phase. This provides for even phases to hold until force-off before serving any residual left-turns. If additional time is desired for left-turn phase, then have detection zones call *odd phase and adjacent through*, so that opposing through can gap out. Note: Lagging left may get called unnecessarily after sneak if not using queue detection Queue detection not recommended for dual lagging left since late arriving vehicles sitting behind the stop bar, but not placing a call on the odd phase may not get adequate chance to sneak, or even phase may already be past force-off.	Have both stop bar & advance detection zones call odd phase. Also assign same detection zones to an output that calls adjacent through phase and switches to opposing through phase. If queue detection desired, don't attach stop bar zones to odd phase. The switching between through phases allows controller to extend whichever phase is already green under light traffic conditions.
Non-Coordinated Street Lead-Lag			
Non-Coordinated Street Lag-lag			

- **Agent (1987)** developed guidelines during the Kentucky Transportation Research Program (FHWA) for the use of Protected/Permissive left turn phasing based on accident analysis. He stated that protected/permissive is the preferable method of left-turn phasing because of savings in time compared with protected only phasing. However, it creates an increased accident potential and it should not be used when any of the following conditions exist:
1. Speed limit is over 45 mph,
2. Protected-only phasing currently in operation and speed limit over 35 mph,
3. Left-turn movement must cross three or more opposing through lanes,
4. Intersection geometries force the left turn lane to have a separate signal head,
5. Double left-turn only lanes on the approach.
6. A left-turn accident problem exists (four or more left-turn accidents in one year or six or more left-turn accidents in two years on an approach).
7. A potential left-turn problem exists as documented by a traffic conflicts study.

➢ **A.F. Al-Kaisy and J.A. Stewart (2001)** developed an approach for warrants of protected left-turn phase at signalized intersections. The models developed by this research showed that the transition from permissive to protected/permissive left turn operation, based on system optimization, is a function of a number of traffic variables and not simply the left-turn and opposing through volume. This research also indicated that the volume of opposing through traffic may have little impact on when a protected left-turn phase is warranted.

➢ **Zhang et al (2005)** tried to combine both existing empirical warrants and an optimization-based volume warrant similar to that proposed by Al-Kaisy and Stewart (2001) to develop a comprehensive decision flowchart for the selection of left-turn control modes. The product of this study is the decision flowchart shown in Figure 2-2.

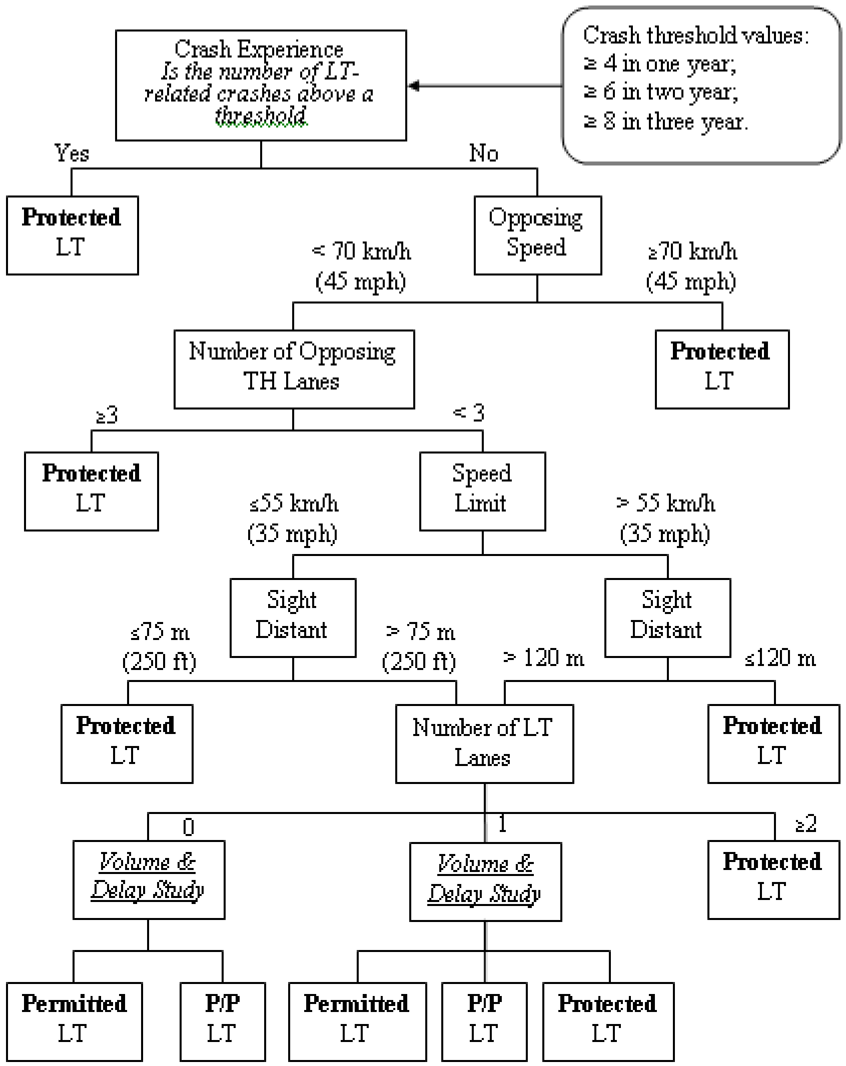


Figure 2-2: Procedure for Determining Left Turn Phasing Type (Zhang, 2005)

➢ Another project for TxDOT conducted by **Yu et al. (2008)** developed guidelines for recommending the most appropriate left-turn phasing treatments at signalized intersections. It investigated all aspects of left-turn operations, including the mode of left-turn signal control, the sequence of left-turn phasing, and left-turn signal displays. Both the operational and safety impacts of different types of left-turn signal operations were analyzed. In the operational impact analysis, based on the results of traffic simulation, cross products of left-turn and opposing through volume (CPOV) – based criteria for selecting the left-turn signal mode between the protected-only and protected/permissive left-turn modes were developed as shown in Figure 2-3.

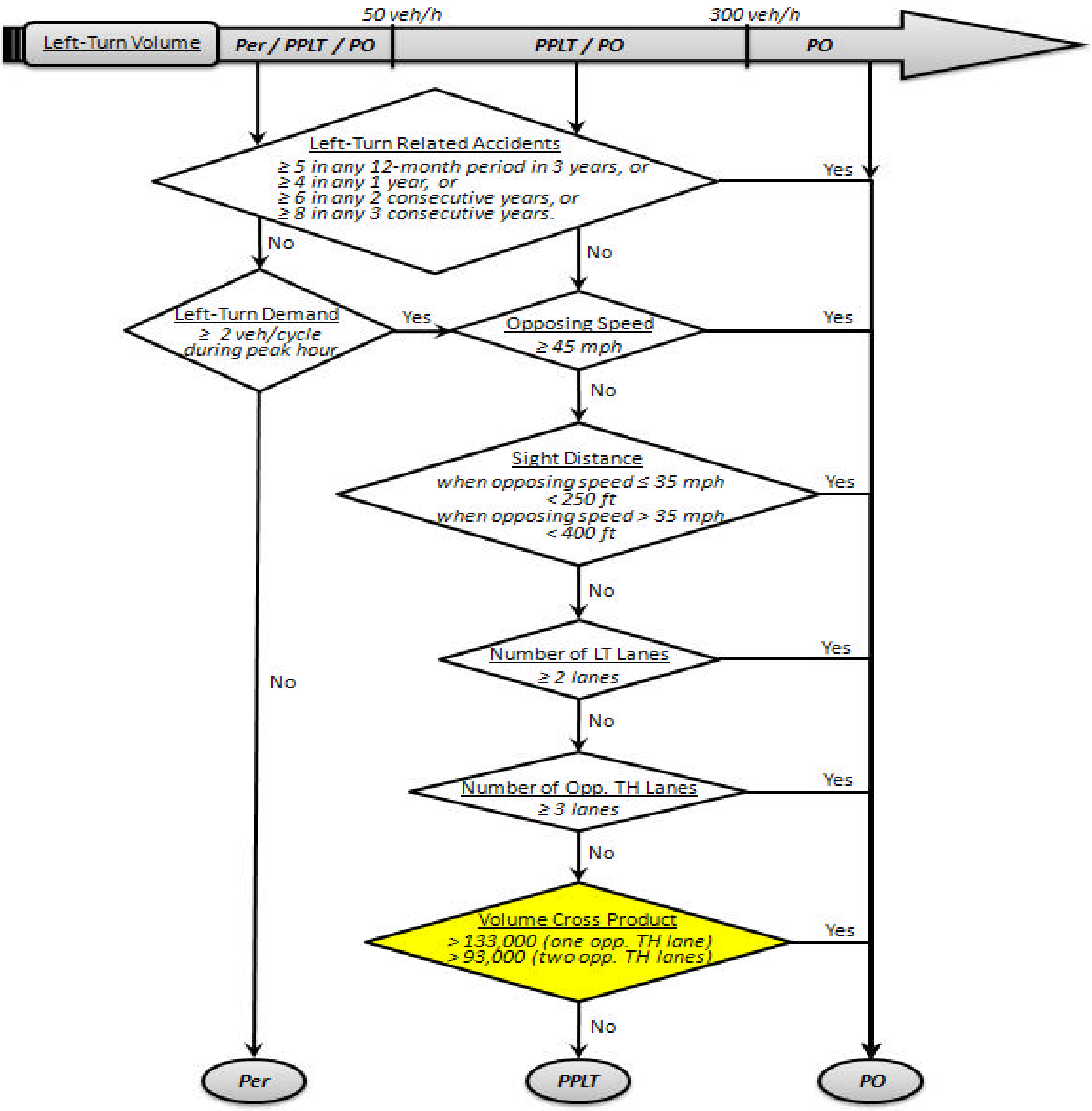


Figure 2-3: Decision-Making Flowchart for LT Signal Control Mode (Yu, 2008)

In the safety impact analysis of the above mentioned project, both simple comparison method and advanced statistic modeling method were employed for analyzing the collected historical accident data from more than 100 intersections. The results of safety study indicated that (1) Protected-only (PO) is the safest signal control mode, followed by permissive only and Protected/Permissive Left-Turn (PPLT); (2) in term of signal phasing sequence, Lead-Lag is the safest, followed by Lead-Lead and Lag-Lag under PO mode, and under PPLT mode, Lead-Lead and Lag-Lag are safer than Lead-Lag when left-turn volume is low, and Lead-Lag is safer than Lead-Lead when left-turn volume is high; (3) split signal phasing results in lower accident rates than non-split signal phasing; and (4) five-section cluster signal display is associated with less accident risk than five-section horizontal signal display. The results are shown in Table 2-2.

Table 2-2: Summary of Findings from Safety Impact Studies (Yu, 2008)

Left-turn Signal design elements	**Safety Performance levels (High ? Low)**		
	1st	**2nd**	**3rd**
Mode	PO	Permissive	PPLT
Sequence	***Under PO mode***		
	Lead-Lag	Lead-Lead	Lag-Lag
	Under PPLT mode (LT volume < 150)		
	Lead-lead	Lag-lag	Lead-Lag
	Under PPLT mode (LT volume >150)		
	Lead-Lag	Lead-lead	
Displays	Doghouse	Horizontal	
Split phasing	With Split Phasing	Without Split Phasing	

The study also developed a table with the parameters that need to be considered while selecting the sequences and modes of left turn signal phasing, and with corresponding scores. The higher score means that parameter is significant and should be considered while determining the sequences and modes as shown in Table 2-3.

Table 2-3: Parameters' Rank for LT Mode & Sequence Determination (Yu, 2008)

Rank	Mode		Sequence	
	Parameters	Scores	Parameters	Scores
1	*Number of Left-Turn Lanes*	*4.50*	*Platoon Progression and Bandwidth*	*4.03*
2	*Historical Rate of Left-Turn–Related Accidents at Intersection*	*4.47*	*Intersection Congestion Level (V/C ratio)*	*3.39*
3	*Sight Distance*	*4.33*	*Historical Rate of Left-Turn–Related Accidents at Intersection*	*3.31*
4	*Left-Turn Traffic Volume*	*4.31*	*Driver Acceptance*	*3.29*
5	*Intersection Alignment*	*4.03*	*Median Width*	*3.22*
6	Opposing Traffic Volume	3.97	Intersection Alignment	3.17
7	Intersection Congestion Level (V/C Ratio)	3.97	Number of Left-Turn Lanes	3.08
8	Number of Opposing Lanes	3.83	Historical Rate of Total Accidents at Intersection	3.03
9	Posted Speed Limit	3.78	Left-Turn Storage Length	3.03
10	Historical Rate of Total Accidents at Intersection	3.61	Left-Turn Traffic Volume	2.97
11	Median Width	3.56	Intersection Delay	2.94
12	Left-Turn Storage Length	3.47	Left-Turn Delay	2.89
13	Left-Turn Delay	3.47	Opposing Traffic Volume	2.75
14	Intersection Delay	3.47	Sight Distance	2.72
15	Driver Acceptance	3.44	Number of Opposing Lanes	2.61
16	Platoon Progression and Bandwidth	3.42	Posted Speed Limit	2.56
17	Vehicle Types/Fleet Compositions (Percent of Heavy Vehicles)	2.97	Vehicle Types/Fleet Compositions (Percent of Heavy Vehicles)	2.53
18	Number of Failed Cycles	2.57	Number of Failed Cycles	2.14
19	Pedestrian and/or Bicycle Crossings	2.19	Pedestrian and/or Bicycle Crossings	1.78

- "Traffic Signal Phase Sequence Guidance Document" Final Report by **Sabra, Wang and Associates (2009)** described the left turn sequence as a function of mode of left turn phase and intersection geometry. (1) For the left turns with PO phasing on opposing approaches and left turns with PO at a T-Intersection, implementation of a Lead or Lag left turn phase sequence is acceptable. (2) For left turns with PO and Permissive mode on opposing approaches, implementation of a Lag left turn phase sequence is not recommended to avoid "Yellow Trap" conditions. Instead, FYA signal displays should be utilized, if one of the left turn phases needs to operate as Lag. (3) For left turns with overlapping paths, a Lead-Lag phase sequence should be utilized to safely accommodate the turning traffic from opposing approaches. This report also has recommended that when determining the left turn phase order, three general factors along with their associated conditions should be considered as follows:

a) Safety

- **Yellow-Trap**: If there will be a yellow-trap issue with a particular phase order, change the signal display to a Flashing Yellow Arrow (FYA), or constrain the phase order such that there would not be a yellow trap issue. If hardware changes such as a FYA are required, compare the benefits of changing the phase order to ensure they outweigh the cost of making the change.
- **Simultaneous Left Turns**: Ensure that there are no geometric issues which prevent left turns from operating simultaneously. If there are, set the incompatible phases in different barriers.
- **Pedestrian / Bike Traffic**: Lag Left Turns that turn into crosswalks that are heavily utilized by pedestrian / bike traffic. Pedestrians often ignore the FDW signal and begin their crossing when they see the side street phase terminating. Thus, leading left turns may conflict with when pedestrians expect to start crossing.

b) Platoon Progression and Bandwidth

- Left Turn Phase Order may default to a Leading Left Turn phase in lieu of traffic platoon progression analyses and for isolated intersections.
- Left Turn Phase Order should be determined based on optimizing bandwidth and platoon progression, and may vary for each coordinated signal timing plan.
- Lag Left Turns are commonly utilized at diamond interchanges, intersections with wide medians that have crossover road signalized, and at other tightly spaced signals. An analysis of platoon progression must be performed with consideration to platoons both from the mainline roadway as well as from the side street / interchange ramps in order to determine the optimal phase order.

c) Queuing

- Lead and Lag Left Turn Phases in the same cycle (Twice per Cycle Left Turns) when the left turning queue cannot be accommodated with the turn bay length.
- Lead Left Turns when left turning traffic spills out of the turn bay and blocks through traffic.
- Lag Left Turns when the through queue blocks access to the turn bay and the left turn phase is "starved" of traffic.

➢ Crash Data Analysis Report, Working Paper 6**,** Prepared by **Kittelson and Associates Inc. (2002)** provided the following key findings from their literature review:

- One author identified that the crash frequency is higher for PPLT intersections with leading left-turns compared with lagging left-turns. However, other authors identified this was true for intersections with three opposing lanes of traffic. It was further identified that the lagging PPLT had the worst crash record when there was two opposing lanes of traffic.
- Almost all literature shows that the leading protected left-turn phasing has the lowest crash rate.
- It was identified that there was no statistical difference in crash frequency among the most common PPLT display arrangements.
- It was identified that the flashing yellow ball display was safer than the green ball display.· It was identified that the use of PPLT phasing can reduce left-turn delay by 50 percent and total delay by 24 percent compared to protected-only phasing.

Similar results were concluded from **Upchurch (1991)** where he compared the relative safety of different types of left-turn phasing, which were: permissive; leading protected/permissive; lagging protected/permissive; leading protected; and lagging protected. A gross crash statistic comparison identified the following trends:

- Leading protected phasing has the lowest left-turn crash rate.
- In the two opposing lanes, lagging protected/permissive has the worst crash rate.
- In the three opposing lanes, leading protected/permissive has the worst crash rate.
- For two opposing lanes, the order of safety (from best to worst) is leading protected, permissive, leading protected/permissive, and lagging protected/permissive. It was noted that there were small differences in the crash rate among the last three types of phasing.
- For three opposing lanes, the order of safety (from best to worst) is leading protected, lagging protected/permissive, permissive, and leading protected/permissive

2.3 Literature Conclusions

The literature included methodologies and decision flow charts for left turn mode and sequence operations and safety aspects as described in the above section. The literature review generated the following major findings:

- Majority of the developed warrants and guidelines were based on either operational efficiency or safety impacts. Very few only considered or accounted for the impacts of both operational efficiency and safety aspects.
- Regarding the studies that accounted for both operational efficiency and safety, similar methodology was implemented either in terms of benefit/cost analysis or before/after study.
- Although the developed guidelines are applicable, they are not considered practical to be implemented in the field. Both methodologies require prior information to be available for before and after study conditions.
- **For left-turn volume warrants**, almost all studies were consistent in applying the cross product methodology of left-turn and opposing through volumes.
- All studies recommended a cross product of left-turn and opposing volumes greater than 50,000 for single-lane approaches and a cross product of left-turn and opposing volumes greater 100,000 for two-lane approaches.
- Although a constant cross product of left-turn and opposing volumes is the most widely used warrant, other studies concluded that it cannot be applied to all types of intersections.
- **Regarding safety aspects**, numerous studies were conducted on analyzing the safety aspects of different types of left-turn phases. These studies utilized two major comparison methodologies, before-and-after and cross-section comparisons, using various criteria of accident rates.

- Most of the results indicated that the protected-only mode of left-turn phasing is the safest. The comparisons between permissive and PPLT showed that the PPLT was safer than the permissive.
- In terms of phasing sequences and comparing the safety impacts of protected-only left-turn phases with different sequences, results indicated that the lead protected-only was safer than the lag protected-only left-turn phases. For the sequences of PPLT phases, majority found that lag PPLT was better, while others indicated that lead PPLT was better.
- In summary, researchers found that (1) protected-only is the safest left-turn phase, (2) lead protected-only was safer than the lag protected-only left-turn phase, and (3) lag PPLT was safer than the lead PPLT left-turn phase.
- **Regarding the operational aspects**, numerous studies were conducted on analyzing the operational efficiency for the different types of left-turn phases. These studies also used two major comparison methods; before-and-after and cross-section comparisons using several criteria for comparisons.
- The results showed that PPLT phasing was the most efficient for left-turn phase. For evaluating different left-turn phasing sequences, mixed results were concluded in terms of lead PPLT with lag PPLT phasing and vice-versa.
- In summary, from the literature review, researchers found that (1) PPLT performed better than the protected-only left-turn phase in terms of the operational efficiency, (2) lag PPLT performance was more efficient in most cases compared to the lead PPLT left-turn phase, and (3) the lag protected-only phase had better operational performance than the lead protected-only phase.

As can be concluded from the literature, majority of the developed warrants and guidelines were based on either operational efficiency or safety aspects. Studies that accounted for both operational efficiency and safety, similar methodology was implemented either in terms of benefit/cost analysis or before/after study. Although the developed guidelines are applicable, they are not considered practical to be implemented in the field. Prior information is needed for before and after study conditions. For left-turn volume warrants, almost all studies were consistent in applying the cross product methodology of left-turn and opposing through volumes as the main warrant. A cross product is generally accepted as a signal warrant but lacks the ability to be inclusive of all intersections. Furthermore, a more comprehensive approach is necessary to continue the advancement of understanding how other parameters affect and interact with each other to provide a more balanced and efficient operation while maintaining safety. Combining the two aspects is rarely achieved and needs to be included in such an analysis.

CHAPTER 3: RESEARCH APPROACH

In order to achieve the stated objectives, the following research methodology was implemented:

1. Development of Candidate Parameters for Framework Evaluation
2. Identifying Criteria for Study Intersections
3. Data Collection
4. Data Extraction
5. Operational Analysis Using SYNCHRO Simulation
6. Design of Experiment (DOE)
7. Statistical Analysis Using JMP Software
8. Model Development and Decision Support System (DSS)
9. Findings of Research Results and Conclusions

The first three tasks of the methodology along with a brief introduction to the design of experiment process are discussed in this chapter. However, the rest of the methodology tasks are discussed in the following chapters.

3.1 Framework Parameters

A preliminary list of candidate parameters was developed based on the literature review findings and previous research experience as shown in Table 3-1. The goal is to determine the operational and safety impact measures of effectiveness (MOEs) for left turns. These parameters along with the recommended guidelines from the literature were examined for the determination of the final data parameters and recommendations that will be used by the decision support system. These parameters represented the basis of the interactive framework to evaluate the suitable left-turn mode under different time of day volume levels. The bold and shaded parameters are further investigated at different levels using experimental design techniques following the data collection phase as will be explained later.

The flashing yellow arrow project required specific data parameters that reflect the nature of the standard being provided. Parameters that constitute the geometrics, safety and operational aspects of the intersection are important to classify the intersection. Additionally, specific categorical data parameters were also chosen that are considered significant enough to affect the characteristics of the traffic flow and behavior of the driver. This is a dramatic departure from the volume based approach that has dominated in the past when determining the warrant for a protected left turn.

