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# MODELLING THE SURROGATE SAFETY OF VARIOUS LEFT-TURN PHASE SEQUENCES

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A Project Presented

by

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Thank you,

Rohith Prakash Panthangi

# DEDICATION

To my family for their constant support and guidance

# ABSTRACT

**MODELLING SURROGATE SAFETY OF VARIOUS LEFT-TURN PHASE SEQUENCES**

APRIL 2019

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Left-turns are the most complex maneuvers in a signalized intersection. Based on the flow of the traffic volume through a given intersection, the left-turn phasing may be controlled in various fashions such as: protected only, permissive only, and protected/permissive. Following the introduction of the flashing yellow arrow (FYA) to the 2009 Edition of the Manual on Uniform Traffic Control Devices (MUTCD), many state agencies have implemented these indications for their left-turn permissive movements. Similar to the existing circular green (CG) permissive indication, the FYA requires drivers to yield to oncoming vehicles before making their left-turn. However, given the novelty of these traffic control devices there is a lack of standardization when it comes to the transition between protected and permissive left-turn phasing. A need exists to evaluate the surrogate safety of their implementation through a means of microsimulation evaluation. This research endeavor aims to model various protected-permissive left-turn (PPLT) phase sequences in the FHWA Surrogate Safety Assessment Model (SSAM). Both the FYA and circular green permissive left-turn indications will be implemented in VISSIM microsimulation models. Further, the phase sequencing for each permissive indication will comprise of two sequence options upon transitioning between protected and permissive left-turns; transitioning with and without the all-red clearance interval. Ultimately, this investigation will yield results to

develop guidance for practitioners in designing the signal sequencing with PPLT phasing, particularly with the newly introduced FYA traffic control device.

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# CHAPTER I

## INTRODUCTION

The Manual on Uniform Traffic Control Devices (MUTCD) is based on a simple fundamental principle – provide a consistent driver expectation[1]. A driver on the road should not be given mixed messages, which confuses or surprises them and could ultimately lead to a conflict or a crash. Traffic engineers and transportation professionals work hard to implement this principle and ensure the safety of the drivers. The left turn movement is considered the highest-risk movements at intersections. According to an intersection safety case study conducted by FHWA, an estimated 27 percent of all intersection related crashes in the United States are associated with left turns with over two-thirds occurring at signalized intersections[2].

Depending on the complexity of the intersection, one of the following three phase sequences is generally used:

1. "Protected-only" phasing consists of providing a separate phase for left-turning traffic and allowing left turns to be made only on a green left arrow signal indication, with no pedestrian movement or vehicular traffic conflicting with the left turn. Added left-turn phase increases the lost time within the cycle length and may increase delay to the other movements. Therefore, this is used in intersections with heavy left-turn traffic.
2. "Permissive-only" displays are signified by a green ball indication. Requires left-turning drivers to yield to the conflicting vehicle and pedestrian traffic streams before completing the turn. It is served concurrently with the adjacent through movement. For most high-volume intersections, “permissive-only” left-turn phasing is generally not practical for major street movements given the high volume of the intersections[20].

3. Protected-Permissive Left turn signal phasing involves the following four steps.

a) A steady Green Left arrow indication - During this time, the opposing vehicles are stopped and the drivers make a left-turn movement. This is the "Protected" portion of the signal phase.

*Figure 1- R10 – 12*

b) A steady Yellow Left arrow indication is displayed which acts a transition between the preceding steady Green Left arrow and succeeding Circular Green signal indications.

c) A steady Circular Green indication follows the Steady Left Yellow indication and the drivers are expected to yield. This is the "Permissive" portion of the signal phase.

d) The signal phase ends with an all red sequence.

In step (c), when a Circular Green indication is displayed, the drivers misinterpret it to be a protected sequence and this confusion leads to conflicts with the oncoming traffic or the pedestrians in the crosswalks. The crashes continued to prevail even after supplementing the signal post with a "Left turn Yield on Green" sign.

To eliminate the inconsistencies, Federal Highway Administration (FHWA) added Flashing Yellow Arrow (FYA) to Manual on Uniform Traffic Control Devices (MUTCD) in 2009 after extensive testing, as an optional configuration [3]. This also is accompanied with a supplemental sign (see Fig. 2). Majority of states nationwide recognized its benefits and began implementing FYA. But, MUTCD did not provide any standardization for transition between Protected and Permissive left turns and thus not utilizing the FYA to its full potential.

*Figure 2- R10 – 12a*

Flashing Yellow Arrow signal head features a flashing yellow arrow in addition to red, yellow and green steady arrow indications. Similar to an intersection with Circular green, the motorist, when displayed FYA, must first yield to oncoming traffic. A national study demonstrated that drivers found FYA left-turn arrows more understandable than traditional yield-on-green indication[3] (further discussed in the review of literature section). It is the duty of traffic engineers to reduce conflicts, both fatal and non-fatal, while not compromising the efficiency of the intersection's performance.

## 1.1 Review of Literature

Knodler et. al. concluded that the FYA permissive indication has a high level of driver comprehension and lower level fail critical rate than CG indication[5].

*Srinivasan et al.* (2011) conducted a study to document the evaluations for two treatments targeted at left-turn crashes at signalized intersections. They are 1) Change from permissive to protected-permissive phasing and 2) Introducing Flashing Yellow Arrow (FYA) for permissive left-turn movements. They concluded that there is a benefit with some kind of permissive left-turn operation before but shows a negative effect on intersections, which had protected only option previously.[6]

But, Protected only left turn signal cannot be used everywhere due to its negative effect on the efficiency of the intersection. Asante, S.A, studied the operational performance of left-turn phasing. They concluded that based on their simulation studies, protected only phasing results in higher delay and is not recommended from an efficiency standpoint unless it is required for safety. PPLT yielded acceptable delays and permissive only indication lowest delays however this is to be considered under very low left-turn and opposing traffic volumes.[7]

Since Flashing Yellow arrow has been introduced, research related to modifying existing intersections to include flashing yellow arrow indication has been done on a large scale. One such research is conducted by Srinivas et al. Six signalized intersections were selected and safety analysis done before and after the installation of FYA indication. To simulate this, Empirical Bayes technique is used to compare the number of crashes after the installation to the estimated number of crashes that would have occurred during the after period if the FYA signal had not been installed. This paper concluded that the number of crashes would have generally increased if the FYA signals had not been installed at the selected signalized intersections[8].

The reduction in crashes conflicts might be the direct result of improved driver understanding of the signal indication presented. Brehmer et al conducted a study in 2003 as a part of NCHRP report 493 concluded that flashing yellow arrow was well understood by the drivers and recommended its use as a permissive left-turn signal indication [3].

Rietgraf, A. et al, further explains this change in driver behavior. They conducted a study to examine the driver behavior to three types of the permissive left-turn interval of PPLT control – FYA, FRA and CG indications. They divided the drivers presented with the signals as Safe, Unsafe, efficient and inefficient drivers. They noticed that the in the intersection with FYA indication, driver behavior and drivers' quicker acceptance of adequate gap sizes indicate that the drivers better understood FYA indication than the CG or FRA[9].

Microsimulation software like VISSIM widely used to build and simulate models for an in-depth analysis of an intersection's safety.

