Before and After Analysis of Changes to Yellow Time and All-Red Clearance Interval at 25 Selected Signalized Intersections in Champaign-Urbana

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CHAMPAIGN COUNTY REGIONAL PLANNING COMMISSION

CUUATS

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1. Introduction

Roadway safety is one of the top priorities for transportation planners and engineers. There are advance standards and practices implemented to address road safety related issues. These practices promote safety with the ultimate goal of reducing the number of crashes.

In the crash data of Champaign County from the Illinois Department of Transportation (IDOT), from 2007 to 2011, 27% of urban area crashes were at traffic signals. 39% of traffic signal related crashes in the urban area were rear end crashes, 31% were turning movement crashes and 18% were angular crashes. The crashes at traffic signals are commonly found to be related to red light running violations or the dilemma zone. A dilemma zone occurs when the driver can neither safely stop before the stop line nor proceed through the intersection before the light turns red. Thus, dilemma zone can occur when the yellow time is not set correctly or the approaching vehicle is travelling faster than the posted speed limit and/or if the driver's perception and reaction time is longer than the designed value [1]. If a driver decides to stop instead of proceeding, rear end crashes could occur and if the driver proceeds instead of stopping, collisions with side street traffic could occur [1]. Thus, it is found that signal timings play a crucial role in controlling these types of crashes at intersections. In a traffic signal, the green time is predominantly decided by the traffic volumes at the intersections. The yellow interval after the green time is to warn the approaching traffic of the imminent right of way change [2]. The yellow and all-red time within the signal cycle constitute the signal change and clearance interval. As the name suggests, the yellow time is referred to as a signal change time given to the approaching vehicle to decide and make a decision as to whether it wants to stop or cross the intersection. The yellow time is followed by all-red clearance interval. The all-red clearance time provides additional time for the vehicles to clear the intersection, especially the ones entering in the later part of the yellow interval.

Thus, the design of yellow change and all-red clearance interval is an important factor in the driver's decision making to cross or stop at the intersection. The conflict between the vehicles at intersections due to change of signal phases is reduced which directly affects the collisions between the vehicles. Studying the impact of change in yellow time and all-red clearance interval on intersection safety is very important. This report presents the background research and the effects of changing the yellow time and all-red clearance interval time on performance and safety of 25 intersections in the Champaign-Urbana urbanized area.

1.1 Background

Van der Horst 1998 [3] observed that the number of red-light running events reduced by half after increasing the duration of yellow timing of 3 seconds (s) to 4s by 1s. The study was done considering 1 year of before and after behavioral study in the northern part of the Netherlands. Similar analysis was done in Philadelphia, Pennsylvania, where the red light running violations reduced by 36% with the change in yellow timing [4]. Bonneson et al (2004) [5] observed that increasing the yellow interval by 1s but less than 5.5s decreased the frequency of red light violations by 50%. Researchers have found that long term effects of increase in yellow time reduces red-light violations for 6 months to 1 year (Bonneson and Zimmerman, 2004 [5]; Van Der Horst, 1998 [3]) but then the drivers adapt to the increase in yellow duration and continue to run red lights (Bonneson and Zimmerman, 2004 [5]). Excessively long yellow time might encourage red-light running because drivers do not want to wait or drivers get adapt to it or some may disregard it considering it as a part of the green light cycle [2].

INTRODUCTION

Retting et al (1997) [6] studied 10 intersections and observed the change in both yellow timing and all-red clearance interval. According to the Institute of Transportation Engineers (ITE) 1985, reduction in red light violations and right angle crashes were observed. Guerin (2012) [7] did the before and after analysis to study the effect of change in yellow timing and red light clearance interval by comparison of frequency of crashes, type of crashes by collision and crash severity. Paired sample t-test was used for this study. Analyzing 20 intersections, statistically significant reduction in property damage type crashes were observed, and 18 intersections showed statistically significant reduction in angular crashes. Since only two intersections were considered for red-light clearance interval study, statistical test was not able to give any significant results.

Souleyrette et al (2004) [8] studied the effect of only red-clearance interval on crashes at 4-way intersections in the City of Minneapolis. Several regression models like the Poisson error distribution, log link function and linear mixed model were used but no safety benefits were found. A before and after analysis of 11 years of crash data indicated short term reduction of crashes (1 year) but no long term reductions were observed. A before and after analysis by Datta et al (2000) [9] demonstrated substantial benefits of red-clearance interval, reduction in red-light violations and right angle crashes were observed.