Table 3-1: Candidate Parameters for Framework Evaluation

Traffic Data	Crash Data	Signal Data	Geometry Data	Land Use
Left-turn traffic volume	**Historical crash data (1-3 years)**	**Signal timing plans**	**3-leg/4-leg/5-leg**	**Residential (Urban/Rural)**
Opposing through traffic volume	**Number of left turn-related crashes**	**Mode**	Number of conflicts or sight obstructions (Bike/Ped crossings)	**Commercial (Urban/Rural)**
Heavy vehicles percentage	Driver behavior (aggressive or nonaggressive)	**Sequence**	**Left turn storage length**	**Downtown (Mixed Use)**
Left-turn delay	Bike and Pedestrian count	Cycle length	**Number of lanes**	**Tourist Area**
Through delay		Platoon progression (coordinated or isolated)	**Posted speed limits**	**School Zone (School/Ped crossings)**
Volume to capacity ratio on both approaches		Number of failed cycles	**Criteria (wide/skewed/median/ ramp terminal/Single lane)**	
Headway (Critical Gap)		**Splits**	**Crossing lanes (opposing plus exclusive lanes)**	
Queuing conditions		Signal display		

3.2 Intersection Criteria

Certain criteria for identifying candidate intersections for field data collection were investigated. These criteria cover a wide range of conditions in order to provide comprehensive results and conclusions. These criteria included:

- Intersection Volumes (left turning movements and opposing traffic)
- Geometry (wide, skewed, dangerous by design)
- Historical crash record (left turn related by time of day, total crashes)
- Surrounding land use data (residential, commercial, mixed use)
- Surrounding area (rural, urban, downtown)
- Posted speed limits
- Special considerations (school/pedestrians crossings)

Majority of the data required field work while other data was collected from other sources. Specific categorical data that did not require field work are listed as follows:

- Time of Day (TOD): to characterize the intersection throughout the day
- Peak Hour (HR): whether or not the analyzed hour is within the intersection's peak timeframe
- Geometry (Gmtry): special characteristics such as wide, skewed or dangerous by design
- Land use (LU): to highlight traffic characterization and the type of driver that may be present
- Criteria (Cri): to take the design environment into account, special facilities or situations
- Crossing lanes (Xing Ln): to have a perspective on total lanes the driver is crossing
- Posted speed (Speed): to determine the need for larger gaps for the driver to accept a left turn
- Left turn crashes (LT Crashes): safety factor and enable greater protection in high risk areas

Several other field parameters are included to snap shot the typical operation of the intersection. These parameters included:

- Permitted green times (PT Grn Time): total amount of permitted green time throughout the hour
- Permitted left turn volume (PT LT Vol): no. of left turns during permitted phase
- Total Left turn volume (Tot LT): total left turn traffic for protected/permitted (PP) phases
- Permitted opposing volume (PT Opp Vol): opposing volume during permitted phase
- Total opposing volume (Tot Opp Vol): total opposing traffic during PP phases
- Left turn truck % (LT Tr%): truck percentage in the subject left turn lane

3.3 Data Collection

The process for obtaining the left turn parameters required several different methods of collection techniques. As previously noted, there were several factors that required no field work and others that were obtained through databases or live data capture in the field. Basic location information was required for each intersection. The research requirements demanded intersections having either a five-section signal head where the protected-permitted phase was used or a flashing yellow arrow signal already installed and operational. Because the FYA signals are new and evolving especially in the Central Florida area, only two intersections were found and included. Additionally, the goal was to find intersections that have one or two thru lanes opposing a single left turn lane. Because of the wide spectrum of intersection types available in Central Florida, the goal for these intersections was to be scattered around the area to obtain a fair sampling of sites. 13 intersections were selected for data collection, ranging from small minor roads and ramp terminals to major arterials as shown on Table 3-2. The previously mentioned criteria were used to identify specific intersections.

Table 3-2: Intersection List for Data Collection

No	Main St	Side Street	Speed	Geometry	Land use/Criteria		(5-yr) Left Turn Crashes	5-yr) Total Crashes
1	SR 50	Chuluota Rd	55	4-Leg	Residential	Rural	22	127
2	SR50	Wal-Mart Entrance	45	3-leg	Commercial	Urban	32	136
3	SR 50	Mills Ave	40	4-Leg	Downtown	Urban/ 5-lanes/ undivided	10	173
4	Dean Rd	SR 408 off Ramp	45	3-leg	Residential	off-Ramp/ sight distance issues	47	86
5	Curry Ford Rd	Chickasaw Trail	45	4-Leg	Residential/ Commercial	Single lane	13	140
6	Chickasaw Trail	Valencia Ln	40	4-Leg	Residential/ School	Single lane	20	68
7	Avalon Park Blvd	Waterford Chase Rd	45	4-leg	Residential/ School	Peds	46	107
8	Lake Underhill Rd	Woodbury Rd	35	4-Leg	Residential/ School	Peds	10	90
9	Lake Underhill Rd	Chickasaw Trail	45	4-Leg	Commercial/ Residential	Skewed/ Single lane	24	148
10	I-Drive South	Vineland Ave	45	3-Leg	Tourist	Peds/Wide Int	15	79
11	CR535	Overstreet Rd	30	4-Leg	Residential/ School	Ped/Single Lane	19	35
12	CR535	Lakeside Village Ln	55	3-leg	Commercial	Rural/ **FYA**	1	4
13	US 192	Academy Drive	55	4-Leg	Residential	Rural/ **FYA**	1	29

The schedule of data collection was also determined to include all days of the week based on traffic patterns in the area, including the weekends and at different times of the day. For example, Saturday was selected for the intersection of Colonial Drive (SR50) at the Wal-Mart Entrance as it is considered the busiest day of the week for this location. Similarly, Sunday was selected for the intersection of International Drive South at Vineland Avenue due to the fact that it is a busy tourist area especially for the week before Thanksgiving.

The categorical data was determined using aerial views and site visits at the study intersections. Signal timing and special considerations were garnished by the respective jurisdictions for each intersection. The crash data for the past 5 years (October 1st 2008 – September 30th 2013) was obtained from the latest crash database website developed by the University of Florida as part of the Signal Four Analytics (S4A) project (Signal 4 Website).

The website information included refined police reports which provide more reliable data than the regular police report.

The database noted approximately 6,600 left-turn related crashes within Orange County, Florida. Figure 3-1 shows a snapshot of the crashes in Orange County. It should be noted that the database recently included a new feature to extract crashes by time of day at each intersection which added a significant benefit to the project. Excerpts from the website showing 5-year intersection left turn related crashes by time of day are included in Appendix A.

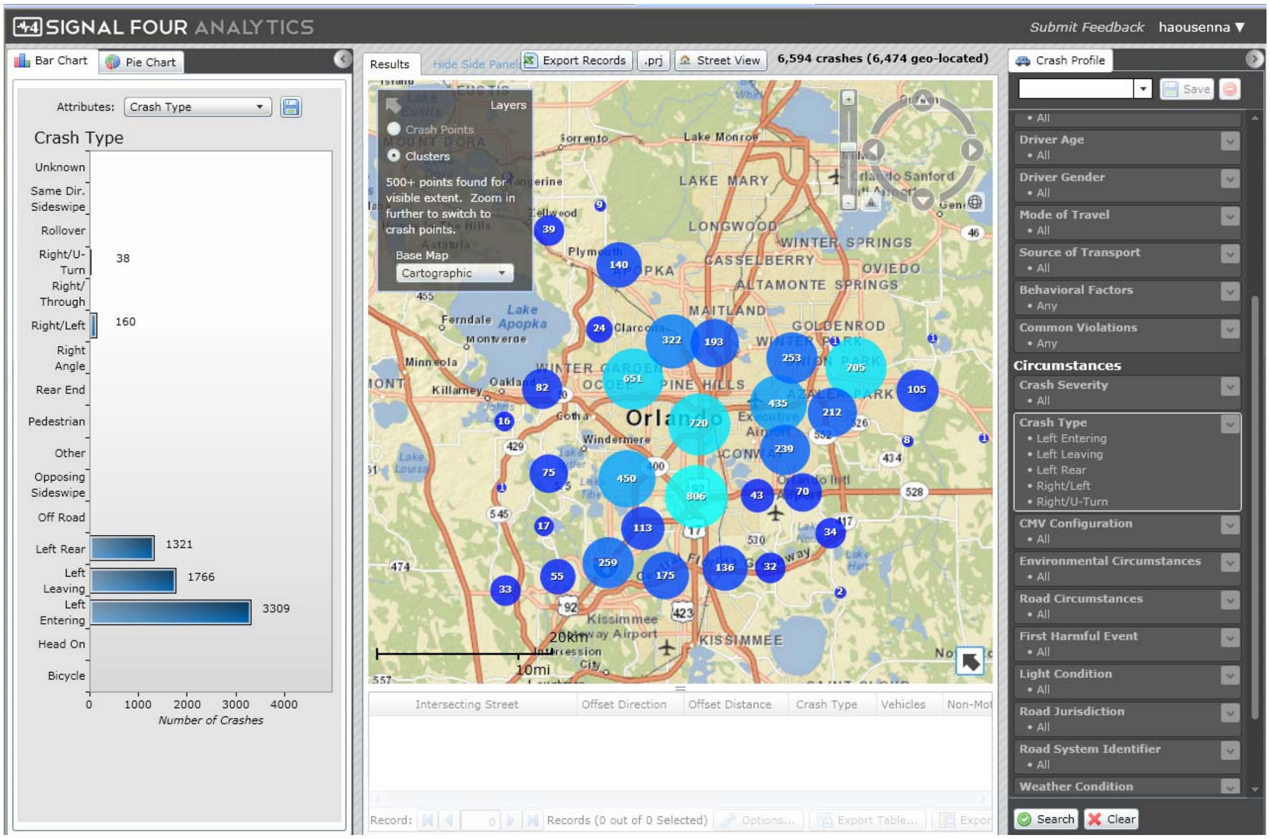


Figure 3-1: A Snapshot for Left-turn Related Crashes in Orange County (S4A by UF)

3.4 Video Collection Unit (VCU)

The rest of the data required the use of a Video Collection Unit (VCU). The VCU for this project was provided by Miovision Technologies (Miovision Website). A special training was necessary for the deployment of the (VCU) equipment from Miovision Technologies. The data collection started in the first week of November and continued for 3 weeks till the end of the month. Pictures of the VCU (and its components) attached to an electric pole at the intersection of Chickasaw Trail and Valencia College Lane is shown in Figure 3-2 and included in Appendix B. The VCU was strapped to the intersections' mast arm or the nearest utility pole and the camera could be extended approximately 25 feet above the intersection to provide a clear view of all intersection approaches as shown in Figure 7. About 10 – 12 hours of video data was recorded at the 13 intersections resulting in a total of 150 hours.

Figure 3-2: VCU Attached to an Electric Pole with Camera at 20 Feet High

Intersections location map as well as five of the thirteen study intersections with their VCU position (blue star) are shown on Google maps and included in Appendix C. After the data collection was completed, the Scout VCU was shipped back to Miovision Company. However, the videos had to be uploaded on Miovision's website using Miouploader tool in order to get processed according to the type of analysis required. All study intersections data are processed for two main types: gap and volume analyses. A snapshot of the Miouploader tool is included in Appendix D. Setup for the video uploads and configuration process through Miovision's Traffic Data Online (TDO) website is shown in Appendix E.

3.5 Experimental Design

In many scientific investigations, the interest lies in the optimization of the system. Experimentation is one of the most common activities used to understand and/or improve a system. This can be achieved by studying the effects of two or more factors on the response through two or more values, known as "levels" or settings, simultaneously. This type of experiment is known as factorial design. Cost and practical constraints must be considered in choosing factors and levels. Hence, two-level factorial designs are essential for factor screening, which is primarily concerned with the discovery of active factors. However, if a non-standard model is required to adequately explain the response or the model contains a mix of different factors with different levels resulting in an enormous number of runs, the requirements of a standard experimental design will not fit the research requirements (Johnson et al., 2011). Under such conditions, optimal custom designs are the recommended design approach. Choosing an optimality criterion to select the design points is another requirement.

The custom design module in JMP (statistical software created by SAS) generates designs using a mathematical optimality criterion (JMP 2007). Accordingly, the D-optimality and I-optimality criteria were the two custom designs employed for this research (Jones et al., 2010).

These are non-regular orthogonal designs that avoid any confounding or correlation between main effects. The multilevel factorial design consisted of ten (10) quantitative factors and one quantitative response.

The custom design of this experiment resulted in 168 runs obtained by considering all combinations of the factors along with two or more possible levels. However, 229 runs were included in the DOE based on the data extracted to provide a more comprehensive sample size. Table 3-3 provides a partial basic layout of the planning matrix in a standard order which describes the experimental plan in terms of the actual values or settings of the factors. Each row of the table represents one set of experimental conditions that when run will produce a value of the response variable y. The response variable will be the number of permitted left turns (P_{LT}) produced in each scenario. The factors (example of six) are designated A though F with the levels (-1) as the low setting and (+1) as the high setting. The experiment is conducted in a randomized run order to avoid the confusion of an increasing or decreasing trend in the response with the effect of a factor. Finally, all possible interactions between the factors (two-way or more) are considered in the analysis.

Based on the above mentioned parameters, the effect of each of the studied parameters on the permitted phase adjustment factor will be investigated. The experiment will also identify a threshold for the permitted left turn adjustment factor along with other significant key factors to work as a guideline in the decision support system (DSS) for warranting a permitted phase.

Table 3-3: Partial Layout of a Generic Custom Design

	A	**B**	**C**	**D**	**E**	**F**	**Y**
Run	**Total LT Volume (vph)**	**Total Opposing Volume (vph)**	**Permitted LT Green Time (min)**	**Land Use**	**Criteria**	**No of LT Crashes**	**No of Permitted LT**
1	-1	-1	-1	-1	-1	-1	Y1
2	1	-1	-1	-1	-1	-1	Y2
3	-1	1	-1	-1	-1	-1	Y3
4	1	1	-1	-1	-1	-1	Y4
5	-1	-1	1	-1	-1	-1	Y5
6	1	-1	1	-1	-1	-1	Y6
7	-1	1	1	-1	-1	-1	Y7
8	1	1	1	-1	-1	-1	Y8
9	-1	-1	-1	1	-1	-1	Y9
10	1	-1	-1	1	-1	-1	Y10
11	-1	1	-1	1	-1	-1	Y11
12	1	1	-1	1	-1	-1	Y12
13	-1	-1	1	1	-1	-1	Y13
14	1	-1	1	1	-1	-1	Y14
15	-1	1	1	1	-1	-1	Y15

CHAPTER 4: MODEL DEVELOPMENT

The process of developing the interactive model including all the previously mentioned parameters for the determination of left turning traffic during the permitted phase required several steps. First, the necessary data from each intersection was extracted from the VCU and processed. Second, SYNCHRO operational analysis was conducted and validated using the extracted field data. Then, the required parameters for each run of the experiment were gathered for the inclusion in the design of experiment and lastly, the statistical analysis was conducted to develop the final model along with the criteria needed for the decision support system. Details of each of the above mentioned steps are discussed in this chapter as follows.

4.1 Data Extraction

Data extraction process began with identifying the left turn approach that would be analyzed The time allocation for permitted left turns is crucial to understand how the timing shifts hourly throughout the course of the day and how effective this timing is to allow left turning vehicles. This specific measure is calculated from the moment that no left turn indication is present on the signal head and adjacent thru traffic has the green phase. The time includes the yellow phase and is stopped at the moment where the thru traffic has been given the red phase. Similarly, it is important that the left turns occurring during the permitted phase only are accounted for. This measure is to be used as a relative volume to the total left turning volume. It also provides the ability to examine the times in which the permitted phase is useful for the operation of the intersection. The traffic volumes in the opposing lanes that are oncoming and impeding the left turning vehicles during the permitted left turn phase provide the study with a parameter that shows what the driver is challenged with in making the left turn. This includes all the opposing thru lanes plus any exclusive right turn lanes affecting the left turning traffic.

Characteristics of the subject left turn in question are also of paramount importance. The data required timing of all left turns from initiation of movement, if stopped, and from behind the stop bar until the point where the entire vehicle completely cleared the intersection and is in the appropriate receiving lane. This is how the left turns were timed to derive an average time making the left turn. This value is critical because of the differing speeds and lengths of the left turn. It is also important in determining the acceptable gap for the driver as well as the critical gap for the intersection. The critical gap was calculated when a platoon of left turning vehicles were queued and is a measure of the average headway between the vehicles making the left turn during the permitted phase. The time between the first vehicle at the end of the left turn and nth vehicle at the same location is taken and then divided by (n) number of vehicles to obtain the critical gap. The left turn truck percentage is also a significant factor where trucks are prominent and require much larger gaps. Similarly, the total volume of the left turning vehicles was collected to be compared with the number of permitted turns. A low number of permitted turns made during a peak time represent the operational efficiency of the permitted phase along with other safety implications for drivers taking more risk and accepting smaller gaps. Likewise, the total opposing traffic was collected to have a clear understanding of all the operational aspects of the conflicting movements. Data collection/extraction analyses along with the turning movement count (TMC) charts are included in Appendix F.

The left turn parameters related to the volume during the permitted green time and the extents of these periods were extracted in the laboratory by watching the videos second-by-second as these specific parameters would not be logically processed by a machine. Subject left turns were also timed from start to finish on the selected approaches by hand along with the calculation of the critical gap. Spread sheets documenting each cycle permitted left turn green times, number of left turns and the corresponding opposing volumes during the permitted phase, for each hour were prepared as shown in Table 4-1. Conversely, Miovision technologies proprietary software was used to extract total turning movement counts and gap analysis at the intersections using automated video detections. Gap analysis from Miovision provides the number of gaps for the intersection during a specified period of time as long as the critical gap is already predetermined. Therefore, the actual critical gap for each left turn approach was identified from the videos to be used in calculating the number of gaps during the hour. Table 6 shows a sample of the calculations for the critical gap and follow up times for the intersection of SR 50 at Chuluota Road.

Gap results provide the total number of adequate gaps/hour based on the critical gap and follow up time for each intersection. Critical gap for each intersection is computed using the equations found in the Manual of Uniform Traffic Studies (MUTS): **[(W/S) + perception & reaction time + (N-1) follow up time]** and are verified from the videos (Table 4-2) to support the calibration process. Gap data are recorded using the same interval as the volume count (for example: every 15 min). Signal timing plans are also obtained from the respective agencies (Orange County, Osceola County and City of Orlando). Calculations for the critical gaps at each intersection based on the turning radii and turning speeds with perception and reaction times of 1.5-2.0 seconds for major and minor movements are shown in Table 4-3.

All of the above mentioned parameters are examined for their differing effect on the number of left turns that could be made during the permitted phase. The parameters selected will have an impact on the determination on whether or not a left turn should be protected only, permitted only or protected/permitted at an intersection. When the characteristics of the intersection in a particular situation warrant that a left turn be protected, the signal would be able to adapt and relay the results of the analysis via the controller through the decision support system. The ultimate goal of the study is to eventually automate the process and have the controller make the determination.

Table 4-1: DOE Left Turn Data and Parameters (Sample Calculations)

Approach	**Major Street:**	SR 50		**Speed:**	55 MPH	
EBL	**Minor Street:**	Chuluota Road		**Geometry:**	4-Leg	
Opposing Lanes:	4 Lanes	**Land Use:**	Residential	**Criteria:**	Rural	
Left Turn Related Crashes (5 years):		22	**Total Intersection Crashes (5 years):**		127	
Date	**Start (hh:mm)**	**End (hh:mm)**	**Total Values for Collection Period**			
Tue 11/27/12	06:00 AM	06:59 AM	**8:21**	**6**	**227**	**21**
Cycle	**Start Clock Time (mm:ss)**	**End Clock Time (mm:ss)**	**Permitted Green Time**	**Left Turn Volume**	**Opposing**	
					TH	**RT**
1	0:48	1:36	0:48	1	13	3
2	2:33	3:18	0:45	0	25	0
3	4:03	4:24	0:21	0	11	1
4	4:49	5:20	0:31	0	19	2
5	6:18	6:58	0:40	1	9	4
6	7:44	8:24	0:40	0	22	1
7	9:18	10:01	0:43	1	18	2
8	11:02	11:22	0:20	0	11	1
9	11:57	12:55	0:58	0	18	1
10	14:03	14:47	0:44	1	21	3
11	15:33	16:23	0:50	1	25	0
12	17:29	18:30	1:01	1	35	3

Table 4-2: Critical Gap and Follow up Times from Videos (Sample Calculations)

Approach	**Major Street:**	SR 50		**Speed:**	55 MPH	
EBL	**Minor Street:**	Chuluota Road		**Geometry:**	4-Leg	
Left Turn Group	**Start 1st Left Clock Time (mm:ss)**	**End 1st Left Clock Time (mm:ss)**	**Total Time for 1st Left (sec)**	**Following Vehicles (no.)**	**End Left Turn Group Time (mm:ss)**	**Follow-Up Time (sec)**
1	1:11	1:22	0:11	0	0:00	0:00
2	6:45	6:57	0:12	0	0:00	0:00
3	9:31	9:38	0:07	0	0:00	0:00
4	14:38	14:45	0:07	0	0:00	0:00
5	16:20	16:23	0:03	0	0:00	0:00
6	25:08	25:15	0:07	2	25:19	0:02
7	26:55	27:01	0:06	0	0:00	0:00
8	28:36	28:44	0:08	0	0:00	0:00
9	30:25	30:32	0:07	0	0:00	0:00
10	30:44	30:49	0:05	1	30:51	0:02
11	39:27	39:33	0:06	0	0:00	0:00
12	39:33	39:38	0:05	0	0:00	0:00
13	41:28	41:33	0:05	0	0:00	0:00
14	53:43	53:49	0:06	0	0:00	0:00
Average Gap			**6.785**			

Table 4-3: Critical Gap MUTS Calculations

Number	Major Street	Minor Street	Major to Minor			Minor to Major		
			App	**Turn (Ft)**	**Gap (Sec)**	**App**	**Turn (Ft)**	**Gap (Sec)**
1	SR 50	Chuluota Rd	EBL	110	7.0	Protected Left Turn		
2	SR 50	Rouse Lake Rd (Walmart)	WBL	93	6.1	Split Phase Operation		
3	SR 50	Mills Ave	EBL	84	5.7	SBL	90	6.0
4	Dean Rd	SR 408 (Off Ramp)	NBL	97	6.4	Protected Left Turn		
5	Curry Ford Rd	Chickasaw Tl	Protected Left Turn			SBL	122	7.6
6	Chickasaw Tl	Valencia College Ln	SBL	70	5.0	EBL	83	5.6
7	Avalon Park Blvd	Waterford Chase Pkwy	NBL	111	7.1	EBL	118	7.4
8	Lake Underhill Rd	Woodbury Rd	Protected Left Turn			SBL	110	7.0
9	Lake Underhill Rd	Chickasaw Tl	EBL	110	7.0	SBL	229	12.9
10	International Dr	Vineland Ave	NBL	129	7.9	Split Phase Operation		
11	CR 535	Overstreet Rd	SBL	149	9.0	WBL	129	8.0
12	CR 535	Lakeside Village Ln	NBL	125	7.7	Protected Left Turn		
13	US 192	Academy Dr	EBL	104	6.7	SBL	119	7.4

Specific data needed to support calibration as well as the design of experiment process were conducted through video observations. These data included identifying:

- Left turning volume during permitted phases,
- Opposing flow rate during permitted phases,
- green time of permitted phase,
- Opposing effective green times
- no of gaps based on critical gap,
- no of gaps based on follow up time,
- Time of day,
- Geometry,
- Crashes,
- Land use,
- No of lanes,
- Posted speeds

4.2 SYNCHRO Simulation

The latest version of Synchro software version 8 was used in the analysis. Synchro decks are modeled for all the 13 intersections using the video processed data along with the field information. In the operational impact analysis, traffic simulation–based method is used for analyzing the operational performance of the study intersections. Two critical issues were investigated: (1) the operational impacts of left-turn signal control modes, with emphasis on the selection between protected-only and protected/permissive left-turn control modes; and (2) the operational impacts of left-turn signal phasing sequences, i.e., lead-lead, lead-lag, lag-lead, and lag-lag. For the impacts of signal phasing sequences, the performance of an intersection using different signal phasing sequences and under different left-turn volume conditions is analyzed by traffic simulation. Synchro was calibrated and validated using the field extracted data from the videos to compare the results especially in terms of the total number of permitted left turn vehicles during the hour. Simulated delay difference between these two signal control modes under different traffic volume conditions were also investigated.