Saleem, Taha, et al conducted a study to find if the simulated conflicts can be used instead of traffic volumes as the key variable to intersection safety. They used VISSIM micro simulation with precalibrated model parameter values to estimate conflicts vs using the Paramics model. The trajectory files from VISSIM were processed by SSAM. They concluded that the use of microsimulation and software like SSAM should be encouraged when it is difficult to evaluate the safety effects of proposed treatments because of inadequate sample sizes.[10]

*Qi et al. (2011)* investigated the safety performance of flashing yellow arrow (FYA) indication with protected-permissive left-turn operation using the surveys of traffic engineers and general motorists and a field conflict study. They concluded that, the FYA did not present safety issues at most test locations although some drivers misinterpreted FYA for steady yellow which could increase the risk of a conflict with oncoming traffic [11].

Collection of data for analyzing the safety of an intersection can be a lengthy and painful process. It involves using data from various sources like police reports and sending personnel to field to observe the conflicts between the vehicles as they pass through the intersection. This process becomes increasingly difficult for engineers to assess the safety of the intersections that are yet to be built.

*Tarko et al. (2009)* noted that the traditional evaluation method based on crash analysis will not be able to deliver timely safety estimates to match the progress in vehicles and in intelligent infrastructure. He also noted that Safety engineering desperately needs a breakthrough in safety evaluation and safety surrogates may serve as one[12].

Multiple studied have been conducted on the surrogate measures as an alternative for the traditional data collection techniques. *Gettman D and Head L (2003)* proposed surrogate measures for the development of SSAM. Their model considered three different types of simulated conflicts, including rear-end, lane-change and crossing conflicts[13].

*Gettman, Sayed, and Shelby* prepared a report that discusses the validation of Surrogate Safety Analysis Model and they concluded that SSAM approach demonstrated significant correlations with actual crash data, consistent with the range of correlations reported in several studies with traditional crash prediction models. SSAM is applicable to the analysis of traffic facilities that have not yet been constructed and for the traffic control policies not yet been enacted in the field. They have also recommended ways to overcome the limitations of this tool such as improving driver behavior modeling, studying the underlying nature of conflicts in real-world data and collecting adequate data[14].

*Stamatiadis et al. (2016)* developed a predictive safety assessment model for the left-turn movements at signalized intersections. They envisioned a model to develop the point where a decision can be made as to whether protected or permissive-only phasing can be implemented based on anticipated safety levels[15].

*Roach D., Christofa E. and Knodler, M.A. (2015)* conducted a study to evaluate the applicability of SSAM for modeling the safety of roundabouts. Although previous research of safety evaluations at roundabouts is very limited, through a combination of video data and micro-simulation tests for conflicts, they observed a strong correlation between the micro-simulation results and video results[16]

Wolfgram J., Christofa E. and Knodler, M.A., conducted research to investigate how the micro-simulation and surrogate safety benefits the continuous flow intersections as well as the effectiveness of using surrogate safety measures to assess safety levels at different intersections. Assessing different types of intersections further increases the scope of research and lays foundation to the use of surrogate measures for safety analysis[17]

## 1.2 Research Problem Statement

Previously, research has been done to sufficiently evaluate the benefits of safety and efficiency of the FYA indication over the yield-on Circular Green Indication. However, there is a need to take this research further to create a standardized phasing sequence so that the full potential of the FYA indication can be used. The following research hypotheses were developed to help start the discussion for a better understanding the problems in achieving the goal.

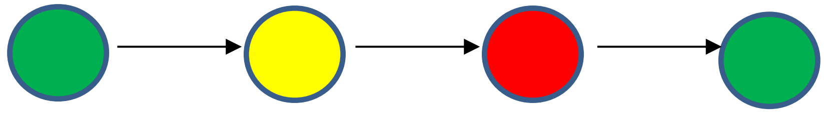
## 1.3 Research Hypotheses

Two research hypotheses were developed that focused on driver behavior at the intersection when all red clearance is displayed and the driver behavior parameters used in VISSIM when differentiating between FYA and CG signal indications.

***Research Hypothesis 1***

- *Left-turn phasing with an all-red clearance interval following the protected indication will result in fewer conflicts and events than phasing which does not use all-red clearance.*

Below is a simple phase sequence for the conventional three section signal head.



The yellow signal indicates the change in right-of-way. According to NCHRP report 03-95, "the duration of this interval is based on the driver's perception-reaction time and deceleration rate, the approach speed and the approach grade. This interval should allow, at a minimum, for a driver to comfortably decelerate to a stop prior to entering the intersection". Dilemma zone is a theoretical area of an intersection approach where the driver is presented with a condition – yellow signal indication and a decision – stop or go[4]. Even though Traffic

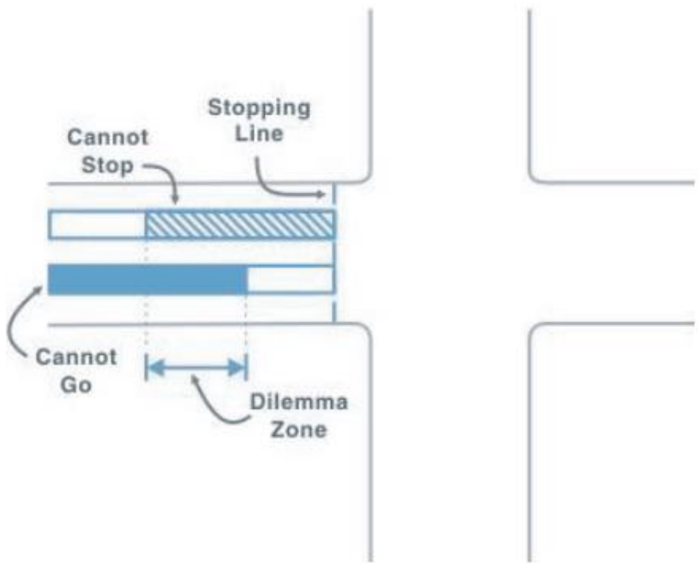



*Figure 3 - The Dilemma Zone concept [4]*

Engineers have been debating about the appropriate time duration for the Yellow Signal indication, there are always drivers who are in the dilemma zone. However, increasing the yellow indication may negatively affect the efficiency and performance of the intersection. Figure 3 represents the dilemma zone in a typical intersection.

One way to try to mitigate the problem is to introduce an all-red clearence inteval. When drivers are presented with a red signal indication, they are expected to stop. By increasing the red signal indication duration, the start time of the oncoming traffic can be delayed. When we combine both of these two conditions, i.e., After yellow, provide some additional time for the drivers to clear the dilemma zone and intersection while delaying the start time of oncoming traffic with red signal indication we could reduce the number of crossing conflicts in the intersection.

### *Research Hypothesis 2*

- *When comparing two intersection models in VISSIM, the same driver behavior cannot be used for both Circular Green and Flashing Yellow indications because the probability of drivers slowing down and stopping at an intersection during left-turn movement at the stop bar is greater when FYA is used than that of the conventioanal signal indicetions like yield-on-circular green.*

Traffic engineers, to convert an existing yield-on-Circular Green intersection to a yield-on-Flashing Yellow arrow intersection, change the signal head indicator in their model, with the same priority rules for their analysis. After a comprehensice array of files and laboratory studies, NCHRP Report 493 concluded that FYA signal indication is safer and effective when compared to a simple circular green light indications and other signals at conveying to drivers that they need to yield before turning left [3]. The FYA indication is easy to understand and imposes more caution on the driver behavior than any other conventional signal.