Overall, changing the yellow time and all-red clearance interval has a significant effect in reducing red-light violations and hence angular crashes. This reduction in crashes is observed for short term, i.e. 6 months to 1 year, while no long term effect is observed. Researchers discourage long yellow times since the drivers may disregard it and continue to make red light violations.

1.2 Objective of the Study

The change in yellow time and all-red clearance interval was one of the short term strategies identified in the Champaign County Comprehensive Highway Safety Plan approved by Champaign Urbana Urbanized Area Transportation Study (CUUATS) in 2008. In this project, 45 signalized intersections in Champaign-Urbana were selected. These intersections were a part of a Highway Safety Improvement Program (HSIP) grant received from IDOT in 2009. CUUATS updated its policy on yellow time and all-red clearance by 2010-2011 and implemented them at 45 intersections. To understand the effect of yellow time and all-red clearance interval, 25 out of 45 intersections were selected. The following were the objectives set for this study:

- Collect data like the Average Daily Traffic (ADT), turning movement counts, roadway geometry, and crashes for the analysis period.
- Evaluate the effect of yellow change and all-red clearance interval on intersection performance level using microsimulation software.
- Perform crash analysis of 5 years before (2006 to 2010) and 5 years of after (2011 to 2015) periods. Comparison of crash frequencies, crash collisions types and injury types by jurisdiction and intersection.
- Comparison of expected crashes estimated from the Highway Safety Manual and observed crashes for before (2006-2010) and after (2011-2015) conditions.

The following section presents the updated CUUATS yellow time and all-red clearance interval guidelines. The effect of signal change on 25 intersections in the City of Champaign, University District and City of Urbana is presented. The effect of signal change on intersection performance is evaluated using a microsimulation software. Five years before and after analysis of crashes at 25 intersections was considered for this study. A comparison of crash frequency, crash collision and injury type was done. Additionally, the crashes were estimated using the Highway Safety Manual 2010 and compared with the observed crashes. A statistical analysis using paired t-test was conducted to determine the significance of the effect of yellow time and all-red clearance interval.

Figure 1: Duncan Road and Windsor Road Intersection

2. Current CUUATS Guidelines for Signal Change and Clearance Interval

The current CUUATS guidelines for yellow time and all-red clearance interval were based on a comprehensive regional traffic operational and safety study that was done in 2010 – 2011. It included analyzing the crash data, performance speed and intersection level of service. An extensive literature review was done to study the guidelines adopted by various local agencies, state DOT's and city governments. Given the fact that there are various governing bodies within the Champaign-Urbana region, it was considered beneficial to adopt consistent guidelines for the region. The current CUUATS guidelines for Yellow Time and Clearance Interval can be summarized as follows:

Through Movements: It was recommended that CUUATS member agencies used the ITE Kinetic Model method to calculate the yellow time and all-red clearance interval for through movement. The yellow time interval was recommended not to be more than 5 seconds, with any additional period to be used in the clearance interval. The maximum all-red clearance time of 2.5 seconds was recommended for intersections in the Champaign-Urbana area [10].

Left Turn Movements: For left turn phases, a yellow change interval of 3 seconds was recommended. This value was in accordance with the ITE Kinetic Model for low speeds of 25 mph. The all-red clearance interval values were derived using the ITE formulas assuming an approach speed of 25 mph and will be limited to a maximum of 2 seconds [10].

In addition to the above recommendations, the yellow time and all-red clearance interval would be revised based on engineering judgement after reviewing intersection conditions [10].

The ITE Kinetic Model formulas that was recommended by CUUATS is shown below:

$$y = t + \frac{v}{2a + 2Gg} \tag{2.1}$$

Where:

y = length of the yellow time interval, to the nearest 0.1 second

t = driver perception/reaction time, generally assumed as 1.0 second

v = speed of the approaching vehicle, in ft. /sec (m/sec)

a = average deceleration, assumed from 10 ft. /sec^2 to 15 ft. /sec^2

G = grade of the approach, in percent divided by 100 (downhill is negative grade)

g = acceleration due to gravity, 32 ft. /sec^2

The approach speed used in the calculation of yellow time interval is the 85th percentile speed, or in some cases 15th percentile speeds to accommodate vehicles traveling at low speeds [11].The average deceleration of 10ft/sec^2 is usually used when calculating the change interval.