It is worth noting that, Synchro analysis was conducted for experimentation purposes only and to further understand intersection operations. The main reason for not including these outputs in the design of the experiment was to simplify the user input parameters of the developed model. Specific intersection parameters were selected for practicality and to avoid preprocessing of collected data. It should be noted also that Synchro simulations are conducted for the peak hours only for calibration purposes and to account for the worst case scenario.

Outputs from the Synchro analyses are used to calculate the LOS and permitted left turn adjustment factor for each intersection. Excerpts from the Synchro analyses are included in Appendix G.

4.3 Custom Design

As mentioned in the research approach section, standard experimental designs either using full factorial or fractional factorial did not fit this research requirements and therefore, optimal custom designs were selected as the recommended design approach. Also, choosing an optimality criterion to select the design points to be run was another requirement. JMP statistical software was used to generate the custom design for this experiment. The custom design approach in JMP (statistical software created by SAS) generates designs using a mathematical optimality criterion. Optimal designs are computer-generated designs that aim at solving specific research problem to optimize the respective criterion. The optimal designs fall under two main categories:

1. Designs that are optimized with respect to the regression coefficients (D-Optimality Criteria) and
2. Designs that are optimized with respect to the prediction variance of the response (I-Optimality Criteria).

D-Optimal designs are most appropriate for screening experiments because the optimality criterion focuses on estimating the coefficients precisely. The D-optimal design criterion minimized the volume of the simultaneous confidence region of the regression coefficients when selecting the design points (Johnson et al., 2011). This was achieved by maximizing the determinant of X‘X over all possible designs with specific number of runs. Since the volume of the confidence region is related to the accuracy of the regression coefficients, a smaller confidence region means more precise estimates even for the same level of confidence (Johnson et al., 2011).

The experiment included eleven (11) main factors and one quantitative response. The factors ‘levels were chosen to cover all possible scenarios as follows:

1. Time of Day (from 6:00 am to 10:00 pm)
2. Left Turn Volume (from 0 vph to 400 vph)
3. Opposing Volume (0 vph to 3,000 vph)
4. Speed (from 25 mph to 55 mph)
5. Left Turn Trucks % (from 0% to 15%)
6. Permitted Green Time (from 0 to 60 min)
7. Left Turn Crashes (from 0 to 10 for last 5 years)
8. Land Use (Res, Com, Res with school-RSC & mixed use-MXD)
9. Criteria (Urban, Rural, Downtown, Single Lane, Skewed, Tourist, Ramp)
10. Geometry (3-leg, 4-leg)
11. Crossing Lanes (Xing Ln: 2, 3, 4) including exclusive lanes
12. Response: Number of permitted left turns during the hour

Across all of the intersections, 23 left turn approaches were analyzed from the 13 intersections totaling 229 hours of video data processed including off peak and peak conditions. Video data extraction was an essential process in constructing and analyzing the design of experiment and eventually developing the new thresholds for the determination of left turn modes by time of day. Table 4-4 provides a sample of 30 runs.

Table 4-4: Design of Experiment Parameters (Sample)

TOD	Xing Ln	Speed	(5-yr) LT Crashes	PT grn Time	LU	Cri	Tot LT	LT Tr%	Tot Opp Vol	PT LT Vol
8:30	3	45	2	55:12	RES	RMP	300	1.74%	470	288
9:30	3	45	0	54:56	RES	RMP	213	3.76%	378	209
13:30	4	45	1	43:15	COM	UR	190	0.00%	1626	21
16:30	4	45	1	35:58	COM	UR	192	0.00%	1678	13
17:30	4	45	1	35:05	COM	UR	183	0.00%	1628	14
6:00	4	55	3	24:39	RES	RU	73	1.37%	1037	17
6:00	4	55	3	24:39	RES	RU	78	10.26%	980	22
7:00	4	35	2	24:45	COM	DTN	94	3.19%	1206	22
7:00	3	45	1	13:56	MXD	SL	87	4.60%	416	26
8:00	3	35	3	7:13	RSC	UR	70	0.00%	302	6
9:00	4	55	2	24:52	RES	RU	142	4.23%	894	39
9:00	3	35	3	10:58	RSC	UR	111	2.70%	235	28
9:45	3	45	2	42:24	RSC	UR	272	1.10%	394	190
9:45	2	25	2	5:18	RSC	UR	67	0.00%	42	19
10:00	3	35	3	11:34	RSC	UR	133	0.75%	105	37
10:45	3	45	2	37:54	RSC	UR	265	1.51%	361	188
10:45	2	25	2	7:20	RSC	UR	85	0.00%	61	19
11:00	3	35	3	12:40	RSC	UR	152	0.00%	147	44
11:45	3	45	2	37:54	RSC	UR	251	1.59%	406	169
11:45	2	25	2	6:27	RSC	UR	96	3.13%	50	14
12:00	3	35	3	14:47	RSC	UR	224	0.00%	201	73
13:00	4	45	0	25:52	COM	TRST	205	0.49%	666	88
14:00	3	55	4	29:13	COM	RU	210	1.90%	659	50
14:45	3	45	2	24:07	RSC	UR	335	0.30%	604	95
15:00	3	35	3	10:28	RSC	UR	217	1.84%	263	38
15:45	3	45	2	23:14	RSC	UR	338	2.37%	646	98
16:00	4	55	0	25:01	RES	RU	290	1.72%	1019	48
16:00	4	35	2	22:03	COM	DTN	139	0.72%	1341	0
16:45	3	45	2	19:17	RSC	UR	337	0.59%	764	29
17:00	4	55	0	22:59	RES	RU	286	1.75%	1103	33
18:00	4	45	1	23:42	COM	TRST	147	0.00%	681	32
19:00	3	55	4	31:21	COM	RU	163	0.61%	452	43
20:00	4	55	1	26:05	RES	RU	236	0.85%	322	116
21:00	3	55	4	34:29	COM	RU	121	0.00%	268	40

4.4 Experimental Design Analysis

Preliminary DOE analysis was conducted for 139 hours of processed data using JMP's forward stepwise regression approach with all main effects and interactions as candidate effects according to the effect hierarchy principle. Stepwise regression is a very basic way of handling variable inclusion issues when there are large numbers of variables. This step-by-step iterative construction of the regression model that involves automatic selection of independent variables can be achieved either by trying out one independent variable at a time and including it in the regression model if it is statistically significant, or by including all potential independent variables in the model and eliminating those that are not statistically significant, or by a combination of both methods.

Preliminary analysis showed an initial model including time of day, permitted green time, speed, total left turn volume, and total opposing volume along with their interaction factors, but the fit was poor, and total opposing volume main effect was not significant. Also, adding land use or criteria did not improve the situation. Land use and criteria, however, are categorical factors and had to be normalized to be included in the model. Therefore, land use, criteria, and geometry were normalized according to JMP's settings (-1 and 1). This improved form of the model included the following significant main effect parameters along with other two-way factor interaction terms:

<u>Main Effect Parameters:</u>

- Time of Day (TOD)
- Permitted Green Time (PT Grn Time)
- Speed
- Total Left Turn Volume (Tot LT)
- Crossing Lanes (Xing Ln)
- Criteria (Cri)
- Land Use (LU)

<u>Two-way Factor Interactions:</u>

- (Time of Day)*(Land Use)
- (PT Green Time) * (Total LT Volume)
- (PT Green Time) * (Xing Lanes)
- (PT Green Time) * (Land Use)
- (Speed) * (Total Opposing Volume)
- (Total LT Volume) * (Total Opposing Volume)
- (Total Opposing Volume) * (Xing Lanes)
- (Total Opposing Volume) * (Criteria)
- (Xing Lanes) * (Land use)

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
PT Grn Time*Tot LT	1.4260404	0.073136	19.50	<.0001*
Tot Opp Vol*Cri{DTN&SL&RU&SKW&TRST&UR-RMP}	-109.8576	6.145653	-17.88	<.0001*
PT Grn Time(0,57)	0.9494681	0.054186	17.52	<.0001*
Cri{DTN&SL&RU&SKW&TRST&UR-RMP}	-69.65417	4.454104	-15.64	<.0001*
Tot LT*Tot Opp Vol	-82.70012	6.019004	-13.74	<.0001*
Tot LT(0,300)	-80.29692	6.272043	-12.80	<.0001*
PT Grn Time*LU{MXD&COM-RSC&RES}	-0.458323	0.04576	-10.02	<.0001*
LU{MXD&COM-RSC&RES}	23.671739	2.792547	8.48	<.0001*
TOD*LU{MXD&COM-RSC&RES}	-12.58798	1.99534	-6.31	<.0001*
Xing Ln{2&4-3}*LU{MXD&COM-RSC&RES}	6.8606485	1.299881	5.28	<.0001*
TOD(0,86400)	-10.46872	2.035466	-5.14	<.0001*
Xing Ln{2&4-3}	28.398949	5.676503	5.00	<.0001*
Speed(25,55)	18.996454	4.764985	3.99	0.0001*
Tot Opp Vol*Xing Ln{2&4-3}	22.186832	5.715353	3.88	0.0002*
Speed*Tot Opp Vol	17.587707	5.552397	3.17	0.0019*
PT Grn Time*Xing Ln{2&4-3}	-0.158789	0.054581	-2.91	0.0043*

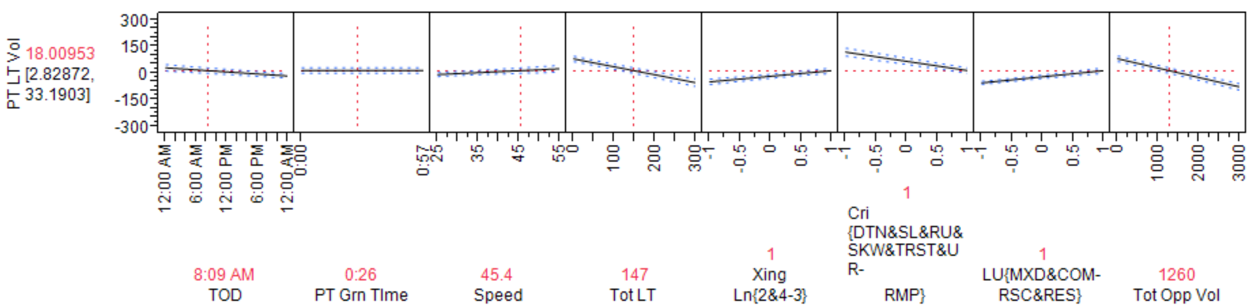


Figure 4-1: Interactive Decision Support Model (Stepwise Regression)

The prediction profiles in Figure 4-1 are dynamic and display the settings at which PT LT Volume can be predicted depending on intersection conditions. For example, on Figure 8, if the intersection is being evaluated for whether a permitted phase would be feasible during the AM peak hour (8:10 am), and the total permitted phase for the subject left turn during the entire hour adds up to 26 minutes, with posted speed limit of 45 mph and total left turning traffic of 147 vph, total opposing volume of 1260 vph, and the driver is expected to cross 4 lanes, and the intersection is located in a commercial area in downtown, then the expected number of left turning vehicles during the peak hour would amount to 18 vph. Based on these conditions, the traffic engineer will be able to determine that, about 12% of the total left turning traffic (147 vph) will make the turn during the permitted phase in addition to the turns during the protected phase. Depending on the intersection conditions and specific thresholds, the permitted phase could be warranted.

The above simple linear regression model showed all main effects in the first degree order only while did not show some of the main factors as significant. Although the coefficient of determination was shown as 97%, the domain was found to be constrained and very limited. That's why it was imperative to investigate other model types specifically Generalized Linear Models as explained in the next section and to include the additional processed data into the model.

4.5 Generalized Linear Models (GLM)

Generalized linear models (GLMs) are a broad class of models that include ordinary regression and analysis of variance for continuous response variables, as well as for categorical response variables. There are three main components to a GLM:

- Random Component – refers to the probability distribution of the response variable (Y); e.g. binomial distribution for Y in the binary logistic regression.
- Systematic Component - refers to the explanatory variables (X_1, X_2, ... X_k) as a combination of linear predictors; e.g. $\beta_0 + \beta_1 x_1 + \beta_2 x_2$ as in logistic regression.
- Link Function, η or $g(\mu)$ - specifies the link between random and systematic components. It says how the expected value of the response relates to the linear predictor of explanatory variables; e.g. $\eta = \text{logit}(\pi)$ for logistic regression.

4.6 Advantage of GLM over Traditional Regression

- No need to transform the response *Y* to have a normal distribution
- The choice of link is separate from the choice of random component thus have more flexibility in modeling
- If the link produces additive effects, then there is no need for a constant variance.
- The models are fitted via Maximum Likelihood estimation; thus optimal properties of the estimators.
- All the inference tools and model checking are applied; e.g., Wald and Likelihood ratio tests, Deviance, Residuals, Confidence intervals, as well as Over-dispersion.

Therefore, the DOE was re-analyzed using the GLM. The best fit was obtained using the Poisson distribution (the random component) and the link function is $g(\mu) = \ln \mu$, then the Poisson regression model form was:

$$\text{Ln}\ \mu(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdot\cdot\cdot + \beta_k x_k) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdot\cdot\cdot + \beta_k x_k.$$

Generalized Linear Model Fit

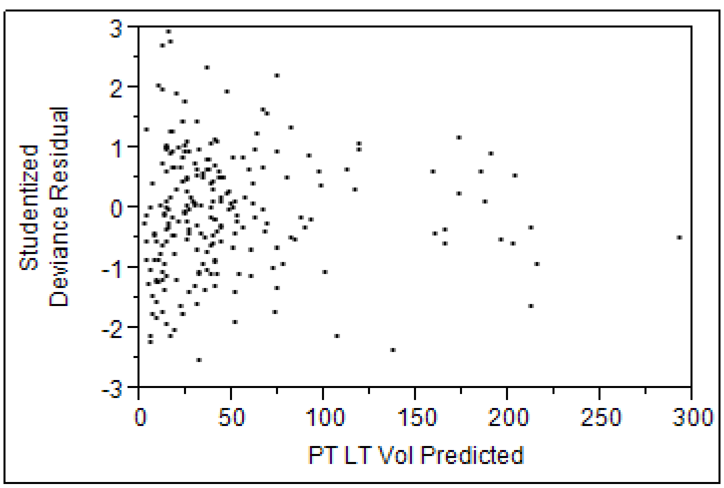
Overdispersion parameter estimated by Pearson Chisq/DF
Response: PT LT Vol
Distribution: Poisson
Link: Log
Estimation Method: Maximum Likelihood
Observations (or Sum Wgts) = 229

Whole Model Test

Model	-LogLikelihood	L-R ChiSquare	DF	Prob>ChiSq
Difference	1612.32875	3224.658	90	<.0001*
Full	300.968855			
Reduced	1913.29761			

Goodness Of Fit Statistic	ChiSquare	DF	Prob>ChiSq	Overdispersion
Pearson	357.0699	138	<.0001*	2.5875
Deviance	364.4007	138	<.0001*	

AICc
911.7612



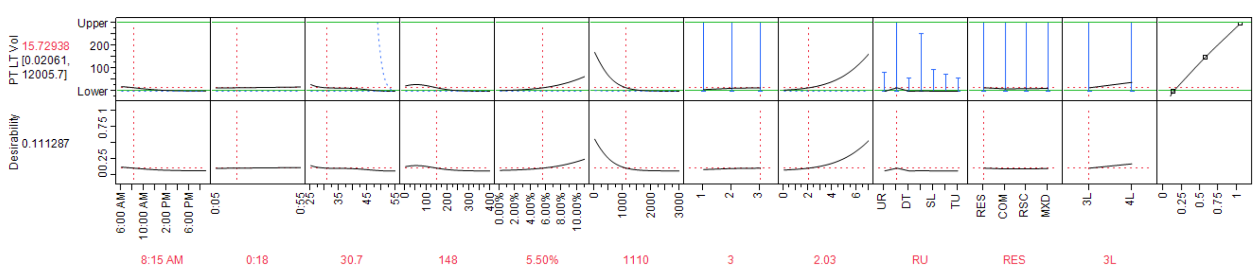


Figure 4-2: Interactive Decision Support Model (Poisson Regression)

In the case of the GLM, the developed Poisson regression model shown on Figure 4-2 provided better prediction profiles and showed the relationship between the significant parameters to a third degree polynomial equation with coefficient of determination (R^2=84%), which means that the model can explain 84% of the observed real life data, in addition to three way factor interactions. Models regression analyses are included in Appendix H.

Significant factors in the Poisson regression model included:

PT Grn Time
Tot Opp Vol
Xing Ln
Cri
TOD*Speed
TOD*Tot Opp Vol
PT Grn Time*Tot Opp Vol
Speed*LT Crashes
TOD*Speed*LT Tr%
TOD*LT Tr%*Tot Opp Vol
TOD*LT Tr%*LT Crashes
PT Grn Time*Speed*Tot LT
PT Grn Time*LT Tr%*Tot Opp Vol
Speed*Tot LT *LT Tr%*
Speed* Tot Opp Vol * LT Crashes
Tot LT* Tot LT* Tot LT
PT Grn Time *PT Grn Time
Tot LT* Tot LT

JMP has an interactive capability of fitting a separate prediction equation for each dependent variable, such as volume or speed, to the observed response (PT LT Volume). This enables prediction of all combinations of parameters on the dependent variable at the same time as shown in the above example. The analysis of the experiment developed an interactive decision support system for left turn mode. Based on the predicted number of left turns during the permitted phase, the analyst can decide whether the permitted left turn phase is feasible or not.

4.7 Decision Support System Criteria and Thresholds

After the model predicts the total number of left turns during the permitted phase, the analyst has to decide on whether this left turn should operate as protected only or protected/permitted. Three (3) criteria were developed in this research for this particular decision. Two of which are related to operational aspects while the third one relates to safety.

The first criteria included an indicator which takes into account (3) main factors:

1. The predicted number of left turns during the peak hour (using the developed model) or if this value can be collected from the field (PT LT Vol)
2. The total opposing volume (Tot Opp Vol) during the hour
3. The permitted green time (PT Grn Time) during the hour

PT LT index = (PT LT Vol * Tot Opp Vol) / (PT Grn Time in seconds) ----------------- 1

The second criteria calculates the percentage of the permitted left turning volume compared to the total left during the hour (demand) and is calculated as:

PT LT Ratio = PT LT Vol / Tot LT Vol ------------------------ 2

And the third criteria determine the average number of left turn related crashes per year for the past 3 years, whether less than 2 or greater than 2 crashes per year in the past 3 years.

LT Crashes/yr < 2 or > 2 crashes in the past 3 years --------------------------- 3

As an example to calculate the PT LT Index from the DOE in Table 8, first row:
PT LT = 288, Tot Opp Vol = 470 and PT Grn Time = 55.2 min*60 = 3312 seconds,
= (288 * 470) / 3312 = 40.87 = 41 which corresponds to a high index value.

In order to arrive at the optimal index and ratio thresholds, the ranking heuristic search function was used. Data from the PT LT Ratio were sorted in an ascending order while data from PT LT Index were sorted in a descending order. From the 2 intersecting curves shown on Figure 4-3, the threshold was found at the point of intersection which corresponded to index (14) and ratio (22%). However, this threshold applies to the two-lane approach intersections while the criteria for the single lane approach intersections were found to be at index (10) and ratio (13%).