## 1.4 Research Objective

The primary objective of this research was to develop a standard phasing sequence in transition from protected to permissive signal indication without compromising the safety or efficiency of the intersection. This objective was carried out by comparing an intersection with the Flashing Yellow Arrow indication and a circular green permissive signal and then building models in VISSIM to evaluate the safety of these intersections using Surrogate Safety Assessment Model (SSAM). An All-Red clearance interval was introduced in between the protected and permissive signal transitions to evaluate the safety and efficiency when compared with intersections without the All-red clearance interval.

## 1.5 Scope

This research mainly focuses on the aforementioned research hypotheses and evaluates the effects on safety and efficiency by adding an all-red clearance interval between the transition from the protected phase to permissive phase of the signal indication. Additionally, this research also focused on issues related to the difference in driver behavior between FYA and yield on Circular Green indications.

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# CHAPTER II

## METHODOLOGY

Two intersections – an intersection with yield-on-circular green signal setting at College St. and S. East St. in Amherst, MA and an intersection with Flashing Yellow Arrow setting at Route 9 and N Main St. in Belchertown were chosen for the analysis. Both the intersection models were built in VISSIM. The base model is then calibrated and validated for left-turn and opposing through traffic by adjusting relevant car following and gap acceptance parameters within VISSIM. Each model has 10 simulation runs resulting in 10 trajectory files (.trj). These Trajectory files were added to the SSAM model and the conflicts are analyzed. Conflicts involved involving the left turn-movements were then filtered to get the results.

### 2.1 College St and S. East St. Intersection, Amherst – Circular Green signal indication

Located on the eastside of Amherst, MA, this pre-timed intersection has a typical four-legged layout. Traffic turning movements are collected manually for one hour over 15 minute intervals. EB movement is observed to be the heaviest turn movement.

| | SOUTH BOUND | | | WEST BOUND | | | NORTH BOUND | | | EAST BOUND | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TIME** | SBR | SB | SBL | WBR | WB | WBL | NBR | NB | NBL | EBR | EB | EBL |
| **4:30 PM TO 4:45 PM** | 18 | 25 | 89 | 1 | 65 | 4 | 6 | 24 | 15 | 30 | 116 | 19 |
| **4:45 PM TO 5:00 PM** | 17 | 33 | 106 | 57 | 0 | 5 | 6 | 35 | 20 | 21 | 111 | 30 |
| **5:00 PM TO 5:15 PM** | 13 | 34 | 83 | 0 | 67 | 4 | 8 | 24 | 15 | 30 | 103 | 32 |
| **5:15 PM TO 5:30 PM** | 12 | 37 | 104 | 2 | 61 | 3 | 4 | 27 | 1 | 0 | 90 | 28 |

*Table 1-PM Peak hour Turning Movements at Amherst Intersection*

*Figure 4- Intersection in Amherst, MA with CG indication*

## 2.2 Route 9 and N. East St. Intersection, Belchertown – Flashing Yellow Arrow signal indication

Located in Belchertown, MA, this intersection is four-legged layout with skewed legs.

| | SOUTH BOUND | | | WEST BOUND | | | NORTH BOUND | | | EAST BOUND | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TIME** | SBR | SB | SBL | WBR | WB | WBL | NBR | NB | NBL | EBR | EB | EBL |
| **4:30 PM TO 4:45 PM** | 4 | 38 | 7 | 5 | 33 | 7 | 4 | 45 | 88 | 108 | 50 | 2 |
| **4:45 PM TO 5:00 PM** | 5 | 46 | 10 | 8 | 39 | 10 | 4 | 39 | 92 | 98 | 75 | 1 |
| **5:00 PM TO 5:15 PM** | 4 | 50 | 9 | 5 | 31 | 3 | 6 | 34 | 71 | 130 | 70 | 3 |
| **5:15 PM TO 5:30 PM** | 5 | 46 | 5 | 11 | 24 | 6 | 5 | 34 | 95 | 123 | 55 | 4 |

*Table 2- PM Peak hour Turning Movements at Belchertown Intersection*

However, it is observed that by changing the signal head in the signal controller, there is no change in the driver behavior. For this, we need to change the probability of driver stopping when a yellow signal is introduced. This can be achieved by altering the probability in each model based on the field observations.

*Figure 5 - FYA indication Intersection in Belchertown, MA*

## 2.3 Decision Model in VISSIM:

One decision: The probability *p* of the driver stopping at amber light is calculated using a logistic regression function with the current speed *v* and the distance from the vehicle front to the stop line *dx* as independent variables and three fitting parameters (Alpha, Beta 1, Beta 2) [6].

$$p = \frac{1}{1 + e^{-\alpha - \beta_1 v - \beta_2 dx}}$$

The provided standard parameters have been derived from empirical values [6]

This brings the Hypothesis 1 into question. If drivers behave differently at these two signal indications, according to FHWA observations, driver in the intersection with FYA signal indication must be more cautious when compared to the intersection with Circular Green signal indication. This results in the higher probability of stopping for FYA signal indication when compared to the Circular Green Indication.

The field observations show that the probability of vehicles stopping in the Amherst-Circular Green Indication intersection and Belchertown – FYA intersection is 0.38 and 0.64 respectively. This shows that the drivers in the FYA indication intersection are more cautious than that of the CG indication green. Since there is one equation and three unknowns, the probabilities along with their respective equations are entered into MS excel to back calculate using trial & error method to obtain the $\alpha$, $\beta_1$ and $\beta_2$ values. The following three rules were followed to correctly identify the unknown values during the trail & error method:

1. Alpha is Greater than default value 1.59
2. Beta 1 is greater than the default value of 0.27.
3. Beta 2 is greater than the default value of -0.26 but less than 0.00.

Tables below show the calculated and observed probability values resulting from back-calculation and field observations respectively.

| | |
|---|---|
| Speed (*v*) | 30 |
| Distance (*x*) | 328.08 |
| $\alpha$ | 1.59 |
| $\beta_1$ | -0.26 |
| $\beta_2$ | 0.27 |
| Calculated Probability | 1 |

*Table 3 – Default Probability for VISSIM*

| | |
|---|---|
| Observed Probability | 0.64 |
| Speed (*v*) | 30 |
| Distance (*x*) | 85 |
| $\alpha$ | 2.4 |
| $\beta_1$ | -0.91 |
| $\beta_2$ | 0.3 |
| Calculated Probability | 0.645 |

*Table 4 – Calculated values for Belchertown FYA intersection*

| | |
|---|---|
| Observed Probability | 0.39 |
| Speed ($v$) | 30 |
| Distance ($x$) | 85 |
| $\alpha$ | 1.6 |
| $\beta_1$ | -0.89 |
| $\beta_2$ | 0.29 |
| Calculated Probability | 0.389 |

*Table 5 - Calculated Probability Values for Amherst CG Intersection*

## 2.4 Calibrating SSAM model

SSAM is used as a tool to analyze the Trajectory files from the VISSIM simulation runs. These TRJ files are the result of several replications with different random number seeds. Ten simulation runs from each intersection are input into SSAM to get conflict analysis. The following surrogate safety measures are calculated by SSAM.