In cases where the all-red clearance time was not provided, the yellow time interval was extended to allow additional time for the vehicles to safely clear the intersection. This extended yellow time can thus be calculated using equation 2.2 below.

$$y = t + \frac{v}{2a + 2Gg} + \frac{w + L}{v} \tag{2.2}$$

Where:

w = width of the intersection (ft.)

L = length of vehicle, in ft. (assumed to be 20 ft.)

For calculating all-red clearance intervals, ITE recommends using the following three formulas based on the presence of pedestrian traffic and/or pedestrian signals.

For intersections with no pedestrian traffic:

$$r = \frac{w + L}{v} \tag{2.3}$$

For intersections with the possibility of pedestrian traffic:

$$r = \frac{P}{v} \tag{2.4}$$

For intersections with considerable pedestrian traffic or for crosswalks protected by pedestrian signals:

$$r = \frac{P + L}{v} \tag{2.5}$$

Where:

r = length of the red clearance interval, to the nearest 0.1 sec

w = width of the intersection (in ft.), measured from the near-side stop line to the far edge of the conflicting traffic lane along the actual vehicle path

L = length of the vehicle (in ft.), assumed to be 20 ft

v = speed of the vehicle through the intersection, in ft. / sec

P = width of the intersection, in ft., measured from the near-side stop line to the far side of the farthest conflicting pedestrian crosswalk along the actual vehicle path

CURRENT CUUATS GUIDELINES FOR SIGNAL CHANGE AND CLEARANCE INTERVAL

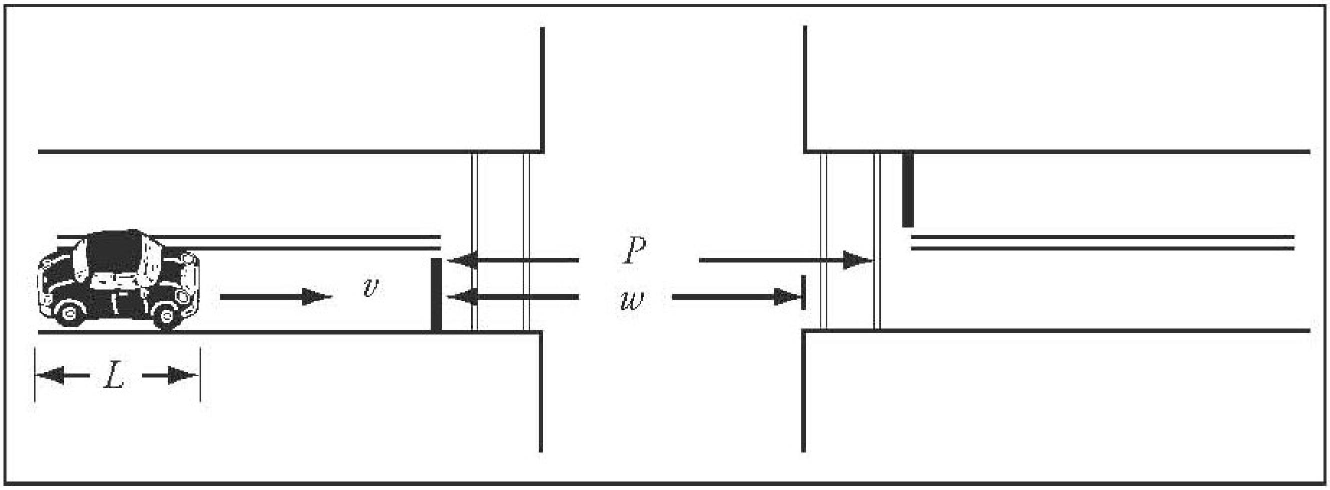

Figure 2: Clearance Widths Used to Calculate All-Red Clearance Interval

3. Intersection Level of Service Analysis

Intersection operational analysis was performed for 25 intersections using Synchro® to determine the updated traffic operational conditions during the PM Peak hours. Selected criteria such as level of service, intersection delay and percentage change in intersection entering volumes were analyzed. Level of Service (LOS) is a qualitative measurement describing operational conditions based on intersection delay, ranging from "A" (best) to "F" (worst) at an intersection. **Table 1** presents the LOS, intersection delay and intersection volumes simulated from the microsimulation software Synchro®.