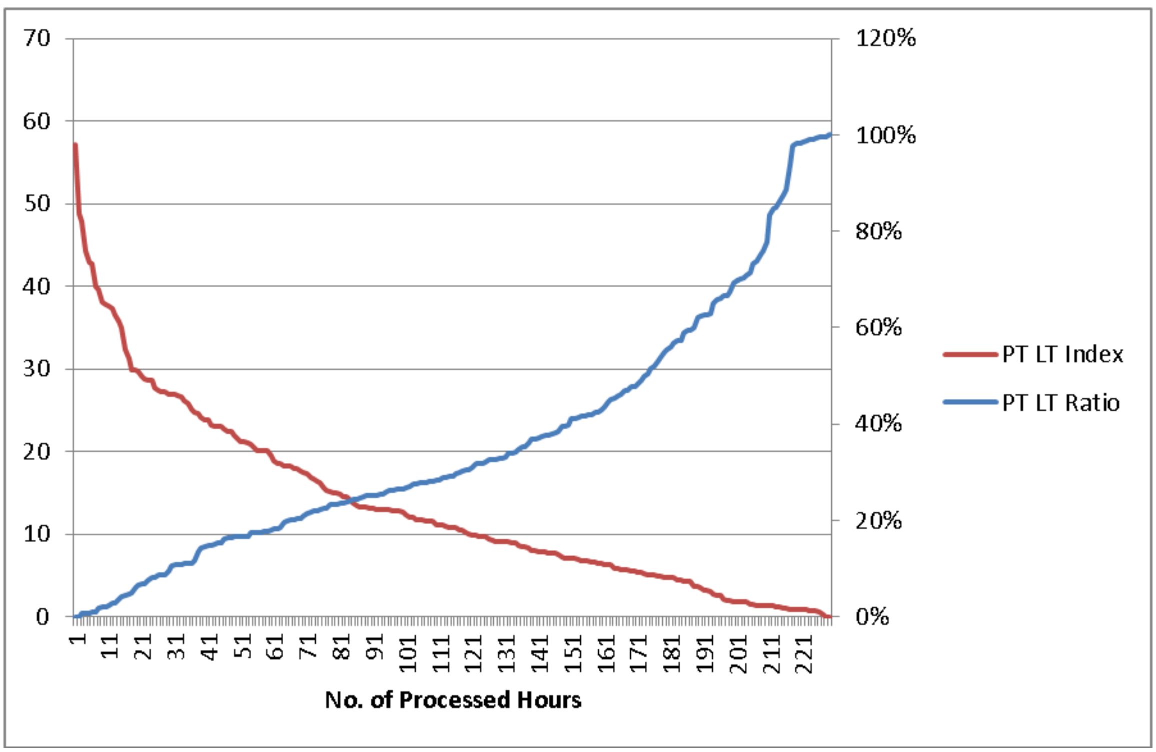


Figure 4-3: Permitted Left Turn Index and Ratio Thresholds

Therefore, using the (3) criteria along with their thresholds, the analyst can decide on accepting a permitted phase during a specified hour of the day or rejecting it. Rejecting a permitted phase means that it is not efficient. A low number of permitted turns made during a specific time of the day represent the operational efficiency of the permitted phase along with other safety implications for drivers taking more risk and accepting smaller gaps. For example, comparing the amount of permitted green time given throughout the hour and the number of permitted left turning traffic shows that the opposing traffic flow was operating near or at saturation. This can be seen in the field when only one or two vehicles at the most can make the turn during the permitted phase every 2 to 3 cycles. Also, having an inefficient permitted phase along with some aggressive drivers can result in a crash. Therefore, eliminating the permitted phase during that time of the day improves the safety as well as the operation. The above criteria take into account whether the opposing traffic is at saturation flow rate or not based on the headway and the amount of acceptable gaps that would allow the left turning traffic to make a turn during the permitted phase.

4.8 Coding the Decision Support System Model in Visual Basic

The model of the decision support system developed from this research was coded in visual basic language. The purpose of the system is to dynamically determine the mode of the left turn for the particular intersection. This determination requires several parameters based on the particular intersection and these values are inserted into the model to generate a solution. This coded model is provided with the inputs for the independent variables. A selected group of these parameters can be chosen from a provided list and the others require manual data entry. The program will display the output for 'Number of Left Turns' as given by the model and the calculated percentage of left turns. The snapshot of the input window is shown in Figure 4-4

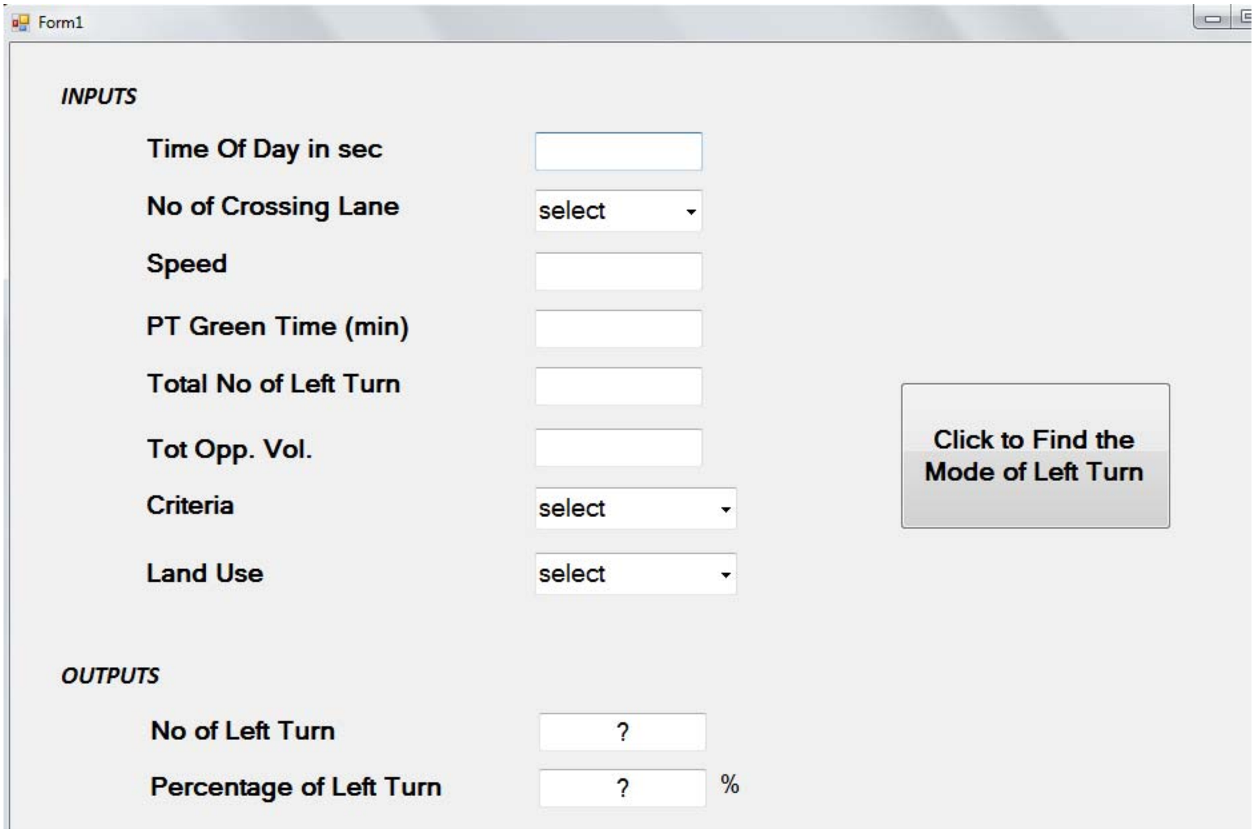


Figure 4-4: Input Window for Decision Support System Coded in Visual Basic

This program ultimately provides a determination, based on the research model, of the mode of the left turn (permissive or protected) and displays in a message box based on the percentage of the left turn given by the model as well as the permitted left turn index as discussed earlier. In this example, the threshold for the decision between permissive and protected is used as 5%. That provides an interpretation that if the left turn percentage is greater than 5%, the mode will be permissive. If left turn percentage is less than 5%, the mode will be protected. If any of the inputs given are out of the range, an error message with limit of that particular parameter would appear and enables the user to provide the input again.

For example, to determine whether the permissive phase is feasible during the 8:10 AM with 4 crossing lanes, posted speed limit of 45 miles per hour, total permissive time of 26 minutes during an hour, total left turning vehicles of 147 vehicles per hour, total opposing volume of 1260 vehicles per hour and the intersection located at commercial downtown area. Figure 4-5 below shows the inputs and outputs. The time of day should be converted to seconds. For this example, 8:10 AM (8 hour and 10 minutes) was converted to seconds which is 29400.

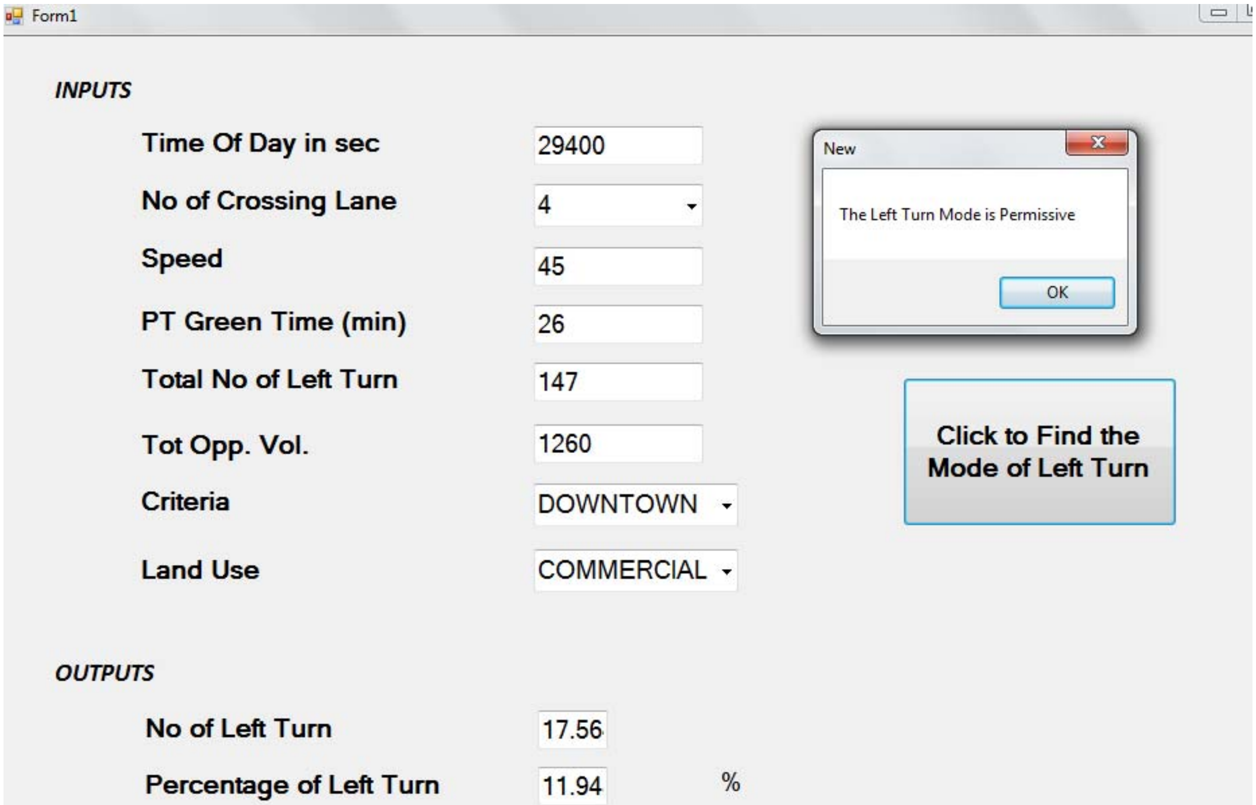


Figure 4-5: Window with Inputs and Outputs Example

The result showed that around 18 vehicles can make left turn during the given condition. This yields a 12% left turn percentage and implies that a permissive phase could be implemented. In the above figure, a message box in the top right corner is displayed with the decision of permissive phase.

Similarly, this program also calculates the PT LT Index along with the percentage of left turns and number of LT crashes for the different inputs of predicting variables, and exhibit the decision if permissive phase is feasible based on the output.

CHAPTER 5: DISCUSSION

This chapter presents major findings that might have direct or indirect implications on the results and conclusions of this research.

5.1 Factors Affecting the Results

As mentioned earlier, the developed model coefficient of correlation or determination (R^2) was 84%, which is considered a relatively high value for fitting random real-life data. However, from the analysis and prediction estimates, it was found that, in some cases, the model underestimates the predicted number of permitted left turns especially when the opposing traffic exceeds the 1,000 vph threshold. This could be attributed to the fact that a majority of the data corresponded to either an off-peak condition or single-lane approach intersections (with volumes less than 1,000 vph). Out of the 229 hours analyzed, about 25% represented a peak condition compared to the rest of the hours. Collecting daily data (10-12 hours) at an intersection results in about 3-4 hours that are considered peak with high volumes when compared to the rest of the day. Moreover, most of the peak hour conditions with volumes around the 1,500 vph resulted in a very low number of permitted left turns.

Fitting the data inclined the model towards lowering the estimates, which is considered more conservative. JMP fits a generalized linear model to the data by maximum likelihood estimation of the parameter vector. There is, in general, no closed form solution for the maximum likelihood estimates of the parameters. JMP estimates the parameters of the model numerically through an iterative fitting process. The dispersion parameter φ is also estimated by dividing the Pearson goodness-of-fit statistic by its degrees of freedom. Covariance, standard errors, and confidence limits are computed for the estimated parameters based on the asymptotic normality of maximum likelihood estimators. Therefore, additional peak hours are needed to confirm whether this could be considered a valid conclusion or a bias in the model.

Another observation is related to the model as well as the permitted left turn index (PT LT Index) criteria. When calculating the index value, the total opposing volumes (Tot Opp Vol) are used. However, it is recommended to use the permitted opposing volume (PT Opp Vol), which is the opposing traffic during the permitted phase. This will reflect a better index value than using the total opposing volume. Likewise, it is recommended to be used in the model inputs instead of the total opposing volume. The main reason for using the total opposing volume instead of the permitted opposing volume is to simplify the data inputs and reduce the amount of calculations on the user. As mentioned earlier, specific parameters were selected for the practicality and simplicity of the data inputs to the model.

Finally, it should be noted that the model is valid for a specific domain and is constrained by the upper and lower limits of the collected data.

5.2 Implications

Based on the above findings, the following is recommended:

1. Expand the design of experiment database to include additional intersection approaches and hours especially peak hours for two main reasons; first, to confirm whether the low estimates when the opposing traffic exceeds the 1,000 vph threshold is considered a valid conclusion, or is it a bias in the model, and second, to improve the coefficient of correlation as well as increase the domain of the model.

2. In order to use the permitted opposing volume in the model and the index calculations instead of the total opposing volumes, an empirical value developed from the analysis can be used to account for the ratio between the total opposing volume and the permitted opposing volume. On average, the permitted opposing volume is found to be approximately 85% of the total opposing volume.

CHAPTER 6: CONCLUSIONS

6.1 Conclusions

The use of a four-section head for the left turn lane only with a flashing yellow arrow (FYA) indication for permissive left turns has been deemed to be the new standard for signalization as recommended in the 2009 Manual on Uniform Traffic Control Devices (MUTCD) based on the National Cooperative Highway Research program (NCHRP) 493 report. FYA treatments at intersections are considered new and evolving fast especially in the Central Florida area. It is acknowledged that there is no nationally accepted methodology for determining left turn phase operation by time of day. The current standards and guidelines for warranting a permitted phase are not practical enough to be implemented in the field and require several steps before applying such as factor conversions or scaling. Furthermore, the warrants are based mostly on peak operations for the left turn and struggle to be relevant in conditions where many variables are in play.

This research collected detailed intersection data at 13 intersections within the Central Florida area resulting in 229 hours of processed data. The design of experiment methodology provided an interactive and simplified systematic decision support system for FYA left turn control using a custom design approach. Specific intersection parameters are selected for the practicality of the model inputs to assess the operational and safety impacts of the left turn mode using multilevel factorial design. Results of the experiment identified significant main effects as well as two-way and three-way factor interactions in addition to second and third degree polynomial fit to predict the number of left turns during the permitted phase under different intersection conditions by time of day.

A decision support system is also developed based on several criteria and thresholds to determine the feasibility of the permitted phase at each approach. Furthermore, the new all-arrow configuration provides the opportunity to change the operation mode throughout the day from fully protected to completely permissive and combinations of the protected-permitted signal phasing using the DSS criteria and thresholds. The developed guidelines would provide traffic engineers with the tools to utilize the efficiency of the permitted left turn phase at both peak and off peak times and reduce the delay at approaches when there are low volumes on the roadways.

As mentioned earlier, future research would expand on the developed database in order to confirm the model estimates, and increase the model domain. Further research is also needed to determine the safety correlation between demand and the number of gaps per cycle. This follow-up effort can better identify how low the gaps per cycle can reasonably be before changing to protected only phasing.

REFERENCES

Agent, K. R. (1987). Guidelines for the use of protected/permissive left-turn phasing. *ITE J.;(United States), 57*(7).

Al-Kaisy, A., & Stewart, J. (2001). New approach for developing warrants of protected left-turn phase at signalized intersections. *Transportation Research Part A: Policy and Practice, 35*(6), 561-574.

Box, P. C., & Oppenlander, J. C. (1976). Manual of traffic engineering studies.

Brehmer, C. L. (2003). *Evaluation of Traffic Signal Displays for Protected/permissive Left-turn Control: NCHRP Report 493* (Vol. 493): Transportation Research Board.

Chang, G.-L., Chen, C.-Y., & Perez, C. (1996). Hybrid model for estimating permitted left-turn saturation flow rate. *Transportation Research Record: Journal of the Transportation Research Board, 1566*(1), 54-63.

Chen, L., Chen, C., & Ewing, R. (2012). *Left-Turn Phase: Permissive, Protected, or Both?* Paper presented at the Transportation Research Board 91st Annual Meeting.

Deskins, J. (2008). *Methods for Operation and Detection of the Flashing Yellow Arrow Display.* Paper presented at the ITE 2008 Annual Meeting and Exhibit.

Institute of Transportation Engineers. ITE Member Forum Digest. Accessed on May 16th 2012: https://www.ite.org/emodules/source/security/Member-Logon.cfm.

Johnson, R., Montgomery, D., & Jones, B. (2011). An Expository Paper on Optimal Design. *Quality Engineering, 23*(3), 287-301. doi: 10.1080/08982112.2011.576203.

Jones, B., & Montgomery, D. C. (2010). Alternatives to resolution IV screening designs in 16 runs. *International Journal of Experimental Design and Process Optimisation, 1*(4), 285-295. doi: 10.1504/IJEDPO.2010.034986.

JMP, Version 10. SAS Institute Inc., Cary, NC, 1989-2007.

Kittleson and Associates and Texas Transportaiton Institute (2002). "Crash Data Analysis Report". Working Paper 6. *Final Report to the Traffic Engineering Community at the Direction of NCHRP*.

Koonce, P., Rodegerdts, L., Lee, K., Quayle, S., Beaird, S., Braud, C., . . . Urbanik, T. (2008). Traffic signal timing manual.

Miovision Technologies. Scout Video Collection Unit Specification Guide. Accessed on November 30th 2012: http://www.miovision.com/products/scout-vcu/.

Noyce, D. A., Bergh, C. R., & Chapman, J. R. (2007). *Evaluation of the Flashing Yellow Arrow Permissive-Only Left-Turn Indication Field Implementation*: Transportation Research Board.

Noyce, D. A., & Kacir, K. C. (2001). Drivers' understanding of protected-permitted left-turn signal displays. *Transportation Research Record: Journal of the Transportation Research Board, 1754*(1), 1-10.

Pulugurtha, S. S., Agurla, M., & Khader, K. S. C. (2011). *How Effective are "Flashing Yellow Arrow" Signals in Enhancing Safety?* Paper presented at the First Congress of Transportation and Development Institute (TDI).

Qi, Y., Yuan, P., Chen, X., & Zhang, M. (2012). Safety of Flashing Yellow Arrow Indication with Protected-Permissive Left-Turn Operation. *In Transportation Research Board 91st Annual Meeting* (No. 12-2263).

Sabra, Wang and Associates (2009). "Signal Phase Sequence Guidance Document". *Final Report to the Maryland State Highway Administration (MDSHA).*

Signal Four Analytics Database. Accessed on June 27th 2012 and August 1st: 2013:http://s4.geoplan.ufl.edu.

Stamatiadis, N., Agent, K., & Bizakis, A. (1997). Guidelines for Left-Turn Phasing Treatment. *Transportation Research Record: Journal of the Transportation Research Board, 1605*(-1), 1-7. doi: 10.3141/1605-01.

Upchurch, J. (1991). *Comparison of left-turn accident rates for different types of left-turn phasing* (No. 1324).

Yi, Q. (2012). Use of Flashing Yellow Operations to Improve Safety at Signals with Protected-Permissive Left Turn (PPLT) Operations: Texas Southern University.

Yin, K., Zhang, Y., & Wang, B. X. (2010). Analytical models for protected plus permitted left-turn capacity at signalized intersection with heavy traffic. *Transportation Research Record: Journal of the Transportation Research Board, 2192*(1), 177-184.

Yu, L., Qi, Y., Yu, H., & Guo, L. (2008). Development of Left-Turn Operations Guidelines at Signalized Intersections, Report No: TxDOT 0-5840-1 for Texas Department of Transportation (TxDOT).

Zhang, L., Prevedouros, P. D., & Li, H. (2005). Warrants for Protected Left-Turn Phasing. *ASCE Journal of Transportation Engineering*.