- Minimum time-to-collision (TTC).
- Minimum post-encroachment (PET).
- Initial deceleration rate (DR).
- Maximum deceleration rate (MaxD).
- Maximum speed (MaxS).
- Maximum speed differential (DeltaS)

The conflicts are classified as Crossing, Rear-end, and Lane Change. [7]

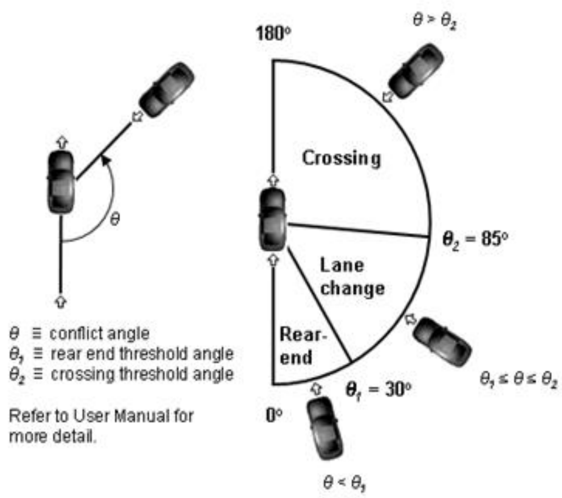
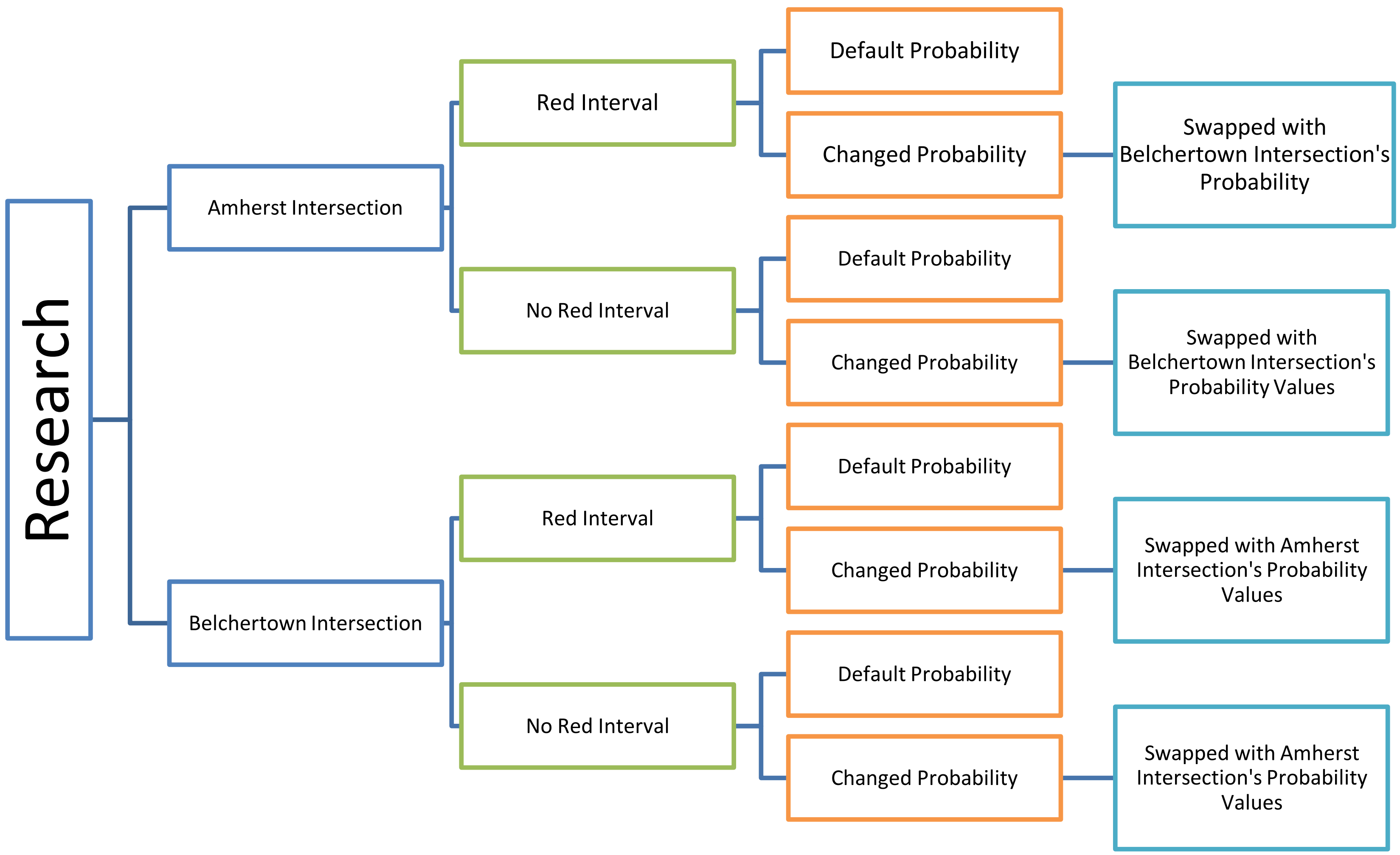



*Figure 6 - SSAM - Conflict Angle Diagram*[22]

First, simulations for both the intersections were run with the default probability values. Then, the back calculated Alpha, Beta1 and Beta 2 values are put into both the models and the simulations are run to get the actual results based on the site specific probability values. An all red clearance of 2 seconds[18] (typically between 2.2 secs and 4.6 secs depending on speed and clearing distance [19]) is introduced into each site, with the default and changed probability values to check if there is any difference change in the results. All these results are put into SSAM to analyze the conflicts and the safety of the intersections under varying signal and driver behavior models. Finally, the probability values are swapped between the Flashing Yellow Arrow indication Intersection and the Circular Green indication Intersection to see if there is an improvement in each site when compared to their previous results.

The flow chart below gives an outline of all the steps in this experiment.