As can be seen in **Table 1**, the intersection of Lincoln Avenue and Windsor Road (**Figure 3)** had, LOS of "E" in 2010, which is indicative of delays that are considered unacceptable to most drivers. It is observed that the LOS improved for the following intersections: Mattis Avenue and Kirby Avenue, Lincoln Avenue and Pennsylvania Avenue, and Lincoln Avenue and Windsor Road. On the other hand, the LOS for the intersections of Fourth Street and Kirby Avenue declined. There was no difference in LOS for other intersections. Mattis Avenue and Olympian Drive observed 17% increase in peak hour traffic volume while 34% reduction in peak hour traffic was observed for Sixth Street and Gregory Drive from 2010 to 2016.

Figure 3: Lincoln Avenue and Windsor Road Intersection

INTERSECTION LEVEL OF SERVICE ANALYSIS

Table 1: Intersection Level of Service at the Study Intersections

Intersections	Intersection Entering Volumes PM Peak Hour		Percent Change	2010 PM Peak Hour Volumes		2016 PM Peak Hour Volumes	
	2010	2016		LOS	Intersection Delay (sec)	LOS	Intersection Delay (sec)
City of Champaign							
Mattis Avenue and Olympian Drive	725	846	17%	B	19.7	B	19.1
Mattis Avenue and Interstate Drive	1,174	1,250	6%	B	10.7	B	10.3
Mattis Avenue and Kirby Avenue	3,308	3,229	-2%	D	35.3	C	34.3
State Street and Bradley Avenue	1,650	1,766	7%	B	11.9	B	11.5
Randolph Street and Bradley Avenue	1,987	2,019	2%	B	15.8	B	13.8
Neil Street and Bradley Avenue	2,669	2,594	-3%	C	24.2	C	23.2
Market Street and Bradley Avenue	1,783	1,699	-5%	C	23.7	C	29.2
Fourth Street and Kirby Avenue	2,266	2,158	-5%	B	18.0	C	22.0
First Street and Kirby Avenue	2,377	2,308	-3%	C	24.9	C	24.0
Oak Street and Kirby Avenue	1,867	1,818	-3%	B	16.7	B	15.0
Duncan Road and Windsor Road	1,755	1,921	9%	C	30.1	C	34.7
Mattis Avenue and Windsor Road	2,465	2,442	-1%	C	24.0	C	24.5
Galen Drive and Windsor Road	2,408	2,158	-10%	B	18.4	B	20.0
Prospect Avenue and Windsor Road	2,694	2,535	-6%	C	26.4	C	26.3
University of Illinois							
Sixth Street and Gregory Drive	769	506	-34%	B	14.1	B	11.6
Sixth Street and Armory Avenue	509	435	-15%	C	33.4	C	22.1
City of Urbana							
Goodwin Avenue and Green Street	1,326	1,429	8%	C	26.1	C	27.1
Lincoln Avenue and Bradley Avenue	2,184	2,346	7%	B	18.4	B	16.9
Lincoln Avenue and Springfield Avenue	2,362	2,149	-9%	C	25.2	C	20.5
Lincoln Avenue and Green Street	2,176	2,211	2%	C	22.2	C	24.4
Lincoln Avenue and Pennsylvania Avenue	2,065	2,034	-2%	D	40.6	C	32.5
Lincoln Avenue and Florida Avenue	2,267	2,264	0.1%	C	28.1	C	29.1
Lincoln Avenue and Windsor Road	2,119	1,711	-19%	E	64.4	D	43.1
Broadway Avenue and Main Street	1,047	1,190	14%	B	10.2	B	10.6
Race Street and Main Street	1,245	1,271	2%	B	12.6	B	12.9

4. Traffic Safety Studies

4.1 Study Area

In the original HSIP grant submitted in 2008, 25 intersections were selected in the Champaign-Urbana area. These included nine (9) intersections in the City of Urbana, fourteen (14) in the City of Champaign and two (2) under the jurisdiction of the University of Illinois. The location of intersections are presented in **Figure 4**.