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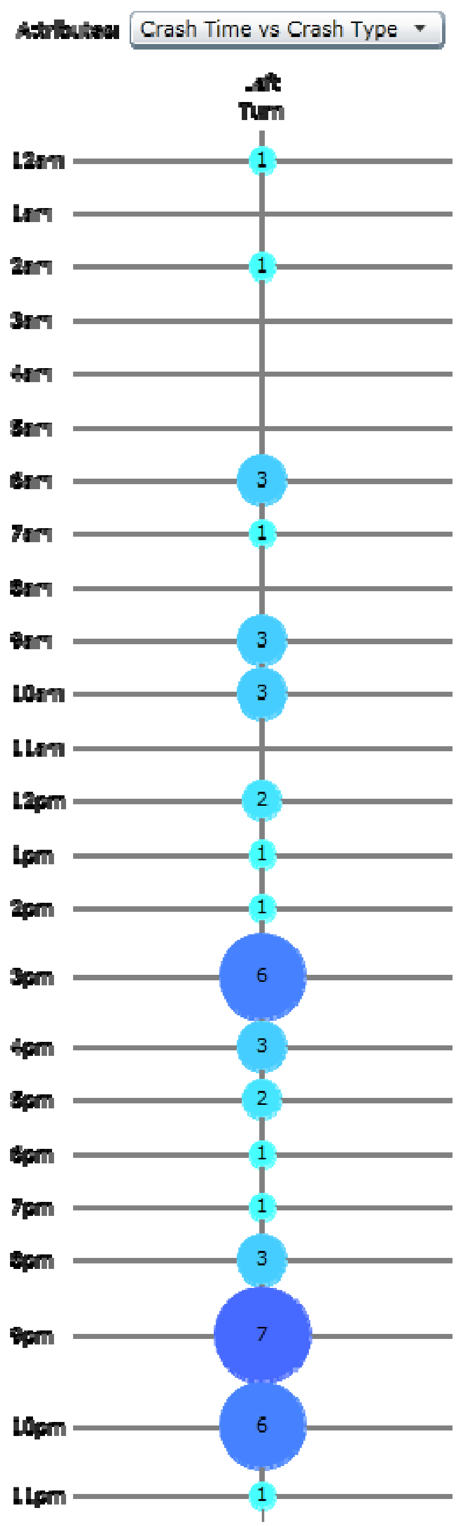
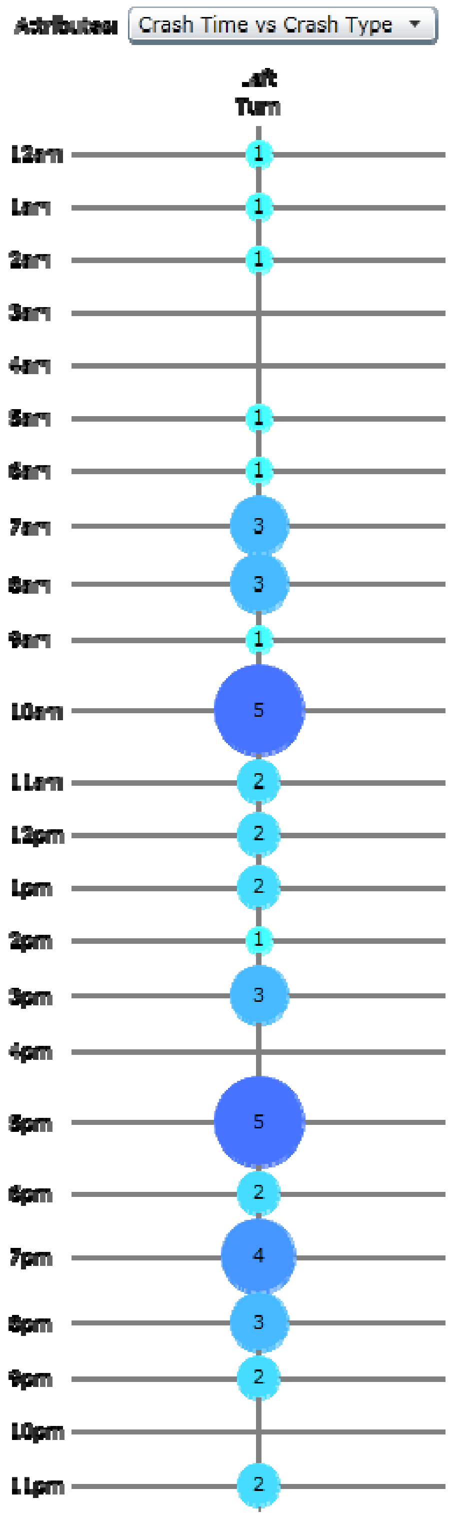
APPENDICES

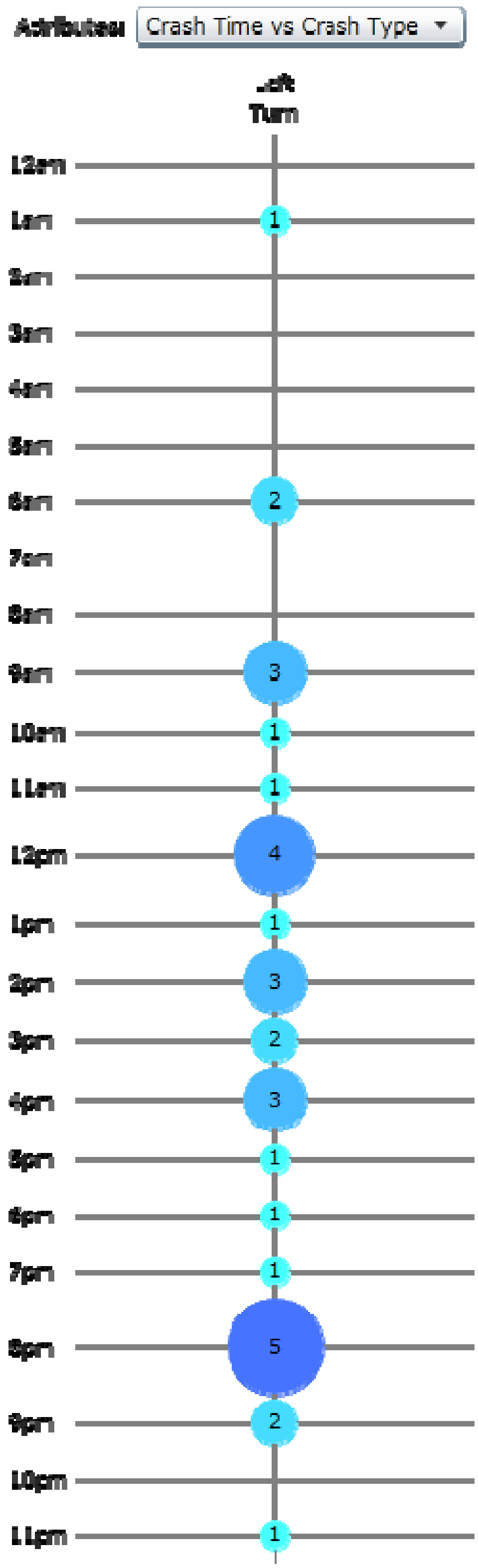
APPENDIX A: FIVE YEAR LEFT-TURN CRASHES BY TIME OF DAY



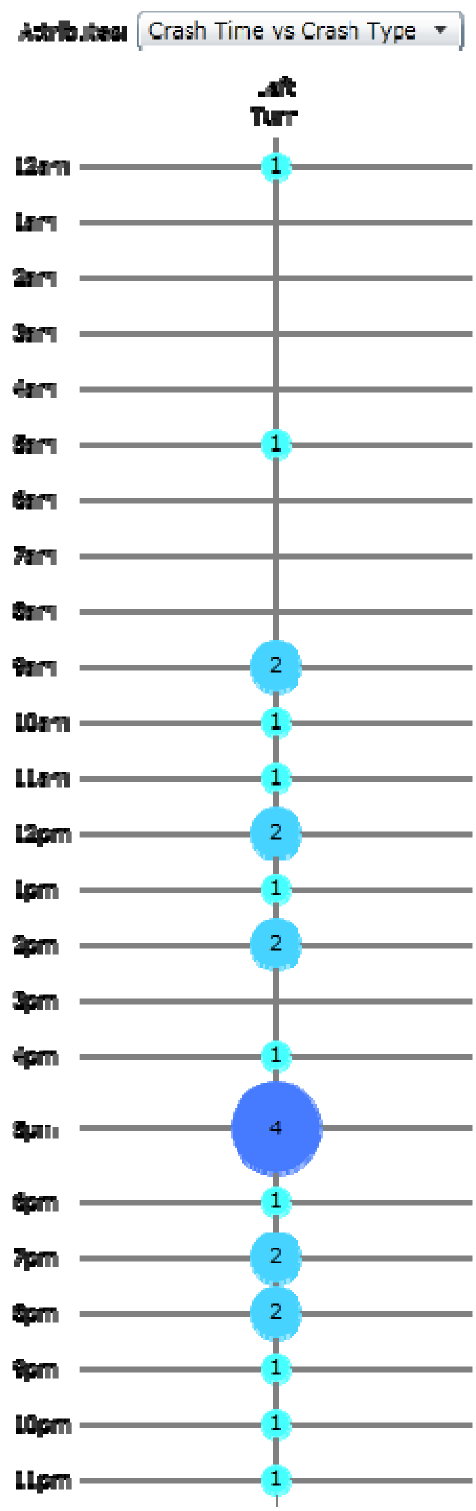
Avalon Park Blvd. @ Waterford Chase Pkwy (Residential)



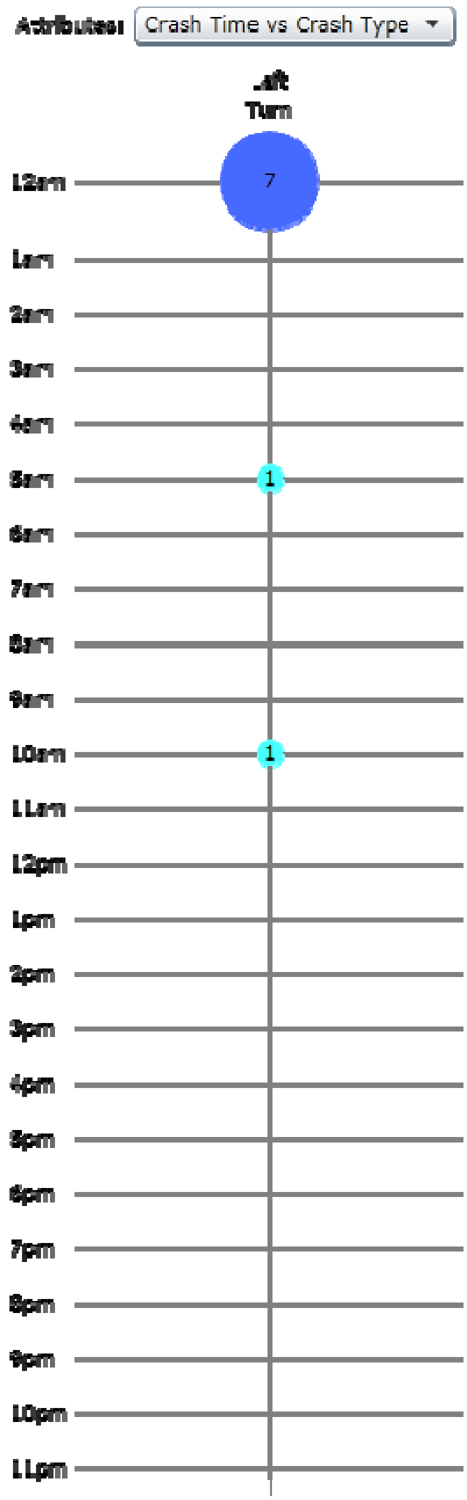
Dean Road @ SR 408 off Ramp (Ramp)



SR 50 @ Wal-Mart Entrance (Commercial)



Lake Underhill Road @ Chickasaw Trial (Skewed)



SR 50 @ Mills Avenue (Downtown)

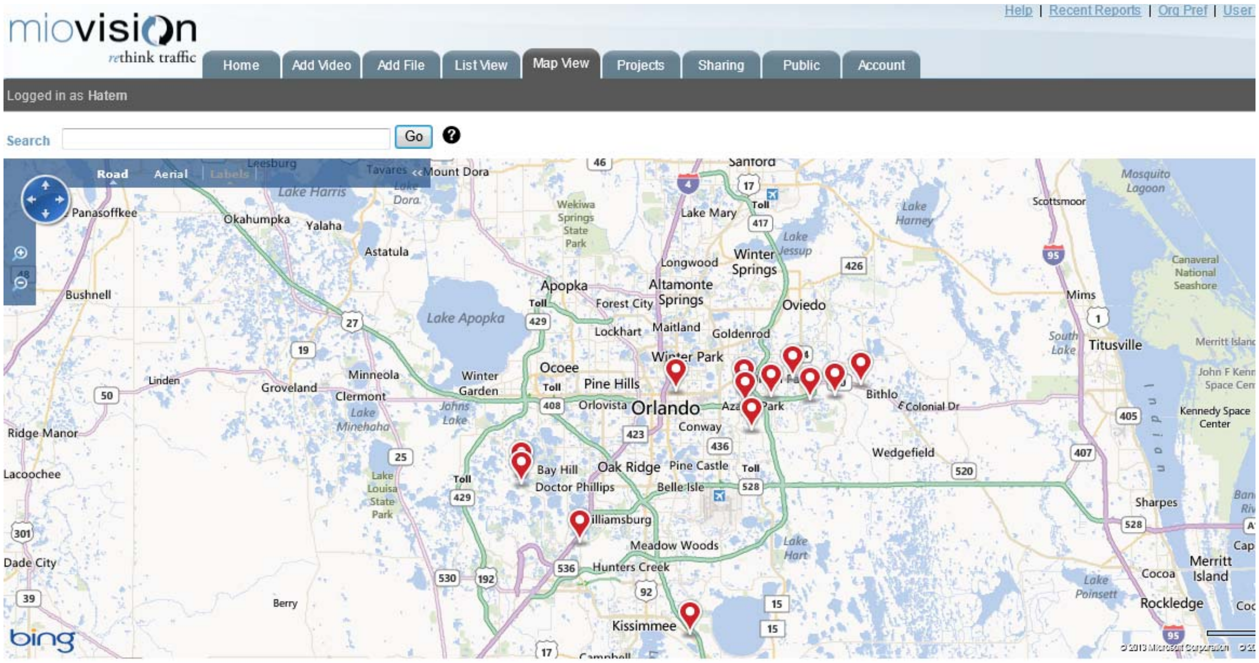
APPENDIX B: PICTURES OF VCU AND ITS COMPONENTS

Scout VCU Unit attached to an electric pole with camera at 20 feet high
@ Chickasaw Trail and Valencia College lane Intersection

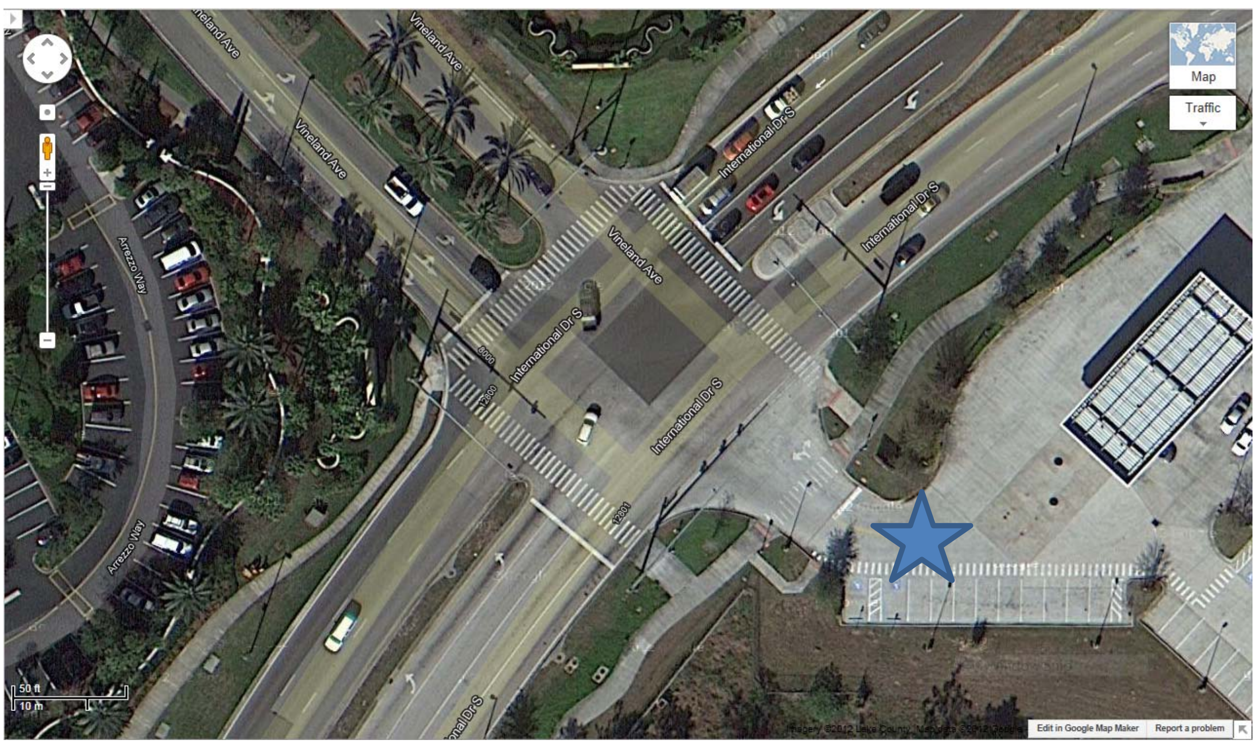
VCU Unit with Straps

VCU Camera at height 20 feet

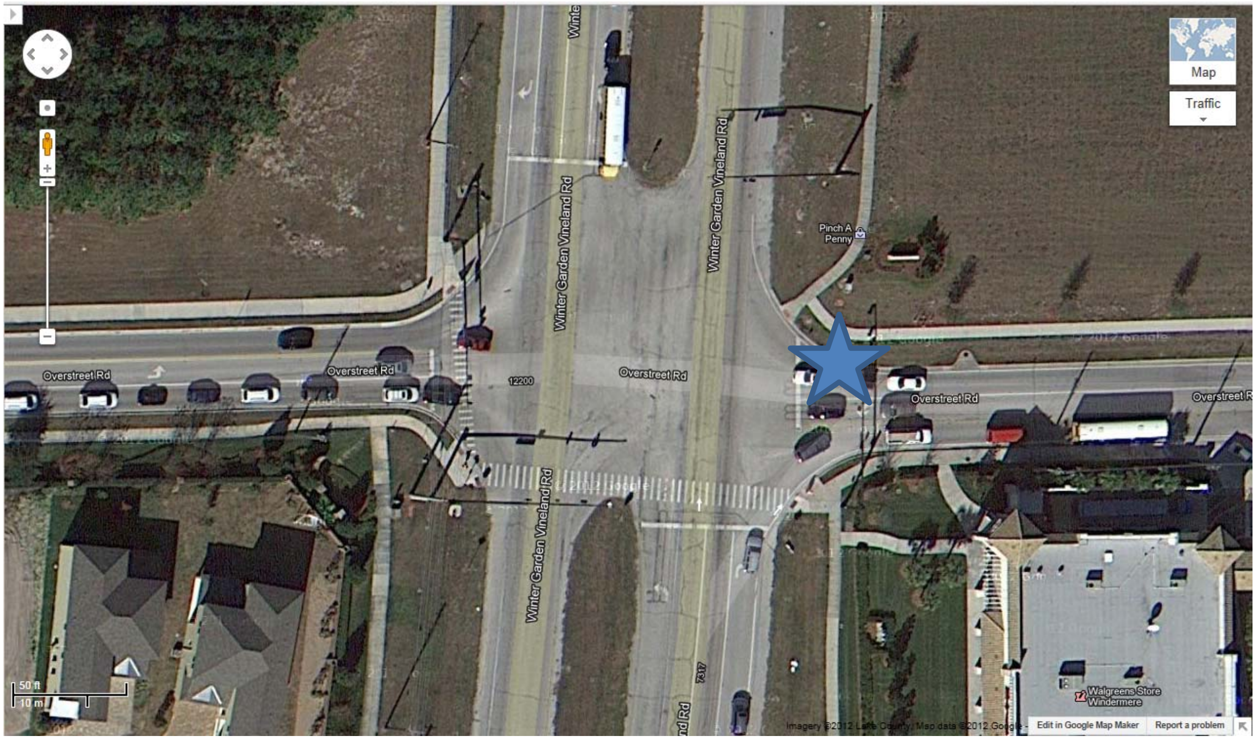
APPENDIX C: INTERSECTION LOCATIONS AND VCU POSITION



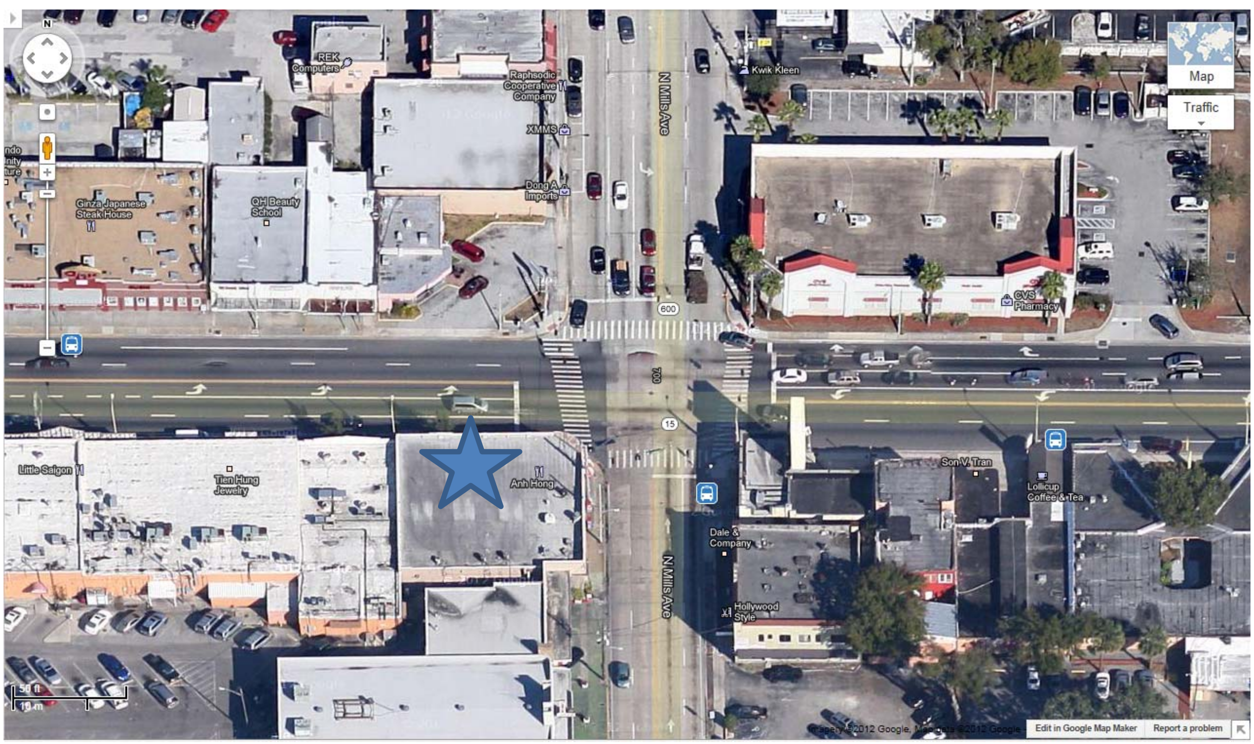
FYA Intersection Locations



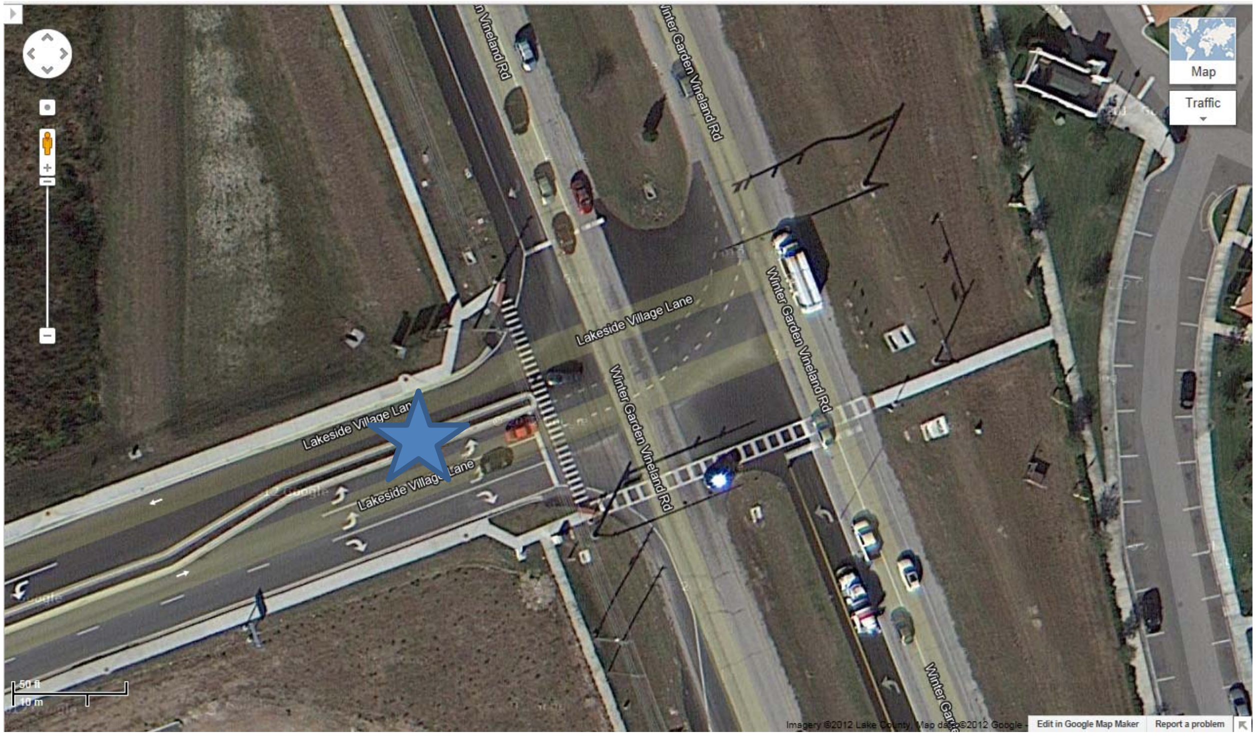
Sunday, November 18, 2012- International Drive South at Vineland Avenue