# CHAPTER III

## RESULTS AND DISCUSSION

### 3.1 Default Probability Values Vs Observed Probability Values - No All-Red Clearance:

#### 3.1.1 Amherst Intersection:

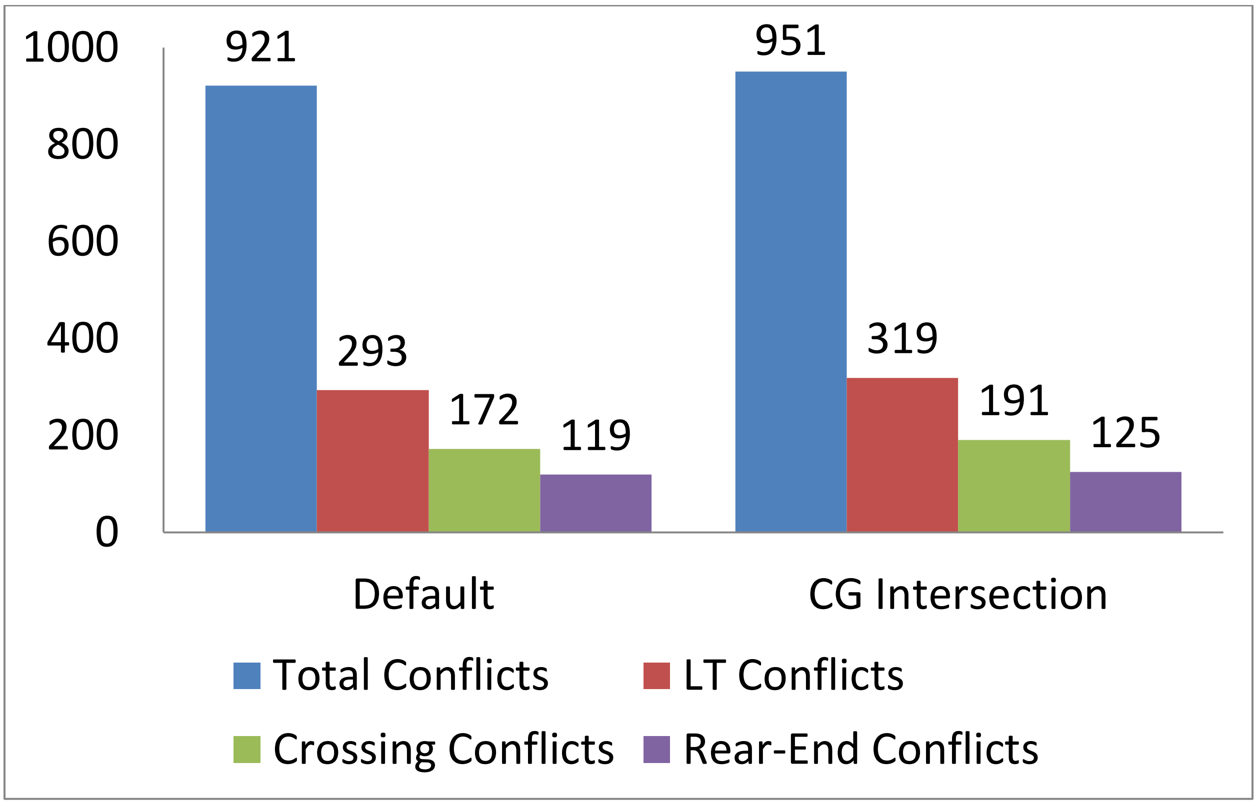



*Figure 7- Amherst Intersection Default vs CG Intersection [No All-Red Clearance]*

From the bar chart above, it is observed that, from the safety analysis of ten trj. files, the number of conflicts with the VISSIM's default probability values are less than that of the probability value observed in the field. This is because the drivers are assumed to be more cautious with VISSIM default probability values set to 1. Therefore, results obtained from the field Probability values will be assumed as the actual probability.

### *3.1.2 Belchertown Intersection*:

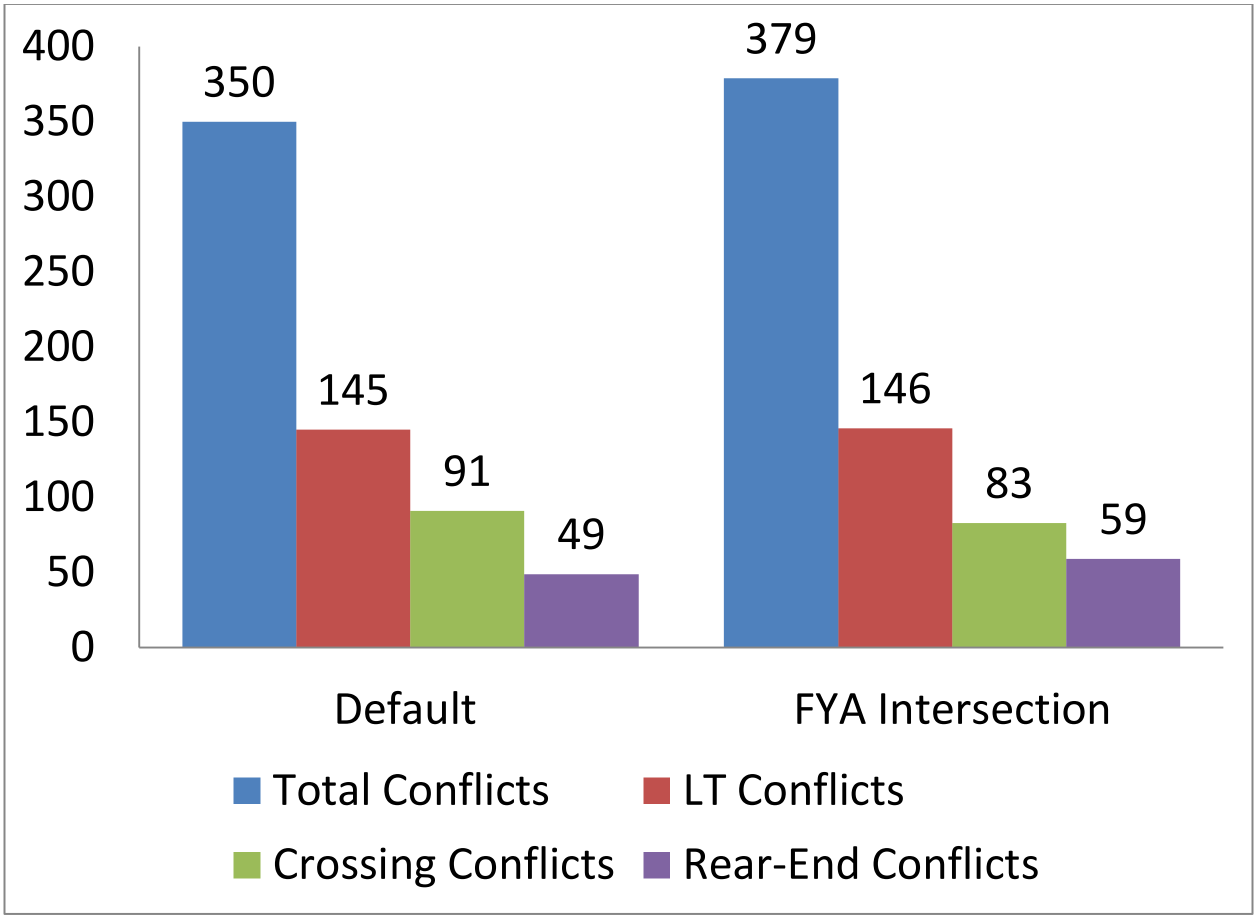



*Figure 8 – Belchertown Intersection - Default vs FYA Intersection [No All Red Clearance]*

For this chart, we observe the same pattern as earlier. The numbers of conflicts are more when the probability values from the field were used than that of the default probability values in VISSIM.