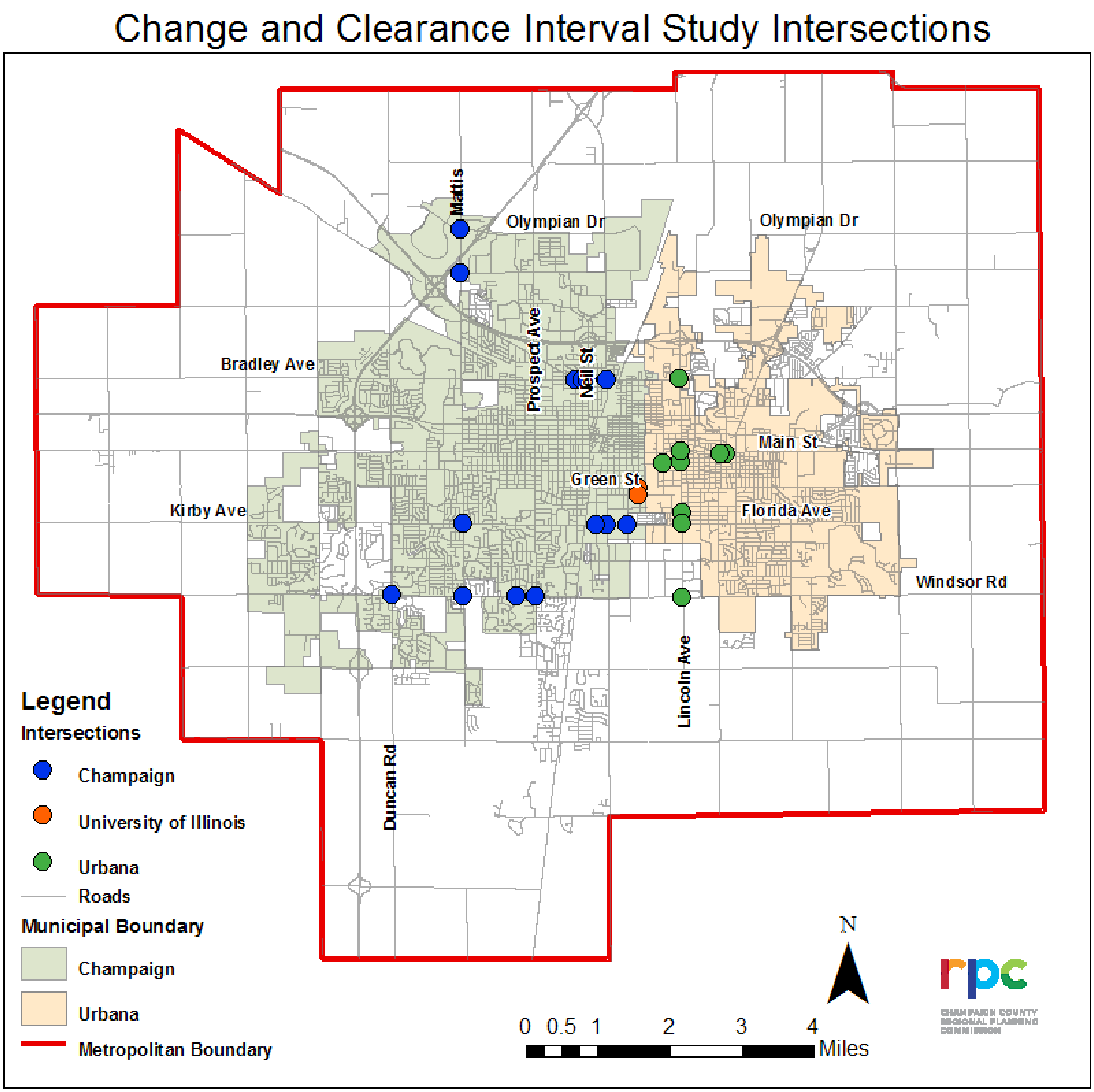

Figure 4: Study Intersections in the Champaign-Urbana Area

TRAFFIC SAFETY STUDIES

This is a complete list of the intersections:

City of Champaign

1. Mattis Avenue and Olympian Drive
2. Mattis Avenue and Interstate Drive
3. Mattis Avenue and Kirby Avenue
4. State Street and Bradley Avenue
5. Randolph Street and Bradley Avenue
6. Neil Street and Bradley Avenue
7. Market Street and Bradley Avenue
8. Fourth Street and Kirby Avenue
9. First Street and Kirby Avenue
10. Oak Street and Kirby Avenue
11. Duncan Road and Windsor Road
12. Mattis Avenue and Windsor Road
13. Galen Drive and Windsor Road
14. Prospect Avenue and Windsor Road

City of Urbana

1. Goodwin Avenue and Green Street
2. Lincoln Avenue and Bradley Avenue
3. Lincoln Avenue and Springfield Avenue
4. Lincoln Avenue and Green Street
5. Lincoln Avenue and Pennsylvania Avenue
6. Lincoln Avenue and Florida Avenue
7. Lincoln Avenue and Windsor Road
8. Broadway Avenue and Main Street
9. Race Street and Main Street

University of Illinois

1. Sixth Street and Gregory Drive
2. Sixth Street and Armory Avenue

All the intersections are four-leg signalized intersections, except for Mattis Avenue and Interstate Drive and Randolph Street and Bradley Avenue which are three-leg intersections, and State Street and Bradley Avenue is a five-leg intersection.