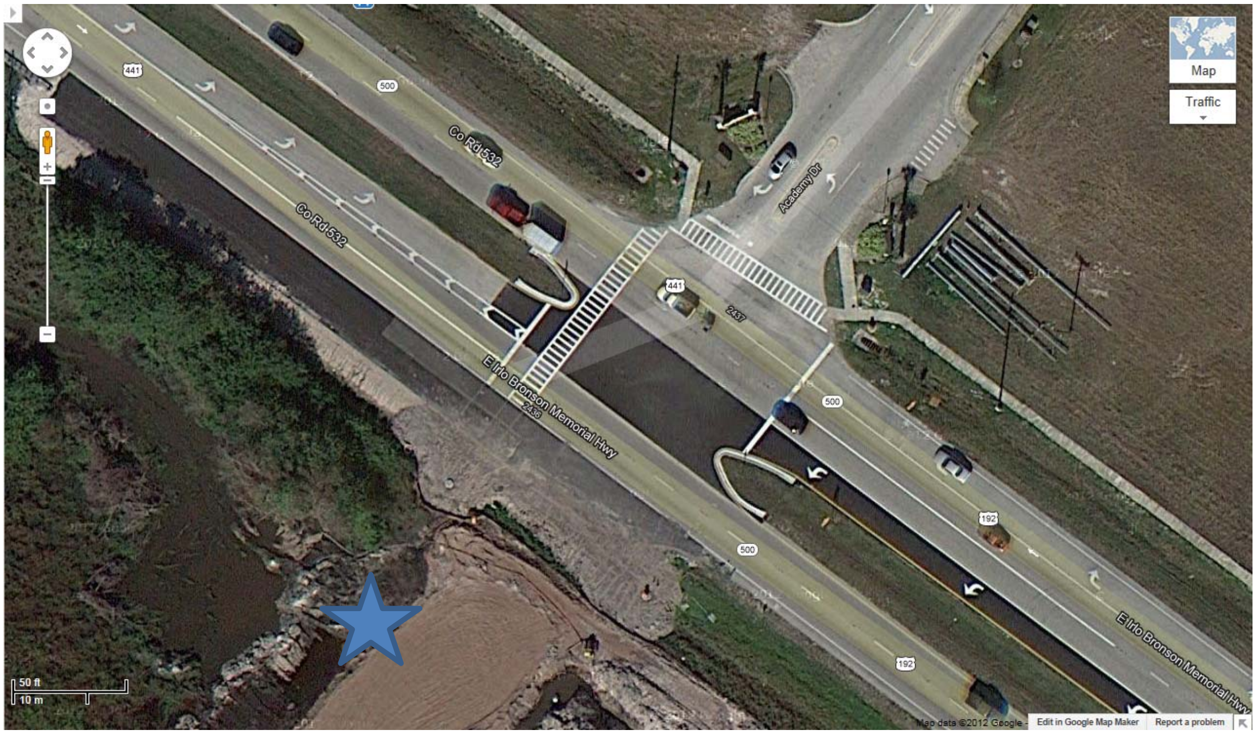
Monday, November 19, 2012- CR 535 at Overstreet Road



Tuesday, November 20, 2012- SR 50 at Mills Avenue



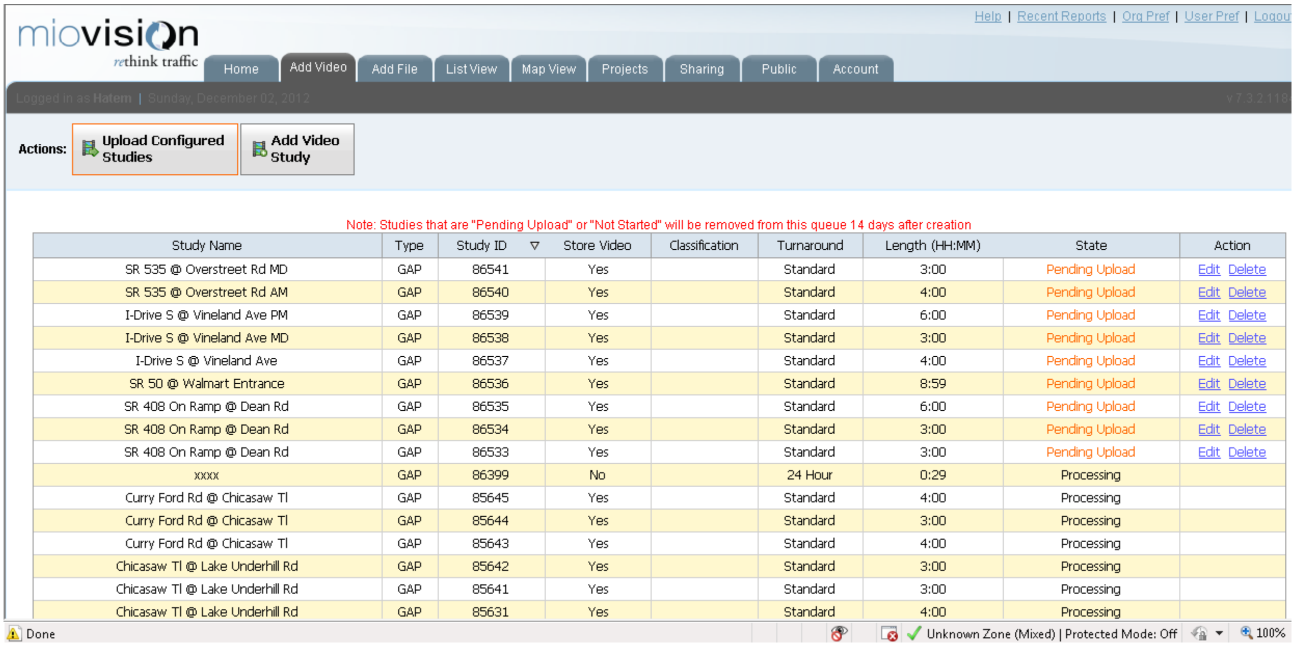
Wednesday, November 21, 2012- CR 535 at Lakeside Village Lane
FY on northbound CR 535 approach only



Monday, November 26, 2012- US 192 at Academy Drive

This is a fairly new signal, the only thing missing from the map is the northbound approach but the geometry is 1 LT and 1 TH/RT Lane. From the eastbound approach add the under construction dedicated RT lane. FY on both US 192 approaches

APPENDIX D: MIOUPLOADER TOOL SNAPSHOT



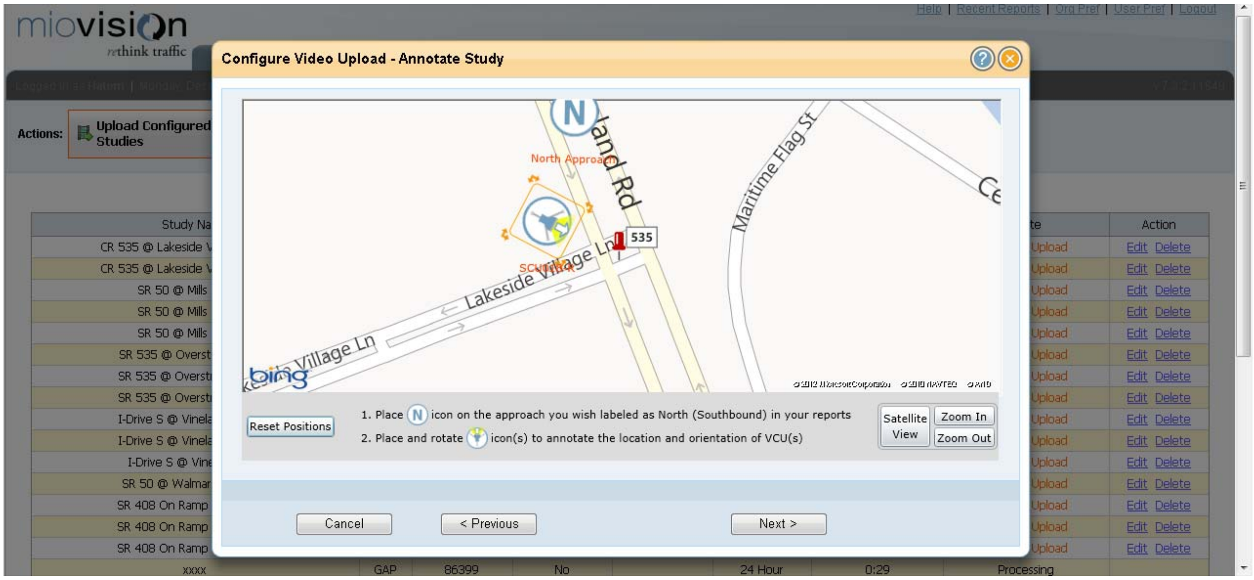
Note: Studies that are "Pending Upload" or "Not Started" will be removed from this queue 14 days after creation

Study Name	Type	Study ID ▽	Store Video	Classification	Turnaround	Length (HH:MM)	State	Action
SR 535 @ Overstreet Rd MD	GAP	86541	Yes		Standard	3:00	Pending Upload	Edit Delete
SR 535 @ Overstreet Rd AM	GAP	86540	Yes		Standard	4:00	Pending Upload	Edit Delete
I-Drive S @ Vineland Ave PM	GAP	86539	Yes		Standard	6:00	Pending Upload	Edit Delete
I-Drive S @ Vineland Ave MD	GAP	86538	Yes		Standard	3:00	Pending Upload	Edit Delete
I-Drive S @ Vineland Ave	GAP	86537	Yes		Standard	4:00	Pending Upload	Edit Delete
SR 50 @ Walmart Entrance	GAP	86536	Yes		Standard	8:59	Pending Upload	Edit Delete
SR 408 On Ramp @ Dean Rd	GAP	86535	Yes		Standard	6:00	Pending Upload	Edit Delete
SR 408 On Ramp @ Dean Rd	GAP	86534	Yes		Standard	3:00	Pending Upload	Edit Delete
SR 408 On Ramp @ Dean Rd	GAP	86533	Yes		Standard	3:00	Pending Upload	Edit Delete
xxxx	GAP	86399	No		24 Hour	0:29	Processing	
Curry Ford Rd @ Chicasaw Tl	GAP	85645	Yes		Standard	4:00	Processing	
Curry Ford Rd @ Chicasaw Tl	GAP	85644	Yes		Standard	3:00	Processing	
Curry Ford Rd @ Chicasaw Tl	GAP	85643	Yes		Standard	4:00	Processing	
Chicasaw Tl @ Lake Underhill Rd	GAP	85642	Yes		Standard	3:00	Processing	
Chicasaw Tl @ Lake Underhill Rd	GAP	85641	Yes		Standard	3:00	Processing	
Chicasaw Tl @ Lake Underhill Rd	GAP	85631	Yes		Standard	4:00	Processing	

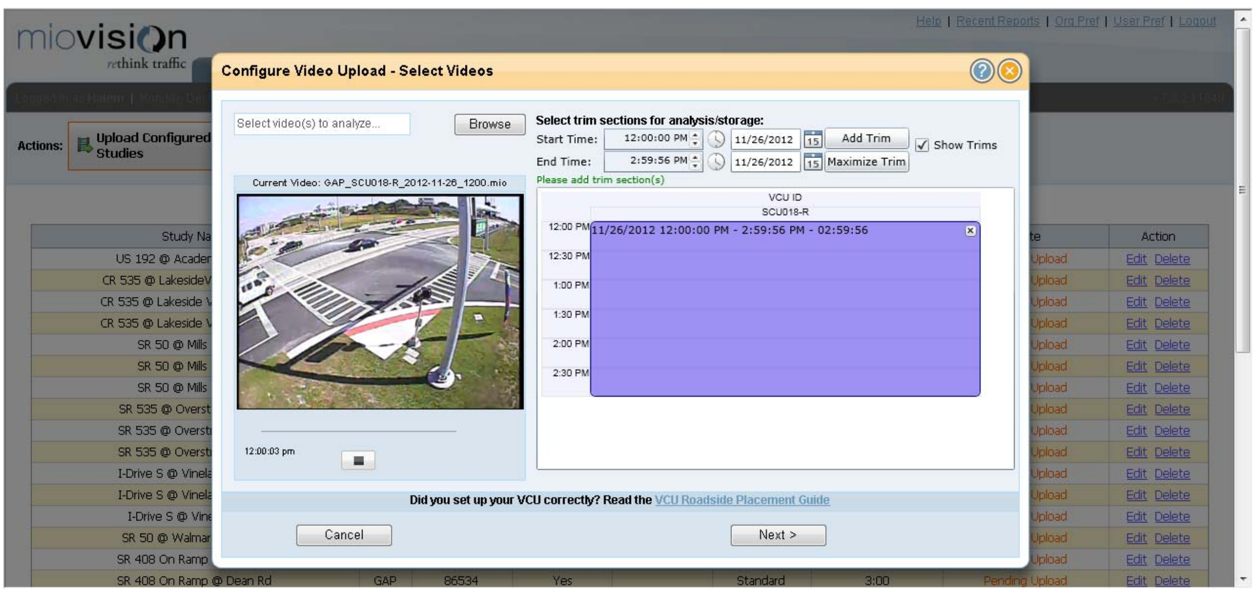
Note: Studies that are "Pending Upload" or "Not Started" will be removed from this queue 14 days after creation

Study Name	Type	Study ID ▽	Store Video	Classification	Turnaround	Length (HH:MM)	State	Action
SR 535 @ Overstreet Rd MD	GAP	86541	Yes		Standard	3:00	Pending Upload	Edit Delete
SR 535 @ Overstreet Rd AM	GAP	86540	Yes		Standard	4:00	Pending Upload	Edit Delete
I-Drive S @ Vineland Ave PM	GAP	86539	Yes		Standard	6:00	Pending Upload	Edit Delete
I-Drive S @ Vineland Ave MD	GAP	86538	Yes		Standard	3:00	Pending Upload	Edit Delete
I-Drive S @ Vineland Ave	GAP	86537	Yes		Standard	4:00	Pending Upload	Edit Delete
SR 50 @ Walmart Entrance	GAP	86536	Yes		Standard	8:59	Pending Upload	Edit Delete
SR 408 On Ramp @ Dean Rd	GAP	86535	Yes		Standard	6:00	Pending Upload	Edit Delete
SR 408 On Ramp @ Dean Rd	GAP	86534	Yes		Standard	3:00	Pending Upload	Edit Delete
SR 408 On Ramp @ Dean Rd	GAP	86533	Yes		Standard	3:00	Pending Upload	Edit Delete
xxxx	GAP	86399	No		24 Hour	0:29	Processing	
Curry Ford Rd @ Chicasaw Tl	GAP	85645	Yes		Standard	4:00	Processing	
Curry Ford Rd @ Chicasaw Tl	GAP	85644	Yes		Standard	3:00	Processing	
Curry Ford Rd @ Chicasaw Tl	GAP	85643	Yes		Standard	4:00	Processing	
Chicasaw Tl @ Lake Underhill Rd	GAP	85642	Yes		Standard	3:00	Processing	
Chicasaw Tl @ Lake Underhill Rd	GAP	85641	Yes		Standard	3:00	Processing	
Chicasaw Tl @ Lake Underhill Rd	GAP	85631	Yes		Standard	4:00	Processing	
Chicasaw Trial @ Valencia Ln	GAP	85630	Yes		Standard	5:00	Processing	
Woodbury Rd @ Lake Underhill Rd 3	GAP	85629	Yes		Standard	11:00	REQUIRES FEEDBACK	
Woodbury Rd @ Lake Underhill Rd 2	GAP	85628	Yes		Standard	1:47	REQUIRES FEEDBACK	
Woodbury Rd @ Lake Underhill Rd	GAP	85627	Yes		Standard	9:14	REQUIRES FEEDBACK	
Avalon Park Blvd @ Waterford Chase Pkwy 2	GAP	85624	Yes		Standard	10:00	REQUIRES FEEDBACK	
Avalon Park Blvd @ Waterford Chase Pkwy	GAP	85623	Yes		Standard	0:46	REQUIRES FEEDBACK	

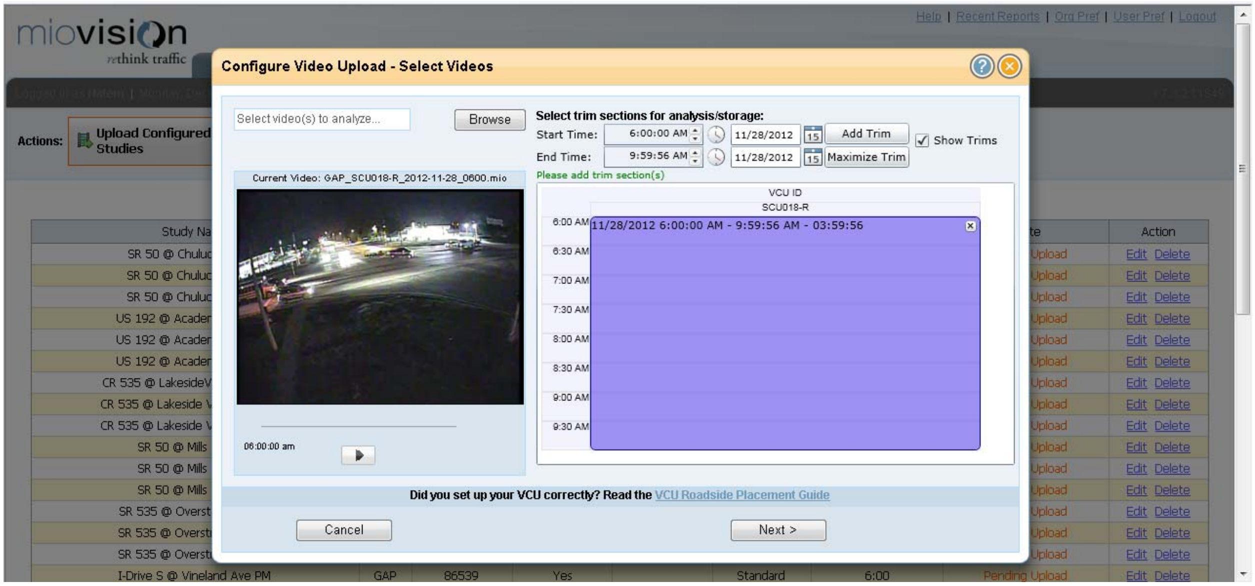
APPENDIX E: TRAFFIC DATA ONLINE (TDO) UPLOADS



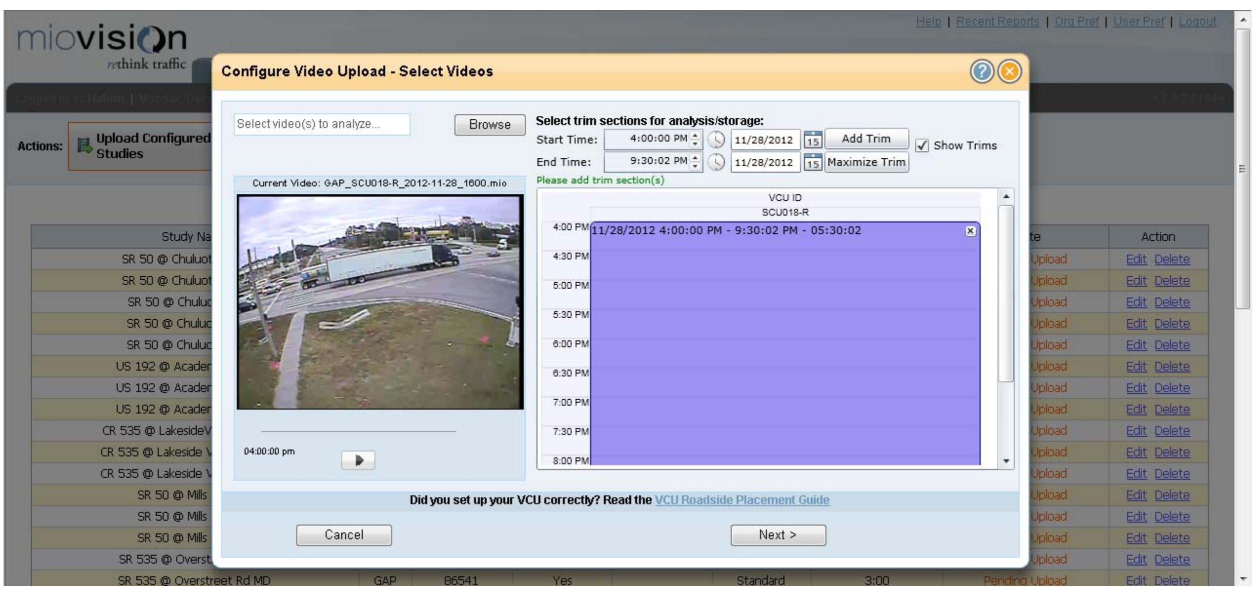
Intersection Location & VCU Position on Traffic Data Online (TDO) Website