### 3.2 Observed Probability Values Without All-Red Clearance Vs Observed Probability Values – With All-Red Clearance:

#### 3.2.1 Amherst Intersection:

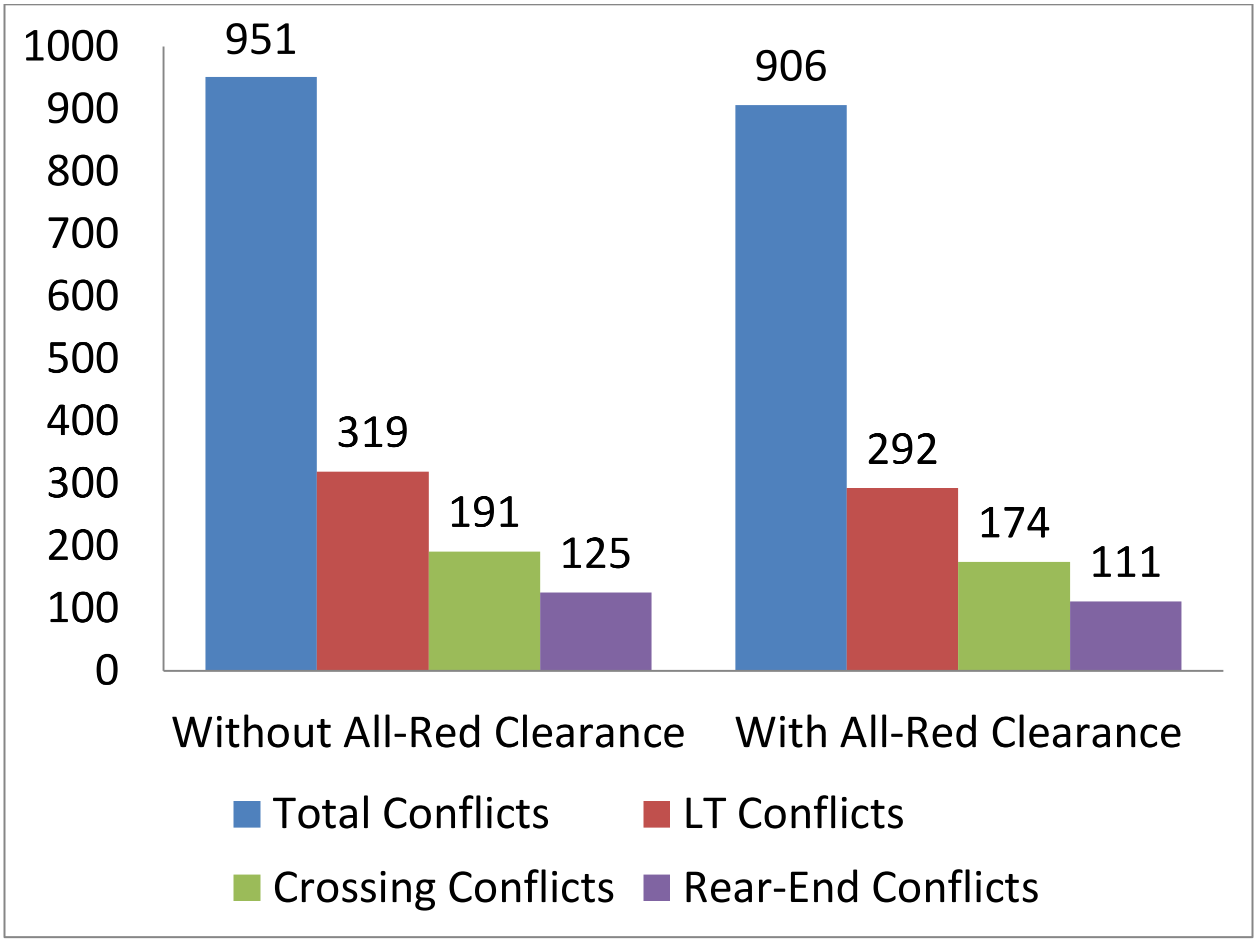



*Figure 9 - Amherst Intersection Observed Probability Values without All-Red Clearance Vs Observed Probability Values – With All-Red Clearance*

| Conflict Type | Mean of Observed probability values without All red clearance | Mean of Observed probability values with All red clearance | t-value | Significance |
|---|---|---|---|---|
| **Crossing** | 19.2 | 17.5 | 0.97 | NO |
| **Rear-end** | 75.4 | 72.4 | 0.86 | NO |
| **Lane Change** | 0.5 | 0.7 | -0.41 | NO |
| **Total** | 95.1 | 90.6 | 1.08 | NO |

*Table 6 - T-test results for Amherst Intersection Observed Probability Values without All-Red Clearance Vs Observed Probability Values – With All-Red Clearance interval.*

From the above figure, it is observed that, the total number of conflicts is decreased from 951 to 906. There is also a decrease in left turn conflicts including rear-end and crossing conflicts. However, when a t-test was conducted, these conflicts were observed as non-significant. This does not agree with the research previously done on the differences between Circular Green and FYA indication. The same experiment should be conducted on multiple intersections to get an accurate and average of those results.

### *3.2.2 Belchertown Intersection*:

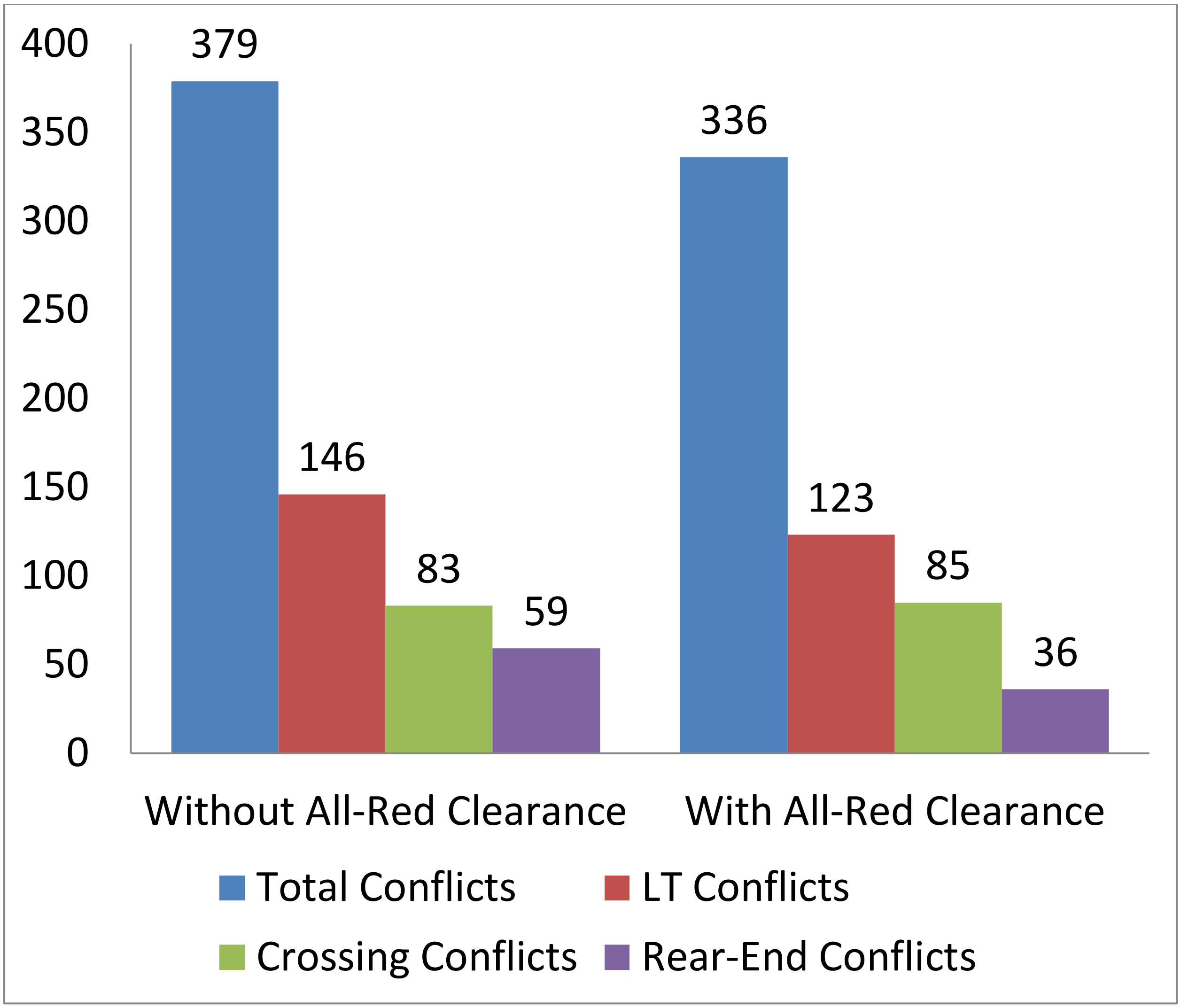



*Figure 10 - Belchertown Intersection Observed Probability Values without All-Red Clearance Vs Observed Probability Values – With All-Red Clearance*