4.1.1 Before and After Crash Data Analysis

The new yellow time and all-red clearance intervals policy was adopted by the CUUATS members including the City of Champaign, City of Urbana, and University of Illinois in 2010-2011. This section presents an analysis based on the study of crashes and their types for before (2006-2010) and after (2011-2015) the implementation of the new yellow time and all-red clearance intervals policy. The before period is defined from 2006 to 2010 and after period as 2011 to 2015. Thus, 10 years of crash data obtained from IDOT was used for this study. In this report, the crashes of only 25 intersections were studied and analyzed.

An immediate comparison of after the implementation of yellow time and all-red clearance interval was not done to avoid a phenomenon in statistics called regression towards the mean. Regression to mean refers to the tendency for a fluctuating characteristic of an entity to return to a typical value in the period after an extraordinary value has been observed [12]. **Figure 5** presents the summation of crashes at the studied 25 intersections from 2006 to 2015. A dip in the graph is observed for 2010 which was when the implementation of yellow time and all-red clearance interval at the 25 intersections was started which continued in 2011, but then again the number of crashes increased for the following years. This significant decrease in crashes in 2010 may be due to the effect known as regression to the mean considering that the crash frequency after 2010 went to a value which typically is the average.

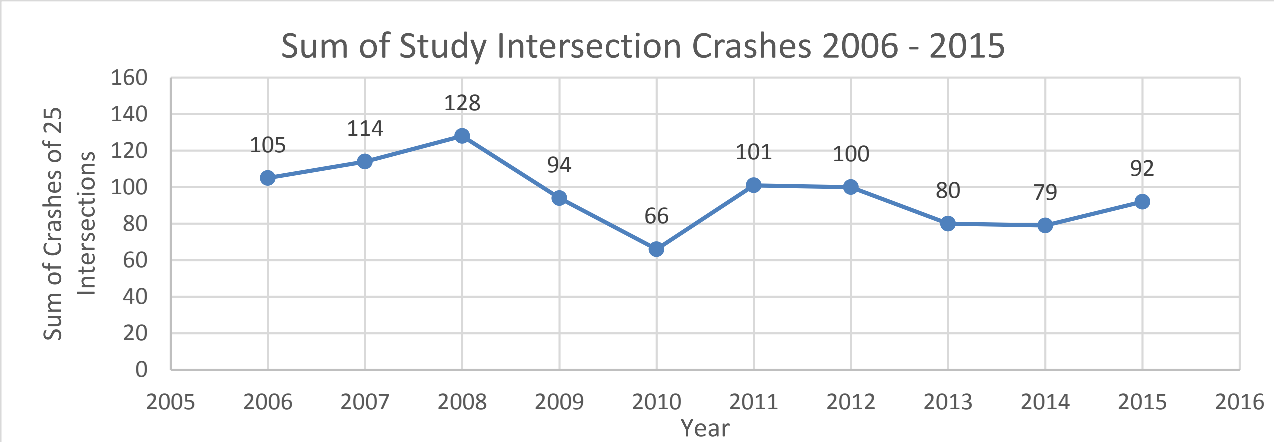

Figure 5: Summation of Study Intersection Crashes from 2006 to 2015

Table 2 presents the summary of intersection crashes for before (2006-2010) and after (2011-2015) conditions by jurisdiction, i.e. summation of crashes of 14 intersections in the City of Champaign, 2 intersections under the jurisdiction of the University of Illinois, and 9 intersections in the City of Urbana.

Comparing the percentage difference of intersection crashes between the before (2006-2010) and after (2011-2015) periods, it is observed that the number of crashes has reduced by 3% in the City of Champaign, 8% in the University of Illinois and 22% in the City of Urbana. The standard deviation of the City of Urbana and City of Champaign are lower in the after (2011-2015) condition which means the 5 years crash frequency is less dispersed compared to the before (2006-2010) condition. On the other hand, the crash frequencies for the after (2011-2015) condition in the University of Illinois is more dispersed.