Uploading data collected from 12:00 – 3:00 pm



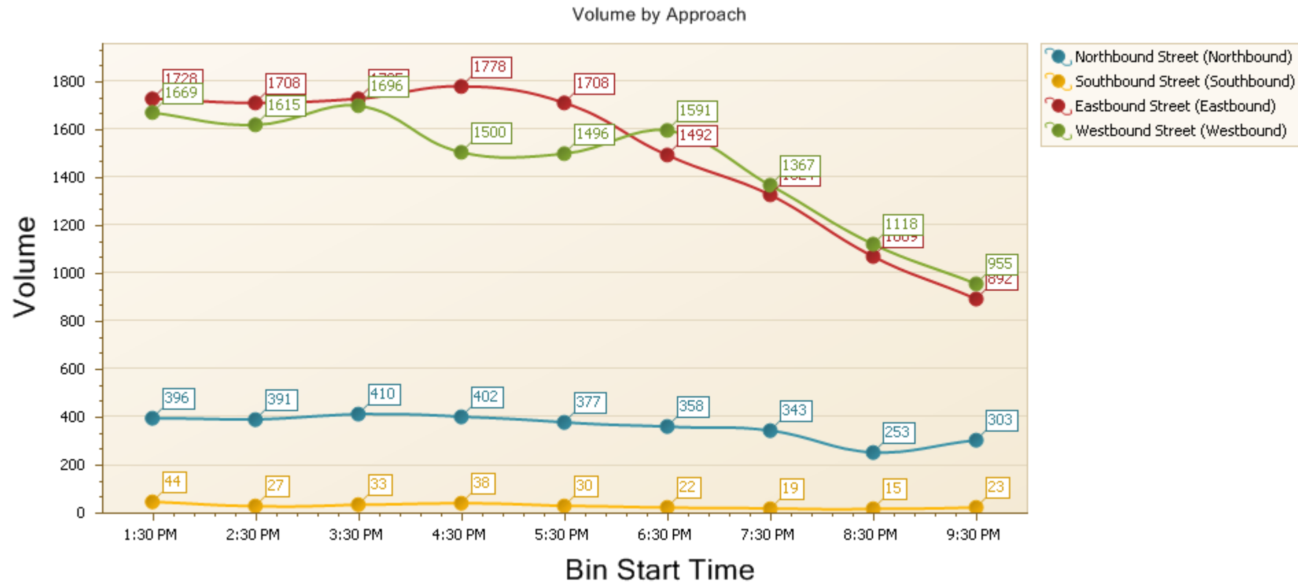
Uploading data collected from 6:00 – 10:00 am



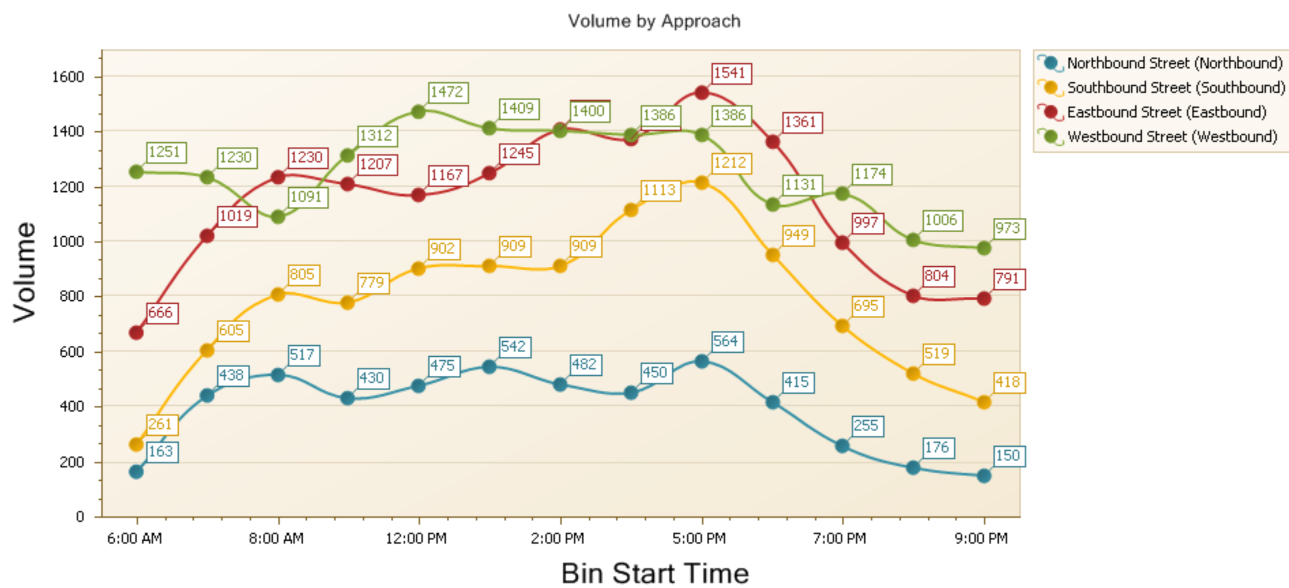
Uploading data collected from 4:00 – 9:30 pm

APPENDIX F: TMC CHARTS AND DATA COLLECTION ANALYSIS

SR 50 @ Walmart Entrance Sat (ID 101150)

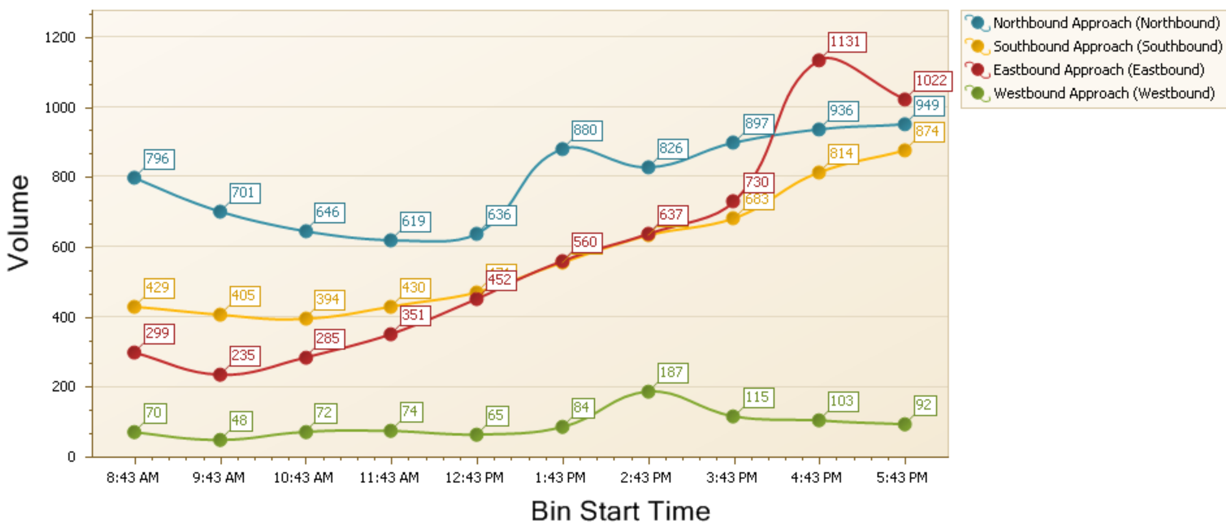


SR 50 @ Mills Ave (ID 101153)



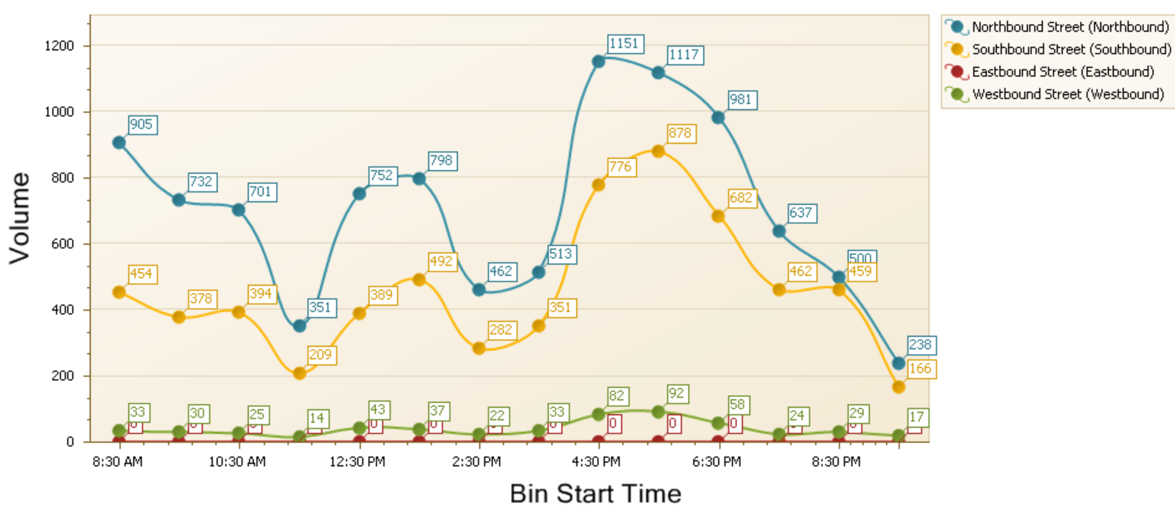
Avalon Park Blvd @ Waterford Chase Pkwy (ID 121321)

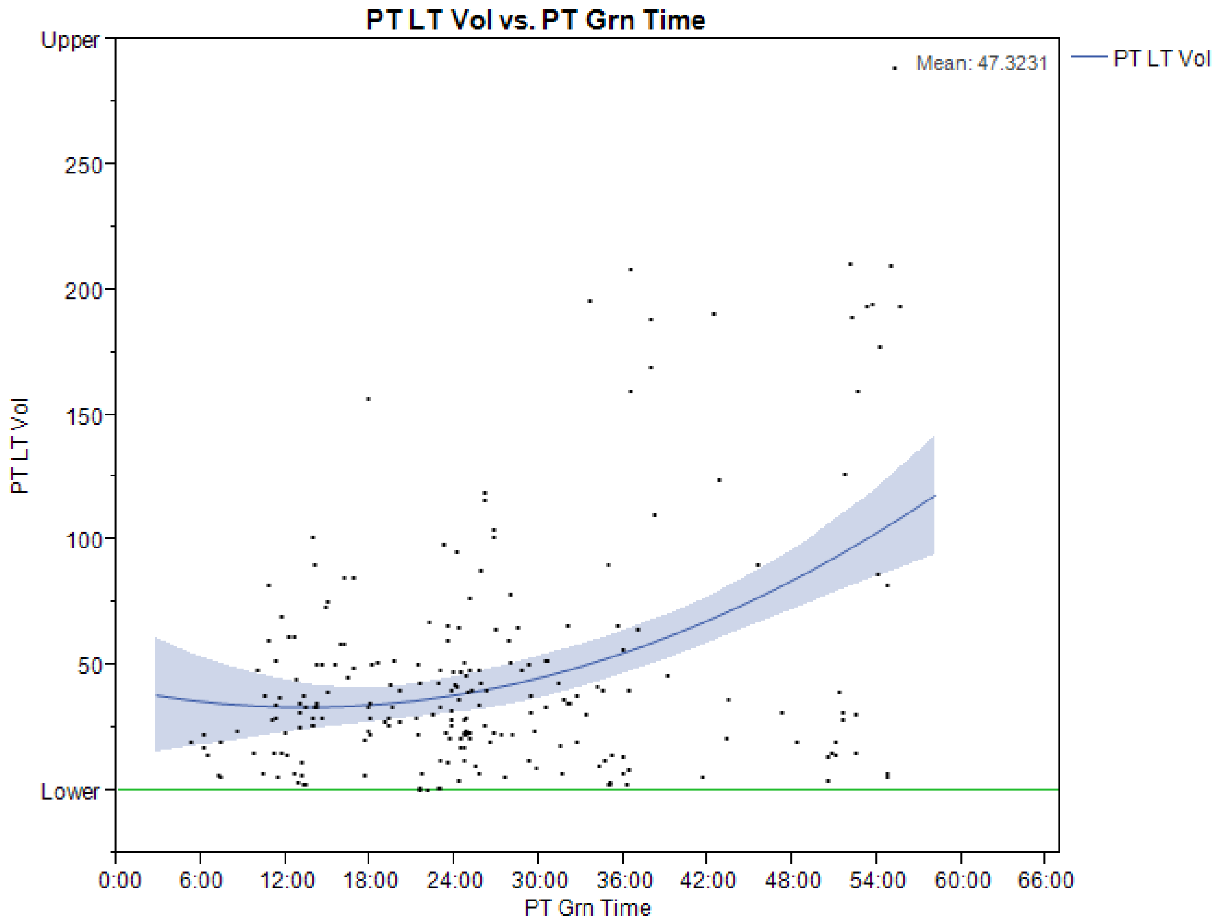
Volume by Approach



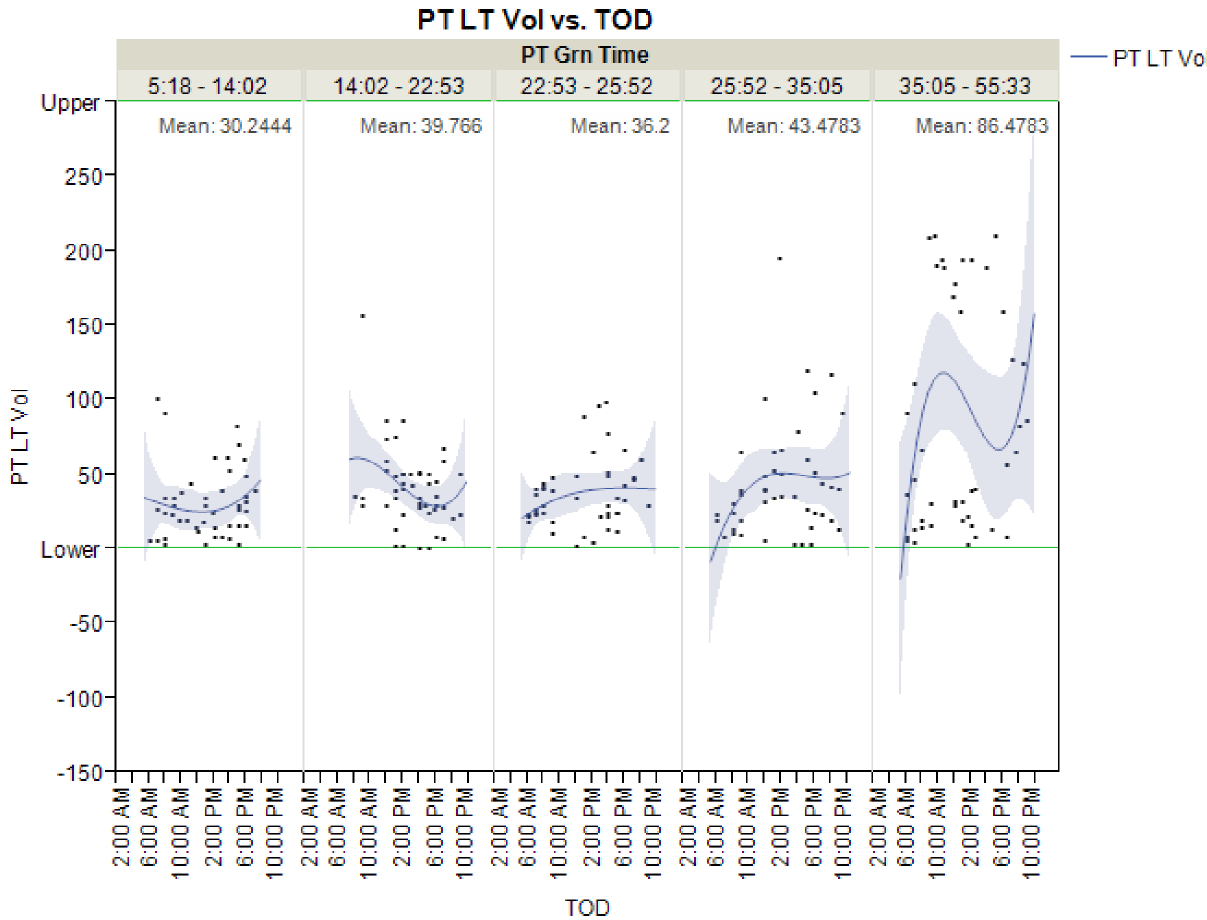
SR 408 On Ramp @ Dean Rd (ID 101148)

Volume by Approach

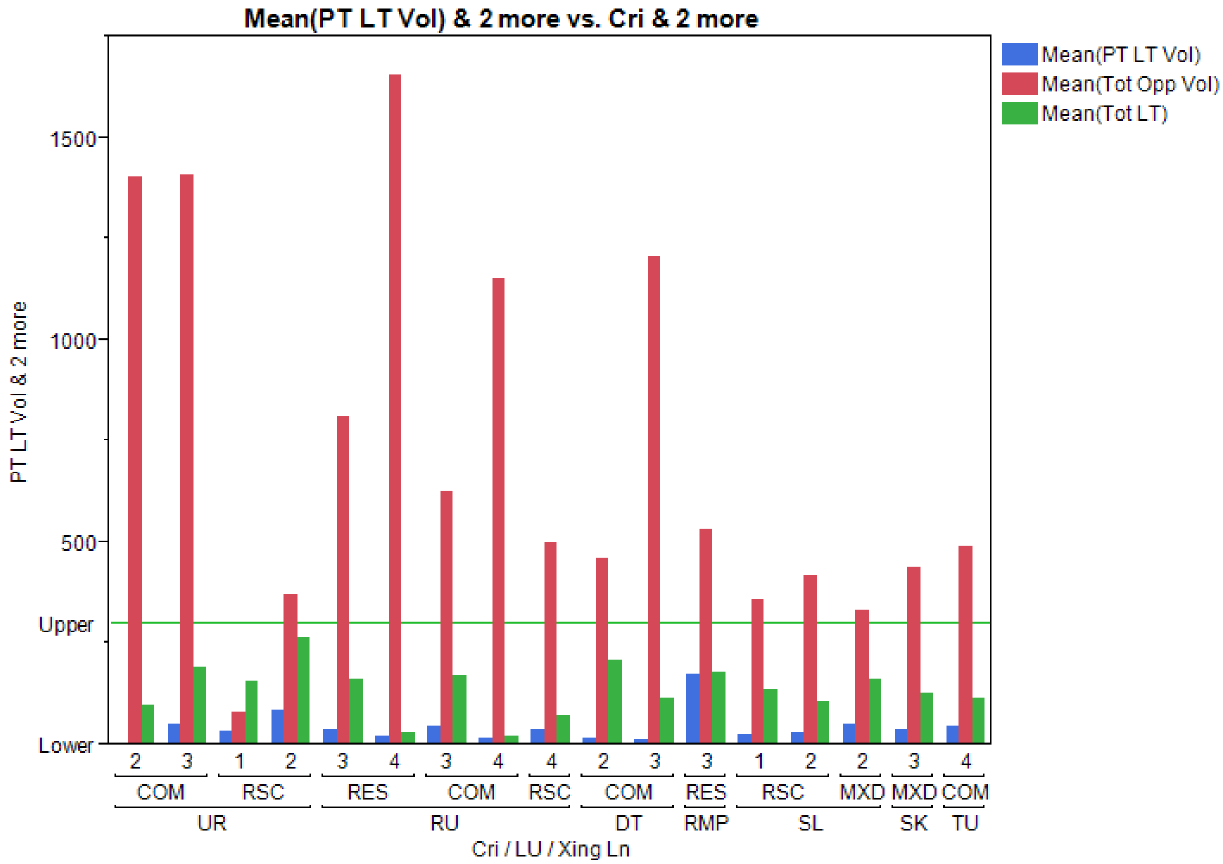




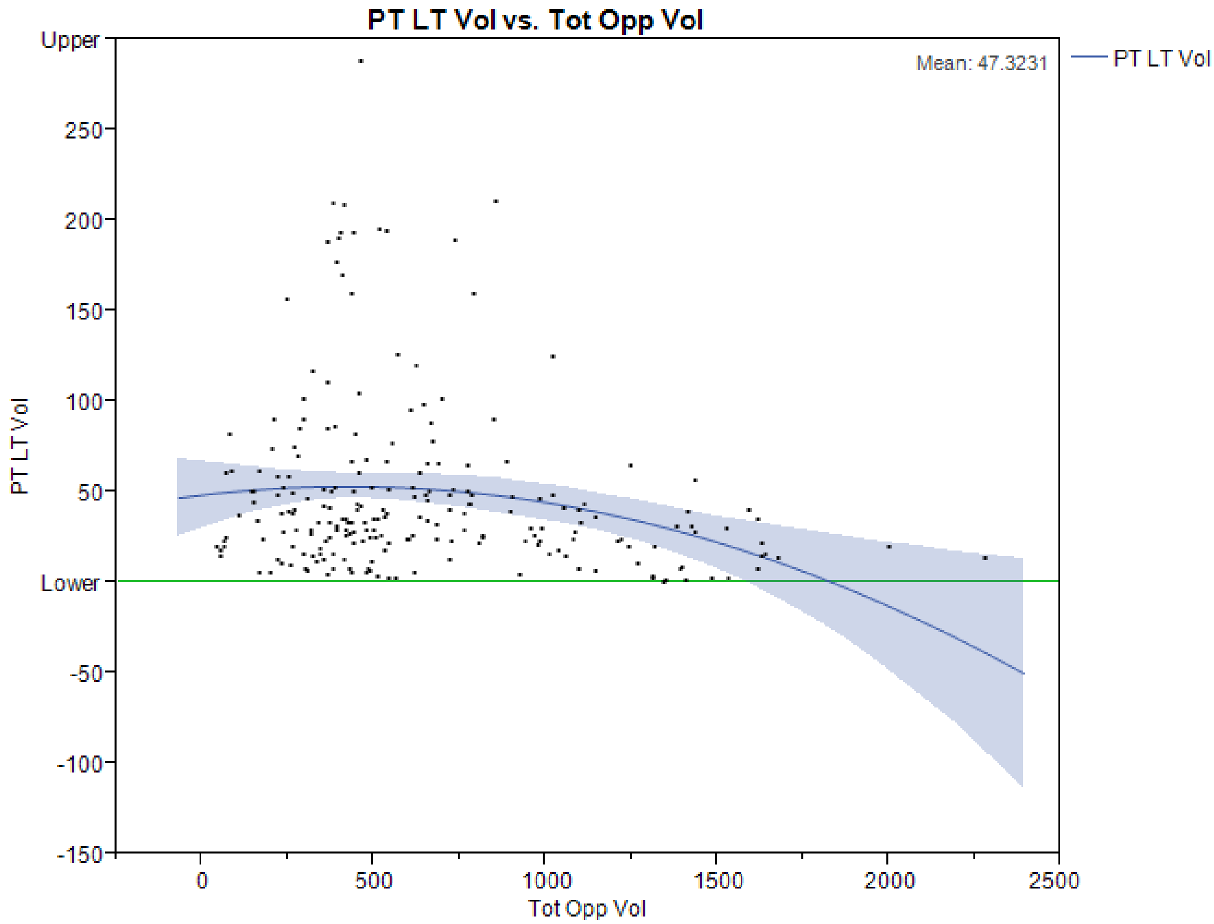
Permitted Left versus Permitted Green Times