| Conflict Type | Mean of Observed probability values without All red clearance | Mean of Observed probability values with All red clearance | t-value | Significance |
|---|---|---|---|---|
| **Crossing** | 8.8 | 10.1 | -1.6 | NO |
| **Rear-end** | 28.3 | 23 | 2.98 | YES |
| **Lane Change** | 0.8 | 0.5 | 0.79 | NO |
| **Total** | 37.9 | 33.6 | 2.33 | YES |

*Table 7 - T-test results for Belchertown Intersection Observed Probability Values without All-Red Clearance Vs Observed Probability Values – With All-Red Clearance*

The intersection in Belchertown also follows the same trend. When an all red clearance interval was introduced, the conflicts reduced from 379 to 336. There is also a decrease in left-turn conflicts because with all introduction of all red clearance interval, there is more time for the drivers taking left-turn to clear the intersection without the interference of the oncoming traffic. There is a slight increase in crossing conflicts but it was not significant based on the t-test conducted. There is a decrease in the rear-end conflicts from 59 to 36 and this is significant based on the t-test.

## 3.3 Observed Probability Values With All-Red Clearance Vs Observed Probability Values – with Swapped Probability Values:

### 3.3.1 Amherst Intersection:

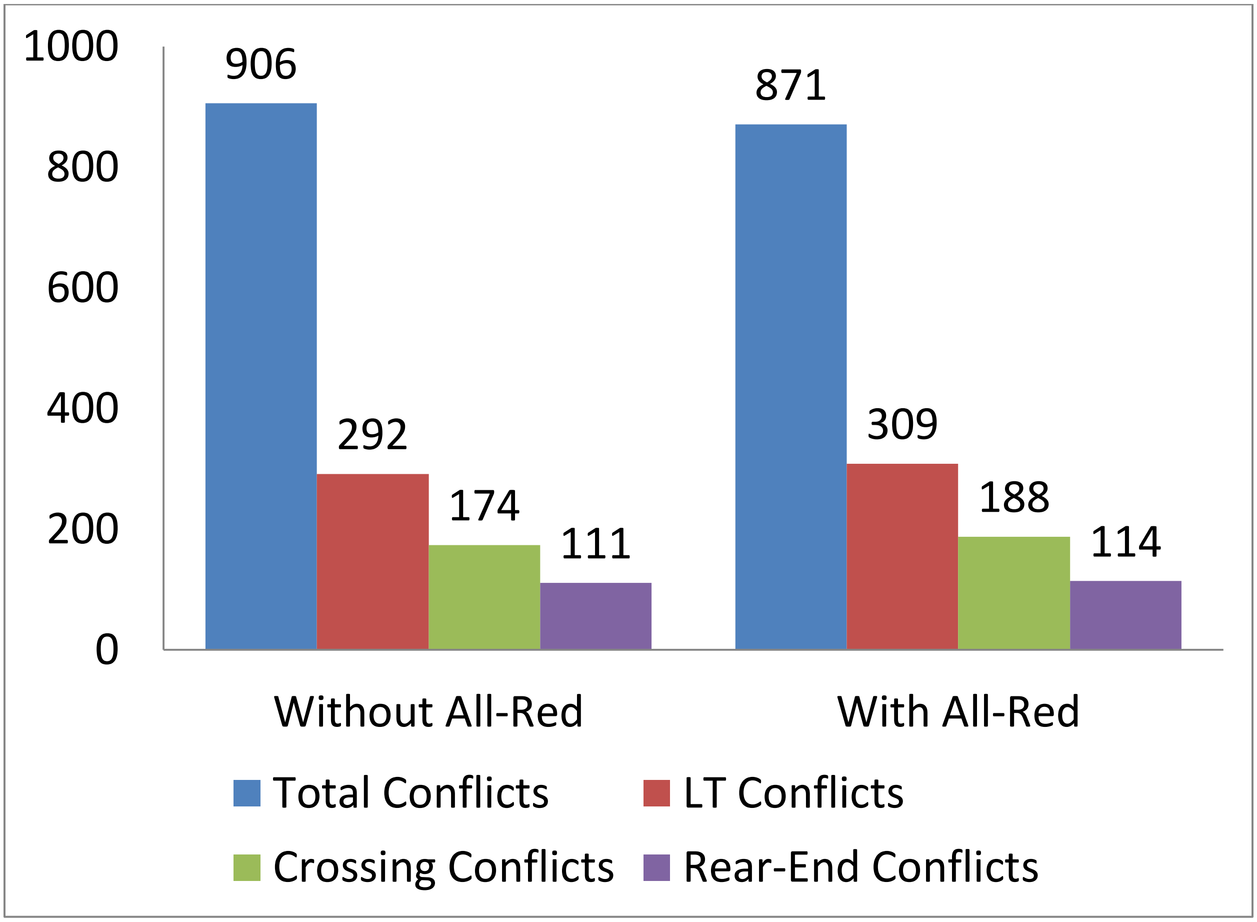



*Figure 11 – Amherst Intersection - Observed Probability Values with All-Red Clearance Vs Observed Probability Values – Swapped with Belchertown Intersection*

| Conflict Type | Mean of Observed probability values for CG intersection with all red clearance | Mean of Observed probability values of FYA intersection with All red clearance | t-value | Significance |
|---|---|---|---|---|
| **Crossing** | 17.5 | 18.8 | -0.62 | NO |
| **Rear-end** | 72.4 | 67.5 | 1.66 | NO |
| **Lane Change** | 0.7 | 0.8 | -0.22 | NO |
| **Total** | 90.6 | 87.1 | 0.9 | NO |

*Table 8 -T-test results for Amherst Intersection - Observed Probability Values with All-Red Clearance Vs Observed Probability Values – Swapped with Belchertown Intersection*

Figure 11 discusses the conflicts before and after changing existing CG intersection to a FYA intersection. It is observed that the conflicts are reduced from 906 to 871 when an all red clearance interval was introduced between protected and permissive phases. Even though there is a decrease in the conflicts; these are insignificant based on the T-Test results. This experiment should be conducted on multiple intersections and the average results must be analyzed to arrive at a conclusion.

## 3.4 Observed Probability values without All Red clearance interval vs FYA probability values with all red clearance interval

### 3.4.1 Amherst Intersection:

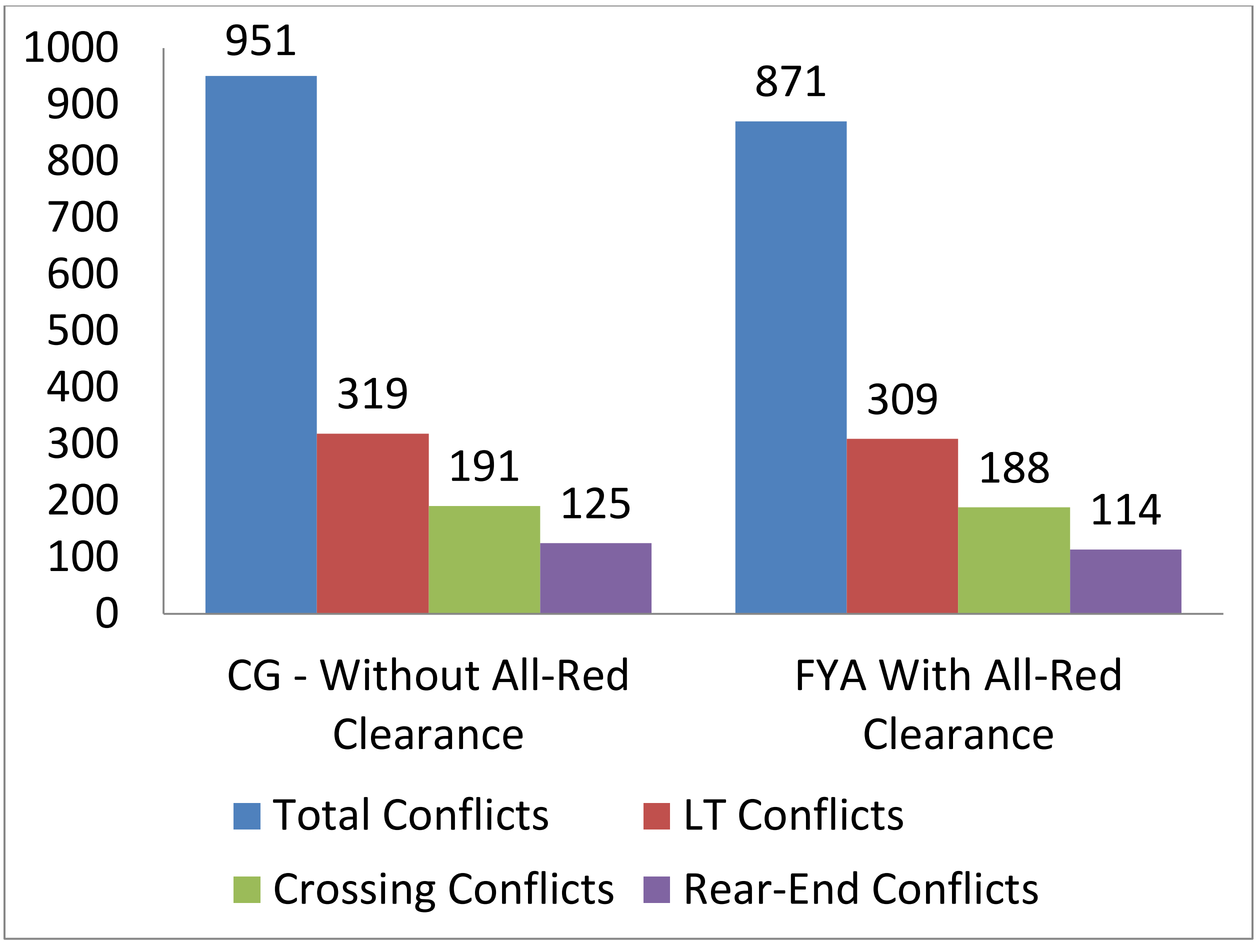



*Figure 12 - Amherst intersection with CG probability values without al red clearance interval vs FYA probability values with all red clearance intervals*

| Conflict Type | Mean of Observed probability values for CG intersection without all red clearance | Mean of Observed probability values of FYA intersection with All red clearance | t-value | Significance |
|---|---|---|---|---|
| **Crossing** | 19.2 | 18.8 | -0.23 | NO |
| **Rear-end** | 75.4 | 67.5 | -2.2 | YES |
| **Lane Change** | 0.5 | 0.8 | 0.62 | NO |
| **Total** | 95.1 | 87.1 | -1.8 | YES |

*Table 9 - T-test results for Amherst intersection with CG probability values without al red clearance interval vs FYA probability values with all red clearance intervals*

In chart, for Amherst Intersection, CG probability values without all red clearance interval and FYA probability values with all red interval are compared. We can see that there is a significant decrease in total number of conflicts proving that when an intersection was changed from CG indication to FYA indication and all red clearance interval was introduced between protected and permissive phases, there is a significant decrease in conflicts.

## 3.5 Effect on the performance:

One of the benefits of adding FYA indication is improved intersection performance. But when an All-Red Clearance interval is added to this, there will be delays. Therefore, Level of Service and average vehicular delay were used as a measure to determine the effects on the performance on the intersection.

| | Amherst Intersection | | Belchertown Intersection | |
|---|---|---|---|---|
| | Without All-Red clearance | With All-Red clearance | Without All-Red clearance | With All-Red clearance |
| | Observed Probability | Observed Probability | Observed Probability | Observed Probability |
| **Average Delay (sec.)** | 27.75 | 29.26 | 25.10 | 28.95 |

*Table 10 - Delay comparison between various conditions*

## 3.6 Conclusion:

From the above results, we can conclude that:

- The driver behavior in the intersection with CG Indication is not same as that of the intersection with FYA Indication.
- Fewer conflicts were observed when an intersection is changed from CG to FYA indication and an All-Red Clearance interval is introduced between protected and Permissive phases.
- When an intersection with CG indication is changed into FYA indication, the total number of crashes reduces with very little negative affect the performance of that intersection as a trade-off.

## 3.7 Limitations:

We were able to analyze the safety and performance of an intersection with FYA indication with an all red clearance interval for left-turn movements, but this study has its limitations.

Red clearance interval of opposing through traffic and the role of bikes and pedestrians were not considered due to its complexity. This is important to get a comprehensive safety and operational analysis of the intersection. This research focused on one intersection with CG indications and one intersection with FYA indication. Applying this analysis to multiple intersections gives us better results that will address the variables such as the intersection's geometry, speed limits, distance to the stop bar etc.

## 3.8 Future Research:

Many states have started implementing complete streets policy to enable safe access regardless of mode of transportation. This makes the intersection complex because; bikes and pedestrians are less protected in an intersection than vehicles. Alhajyaseen et. al concluded that "The main threat to pedestrian safety comes from turning vehicles, since, in common signal plans, pedestrians and turning vehicles share the same phase" [20] . Although we are able to design a standard phasing sequence for drivers doing a left-turn movement, there is more scope to this research to take it to the next level by studying the impact of bikes and pedestrian in an intersection. This data can be included in the further research to get a comprehensive idea of the bike and pedestrian safety in an intersection with FYA indication.

Furthermore, changing the oncoming traffic's red interval - using lagging or leading green can be explored to fully analyze the impact of all-red clearance time on the performance of the intersection.

## 3.9 Contributions:

This research explores the need to analyze the difference between two permissive indications – left-turn in circular green and left-turn in FYA using microsimulation tools like VISSIM and using the driver behavior at amber signal to distinguish between these two indications. Until now, the comparison between these two indications has always been a mere change in graphical representation. This research opens the possibility of building microsimulation models that reflects the driver behavior in field on a case-by-case basis rather than using the default values used by VISSIM. This research will be an exploratory study for the engineers who are modifying the existing intersection with CG indication to FYA indication.

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