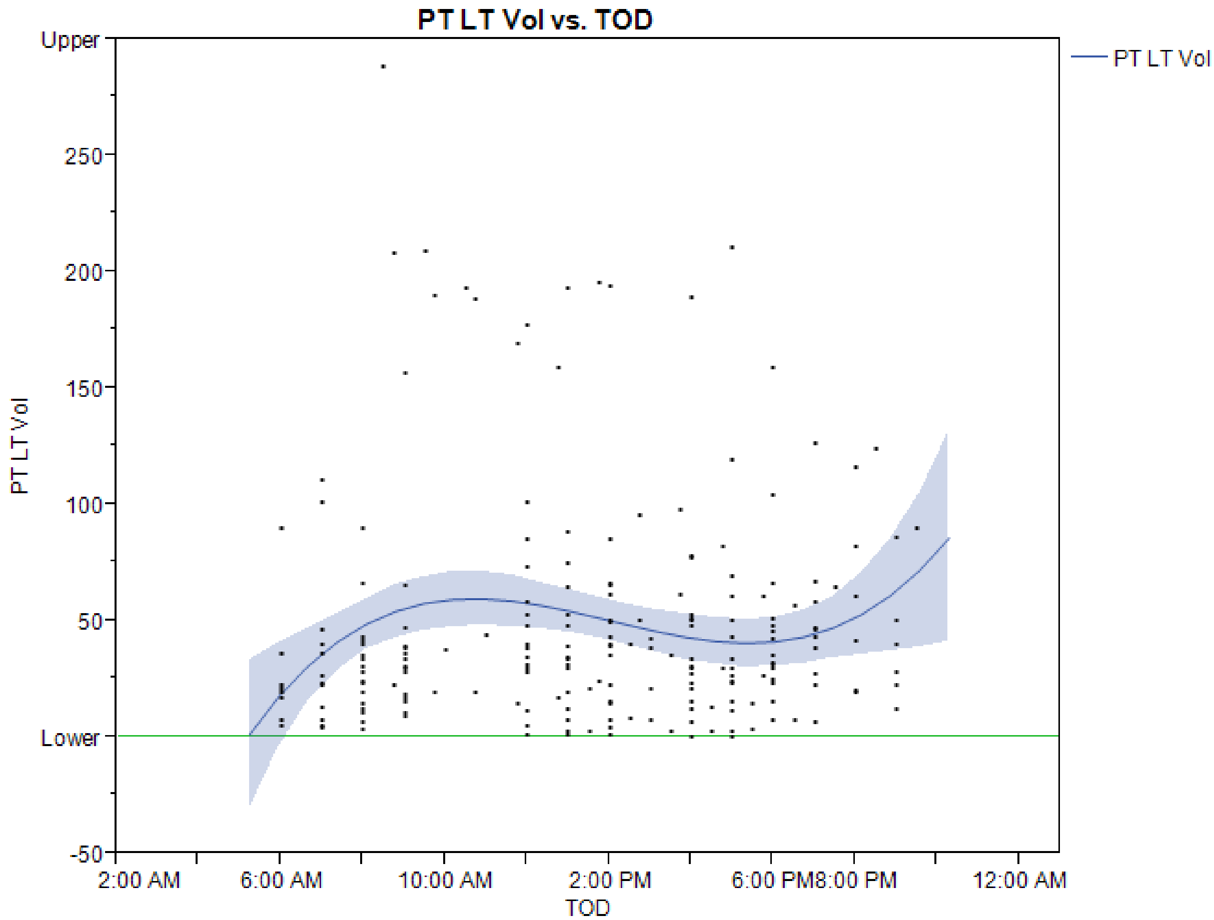
Permitted Left versus Time of Day by Permitted Green Times



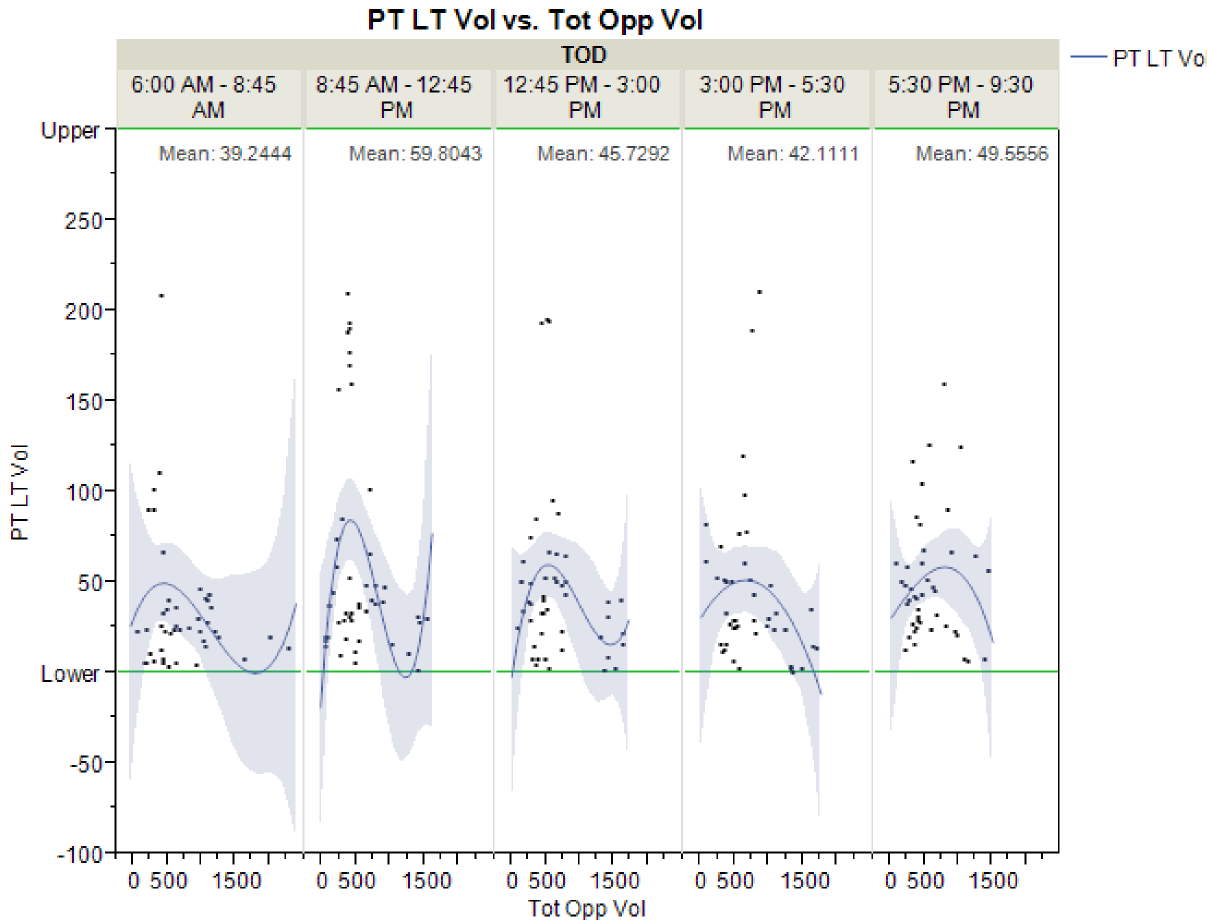
Permitted Left, Total Opposing, & Total Left
by
Land use, Criteria & Crossing Lanes



Permitted Left versus Total Opposing Volume



Permitted Left by Time of Day



Permitted versus Total Opposing by Time of Day

APPENDIX G: SYNCHRO LOS OUTPUT AND PERMITTED LT ADJ. FACTORS

APPENDIX H: MODEL STEPWISE AND POISSON REGRESSION ANALYSIS

Stepwise Fit for LT Vol

Stepwise Regression Control

Go | Stop | Step

SSE	DFE	RMSE	RSquare	RSquare Adj	Cp	p	AICc	BIC
919.09842	13	8.408322	0.9004	0.8468	6.9779756	8	173.3153	166.3524

Current Estimates

Lock	Entered	Parameter	Estimate	nDF	SS	"F Ratio"	"Prob>F"
✓	✓	Intercept	154.471395	1	0	0.000	1
☐	✓	Time of Day	-0.0024791	4	1936.79	6.849	0.00341
☐	☐	Crossing Lanes	0	0	0	.	.
☐	☐	Posted Speed	0	0	0	.	.
☐	☐	LT Crashes	0	0	0	.	.
☐	✓	PT Green Time	-0.1339782	2	3695.753	26.137	2.79e-5
☐	✓	Opposing Vol	0.08802754	2	1964.926	13.896	0.00059
☐	✓	Hour{PK-OFF}	-21.082268	2	399.2127	2.823	0.09588
☐	☐	Time of Day*Crossing Lanes	0	0	0	.	.
☐	☐	Time of Day*Posted Speed	0	0	0	.	.
☐	☐	Time of Day*LT Crashes	0	0	0	.	.
☐	✓	Time of Day*PT Green Time	3.68581e-6	1	720.1471	10.186	0.00708
☐	✓	Time of Day*Opposing Vol	-3.2012e-6	1	441.3115	6.242	0.02667
☐	✓	Time of Day*Hour{PK-OFF}	0.00055389	1	267.1905	3.779	0.07386
☐	☐	Crossing Lanes*Posted Speed	0	0	0	.	.
☐	☐	Crossing Lanes*LT Crashes	0	0	0	.	.
☐	☐	Crossing Lanes*PT Green Time	0	0	0	.	.
☐	☐	Crossing Lanes*Opposing Vol	0	0	0	.	.
☐	☐	Crossing Lanes*Hour{PK-OFF}	0	0	0	.	.
☐	☐	Posted Speed*LT Crashes	0	0	0	.	.
☐	☐	Posted Speed*PT Green Time	0	0	0	.	.
☐	☐	Posted Speed*Opposing Vol	0	0	0	.	.
☐	☐	Posted Speed*Hour{PK-OFF}	0	0	0	.	.
☐	☐	LT Crashes*PT Green Time	0	0	0	.	.
☐	☐	LT Crashes*Opposing Vol	0	0	0	.	.
☐	☐	LT Crashes*Hour{PK-OFF}	0	0	0	.	.
☐	☐	PT Green Time*Opposing Vol	0	0	0	.	.
☐	☐	PT Green Time*Hour{PK-OFF}	0	1	3.139062	0.041	0.84269
☐	☐	Opposing Vol*Hour{PK-OFF}	0	0	0	.	.

Stepwise Regression Analysis

Parameter Estimates

Term	Estimate	Std Error	L-R ChiSquare	Prob>ChiSq	Lower CL	Upper CL
Intercept	-4.511152	2.550856	3.138817	0.0764	-9.523653	0.4786425
TOD(21600,75600)	-2.167596	1.2551097	2.980254	0.0843	-4.628263	0.2935791
PT Grn Time(5,55)	0.185134	0.0473249	15.357765	<.0001*	0.0924812	0.2780308
Speed(25,55)	0.2498146	2.201501	0.0128769	0.9097	-4.064989	4.5673235
Tot LT(0,400)	-0.185151	2.0127496	0.008462	0.9267	-4.1309	3.7605845
LT Tr%(0,0.11)	-0.11607	1.7982894	0.0041666	0.9485	-3.6497	3.4035717
Tot Opp Vol(0,3000)	-8.768002	2.5127837	12.336321	0.0004*	-13.71788	-3.862997
Xing Ln[1]	-1.181692	0.2609467	20.374373	<.0001*	-1.692951	-0.669734
Xing Ln[2]	-0.54138	0.1723597	9.9167406	0.0016*	-0.88019	-0.204199
Xing Ln[3]	1.2580239	0.2313336	30.483297	<.0001*	0.8077678	1.7154413
LT Crashes(0,7)	2.7496766	1.8940535	2.1182744	0.1456	-0.950389	6.4778371
Cri[UR]	0.2086842	0.3761842	0.3074564	0.5792	-0.529956	0.945079
Cri[RU]	-0.024388	1.5318078	0.0002535	0.9873	-3.019512	2.9869647
Cri[DT]	0.7231849	0.492294	2.1568937	0.1419	-0.242075	1.6881266
Cri[RMP]	-0.217428	0.6043422	0.1294675	0.7190	-1.403343	0.9668443
Cri[SL]	0.6105079	0.3762213	2.6167449	0.1057	-0.12973	1.3455003
Cri[SK]	-1.682039	0.3926535	18.813071	<.0001*	-2.457564	-0.917398
LU[RES]	-0.372383	0.2659271	1.9475424	0.1629	-0.892185	0.1515238
LU[COM]	-0.539683	0.2124125	6.4912722	0.0108*	-0.957124	-0.124279
LU[RSC]	0.4508262	0.2081708	4.7051487	0.0301*	0.0434308	0.8598326
Gmtry[3L]	-0.208805	0.1628103	1.6387886	0.2005	-0.527613	0.1113297
TOD*PT Grn Time	-0.010678	0.0146356	0.5327669	0.4654	-0.039406	0.0179734
TOD*Speed	2.3515004	1.0011057	5.5397253	0.0186*	0.3928139	4.318492
TOD*Tot LT	1.5074276	1.1047619	1.8593893	0.1727	-0.660105	3.6718715
TOD*LT Tr%	-0.850175	0.9458531	0.810333	0.3680	-2.711461	0.9981687
TOD*Tot Opp Vol	-3.888121	1.3605324	8.2571276	0.0041*	-6.568268	-1.232129
TOD*LT Crashes	0.3905557	1.0049638	0.1511991	0.6974	-1.574671	2.3673896
PT Grn Time*Speed	-0.012158	0.024415	0.2480362	0.6185	-0.060045	0.0356869
PT Grn Time*Tot LT	0.0302338	0.0243159	1.5494249	0.2132	-0.017346	0.0779949
PT Grn Time*LT Tr%	0.0411035	0.0246287	2.7862259	0.0951	-0.00716	0.0894018
PT Grn Time*Tot Opp Vol	0.1086099	0.0321495	11.374359	0.0007*	0.0455451	0.1715927
PT Grn Time*LT Crashes	0.0249893	0.0193019	1.6760598	0.1954	-0.012846	0.0628341
Speed*Tot LT	0.5466336	1.5132122	0.1304116	0.7180	-2.424908	3.5081668
Speed*LT Tr%	-0.122199	1.481893	0.0067984	0.9343	-3.021417	2.7911997
Speed*Tot Opp Vol	-0.003319	2.3842443	1.9373e-6	0.9989	-4.6794	4.6694785
Speed*LT Crashes	-3.846918	1.831099	4.4111003	0.0357*	-7.436915	-0.257121
Tot LT*LT Tr%	2.5178419	1.7611224	2.0364322	0.1536	-0.943012	5.9629139
Tot LT*Tot Opp Vol	-0.708222	2.3530318	0.090603	0.7634	-5.323344	3.9025013
Tot LT*LT Crashes	-0.547689	1.3374029	0.1677789	0.6821	-3.172748	2.07144
LT Tr%*Tot Opp Vol	-0.697137	2.1376642	0.1063802	0.7443	-4.892562	3.4915754
LT Tr%*LT Crashes	2.246157	1.7135165	1.7274146	0.1887	-1.09983	5.6217456
Tot Opp Vol*LT Crashes	2.5907507	2.2955244	1.2832025	0.2573	-1.881138	7.1242357
TOD*PT Grn Time*Speed	-0.001859	0.0085347	0.0474051	0.8276	-0.018562	0.0149033
TOD*PT Grn Time*Tot LT	0.00109	0.0051485	0.0448121	0.8323	-0.00901	0.0111753
TOD*PT Grn Time*LT Tr%	-0.013752	0.0097033	2.0082879	0.1564	-0.032773	0.0052692
TOD*PT Grn Time*Tot Opp Vol	-0.004368	0.0140018	0.09724	0.7552	-0.031743	0.0231614
TOD*PT Grn Time*LT Crashes	-0.008221	0.0053852	2.3326018	0.1267	-0.018789	0.0023286
TOD*Speed*Tot LT	-0.773306	0.470289	2.6984934	0.1004	-1.694222	0.1495438
TOD*Speed*LT Tr%	1.3630566	0.5564568	6.0014037	0.0143*	0.2726142	2.4547636
TOD*Speed*Tot Opp Vol	1.2513918	0.8827512	2.0184913	0.1554	-0.473734	2.9882671
TOD*Speed*LT Crashes	0.713528	0.5235077	1.8641202	0.1722	-0.310099	1.7427264
TOD*Tot LT*LT Tr%	0.519444	0.5072615	1.0504987	0.3054	-0.473221	1.5158776
TOD*Tot LT*Tot Opp Vol	0.9171726	1.0681026	0.7395992	0.3898	-1.169585	3.0192724
TOD*Tot LT*LT Crashes	0.0588981	0.3968102	0.0220258	0.8820	-0.720249	0.8355827
TOD*LT Tr%*Tot Opp Vol	-3.347691	1.1585698	8.5590494	0.0034*	-5.643672	-1.09685
TOD*LT Tr%*LT Crashes	1.3607988	0.5594652	5.9677386	0.0146*	0.2681941	2.4622216
TOD*Tot Opp Vol*LT Crashes	-0.994098	0.9359695	1.1322941	0.2873	-2.837568	0.8348508
PT Grn Time*Speed*Tot LT	-0.024594	0.0120923	4.1003828	0.0429*	-0.048208	-0.000793
PT Grn Time*Speed*LT Tr%	-0.015034	0.013507	1.2330019	0.2668	-0.041425	0.0115576
PT Grn Time*Speed*Tot Opp Vol	0.004659	0.0263663	0.0312205	0.8597	-0.047068	0.056329
PT Grn Time*Speed*LT Crashes	0.0072384	0.0148014	0.2388633	0.6250	-0.021853	0.0361944
PT Grn Time*Tot LT*LT Tr%	0.0016795	0.0103842	0.0261672	0.8715	-0.018635	0.0220854
PT Grn Time*Tot LT*Tot Opp Vol	0.0290304	0.0287251	1.0257333	0.3112	-0.027046	0.085588
PT Grn Time*Tot LT*LT Crashes	-0.005626	0.0097722	0.3315324	0.5648	-0.024789	0.0135279
PT Grn Time*LT Tr%*Tot Opp Vol	0.0523981	0.0251648	4.3421637	0.0372*	0.0031123	0.101785
PT Grn Time*LT Tr%*LT Crashes	0.0079619	0.0154331	0.2660027	0.6060	-0.022323	0.0381857
PT Grn Time*Tot Opp Vol*LT Crashes	0.0428976	0.0229961	3.4646925	0.0627	-0.002278	0.0879027
Speed*Tot LT*LT Tr%	-1.890998	0.852316	4.8909966	0.0270*	-3.558064	-0.215817
Speed*Tot LT*Tot Opp Vol	0.5433688	1.1382298	0.2280259	0.6330	-1.68539	2.7778831
Speed*Tot LT*LT Crashes	0.4552794	0.6784708	0.4502296	0.5022	-0.874999	1.7852772
Speed*LT Tr%*Tot Opp Vol	-0.222489	1.3489616	0.0271869	0.8690	-2.858759	2.4323735
Speed*LT Tr%*LT Crashes	-0.201301	0.6930671	0.0842995	0.7716	-1.557079	1.1609483
Speed*Tot Opp Vol*LT Crashes	-4.557324	1.7307657	6.9671902	0.0083*	-7.957468	-1.171474
Tot LT*LT Tr%*Tot Opp Vol	3.3075594	2.1430351	2.3764941	0.1232	-0.899329	7.5044337
Tot LT*LT Tr%*LT Crashes	-0.740134	0.8121328	0.8317549	0.3618	-2.33509	0.8494124
Tot LT*Tot Opp Vol*LT Crashes	0.1677403	1.4401345	0.0135651	0.9073	-2.658523	2.9891673
LT Tr%*Tot Opp Vol*LT Crashes	3.3179325	2.0314926	2.684865	0.1013	-0.648932	7.3225205
TOD*TOD*TOD	0.0818195	0.254697	0.1032277	0.7480	-0.417008	0.5816034
PT Grn Time*PT Grn Time*PT Grn Time	3.8829e-6	2.0103e-6	3.7337068	0.0533	-5.563e-8	7.8269e-6
Speed*Speed*Speed	-0.376642	1.0930995	0.1188674	0.7303	-2.527447	1.7591024
Tot LT*Tot LT*Tot LT	1.0118263	0.2773987	13.446013	0.0002*	0.4697514	1.5573208
LT Tr%*LT Tr%*LT Tr%	-0.087534	0.2763218	0.1004255	0.7513	-0.630838	0.4531545
Tot Opp Vol*Tot Opp Vol*Tot Opp Vol	2.0560233	1.2093402	2.8680163	0.0904	-0.325698	4.4258388
LT Crashes*LT Crashes*LT Crashes	-0.033554	0.2556378	0.0172212	0.8956	-0.533246	0.469068
TOD*TOD	0.0016331	0.1238805	0.0001738	0.9895	-0.241518	0.2441649
PT Grn Time*PT Grn Time	-0.00108	0.0004451	5.9107684	0.0150*	-0.001954	-0.000209
Speed*Speed	-0.341166	0.9011629	0.1435794	0.7047	-2.116532	1.4176947
Tot LT*Tot LT	-0.831701	0.1657398	25.924779	<.0001*	-1.158629	-0.508786
LT Tr%*LT Tr%	0.0508501	0.2819801	0.0324912	0.8570	-0.505134	0.6016082
Tot Opp Vol*Tot Opp Vol	0.7013773	1.3334924	0.2757635	0.5995	-1.936433	3.3134562
LT Crashes*LT Crashes	0.0196105	0.2810379	0.0048698	0.9444	-0.530258	0.5716925

Poisson Regression Analysis