Similar to Guerin (2012) [7], a statistical paired t-test [13, 14] was conducted to determine if there is any significant difference in the mean of crashes between the before (2006-2010) and after (2011-2015) conditions. The null hypothesis is that there is no significant difference in the 5 years of crashes after implementing the yellow time and all-red clearance interval at signalized intersections. The P-values from **Table 2** are greater than 0.05, thus it is not convincingly enough to say that the mean of before (2006-2010) and after (2011-2015) condition crashes differ significantly. It is important to look closer at individual intersections to get a clear picture. The following section presents the analysis of crashes by intersection, by collision and injury severity type.

Table 2: Summary of Before (2006-2010) and After Crashes (2011-2015) by Jurisdiction

Jurisdiction	Crash Frequency		% Difference	Mean		Standard Deviation		t-Test α=0.05
	Before	After		Before	After	Before	After	P Value
City of Champaign	285	277	-3%	57	55	9	3	0.74
University of Illinois	13	12	-8%	3	2	1	2	0.80
City of Urbana	209	163	-22%	42	33	15	7	0.30
Total	507	452	-11%	101	90	23	11	0.41

4.1.2 Analysis of Crashes by Intersections

Table 3 shows the average crashes over 5 years of before (2006-2010) and after (2011-2015) conditions for each intersection, the difference between them and the standard deviation. If the difference is negative, it means there was a decrease in the average number of crashes; a positive value means an increase; and zero means no change in average crashes.

Table 3: Summary of Before (2006-2010) and After (2011-2015) Crashes by Intersection

Location	Intersection	Crash Average over 5 years		Change in Crash Average	Standard Deviation	
		Before	After		Before	After
City of Champaign	Mattis Avenue and Olympian Drive	1	0	-1	1	0
	Mattis Avenue and Interstate Drive	3	3	0	2	3
	Mattis Avenue and Kirby Avenue	9	7	-2	4	4
	State Street and Bradley Avenue	6	7	1	3	3
	Randolph Street and Bradley Avenue	3	3	0	1	2
	Neil Street and Bradley Avenue	8	10	2	3	3
	Market Street and Bradley Avenue	4	4	0	2	2
	Fourth Street and Kirby Avenue	5	4	-1	3	3
	First Street and Kirby Avenue	6	3	-3	3	1
	Oak Street and Kirby Avenue	2	2	0	1	1
	Duncan Road and Windsor Road	2	4	2	1	2
	Mattis Avenue and Windsor Road	3	3	0	1	2
	Galen Drive and Windsor Road	1	2	1	1	1
	Prospect Avenue and Windsor Road	5	2	-3	3	1
	Total	57	55	-2	9	3
University of Illinois	Sixth Street and Gregory Drive	1	2	1	1	2
	Sixth Street and Armory Avenue	1	1	0	1	1
	Total	3	2	-1	1	2
City of Urbana	Goodwin Avenue and Green Street	5	2	-3	2	1
	Lincoln Avenue and Bradley Avenue	7	6	-1	4	3
	Lincoln Avenue and Springfield Avenue	5	4	-1	3	2
	Lincoln Avenue and Green Street	8	4	-4	3	2
	Lincoln Avenue and Pennsylvania Avenue	5	3	-2	2	1
	Lincoln Avenue and Florida Avenue	5	5	0	2	1
	Lincoln Avenue and Windsor Road	3	4	1	2	2
	Broadway Avenue and Main Street	1	1	0	1	0
	Race Street and Main Street	4	3	-1	2	1
	Total	42	33	-9	15	7

Note: Rows with difference greater than zero are highlighted.

There are 11 out of 25 intersections which observed a reduction in the average number of crashes in the after (2011-2015) period of analysis, 6 intersections observed an increase in the average number of crashes and the remaining 8 intersections observed no difference in the average number of crashes. The intersections which observed an increase in average crashes per year after 2010 are State Street and Bradley Avenue, Neil Street and Bradley Avenue, Duncan Road and Windsor Road, and Galen Drive and Windsor Road in the City of Champaign; Sixth Street and Gregory Drive on the University of Illinois campus and Lincoln Avenue and Windsor Road in the City of Urbana.

Neil Street and Bradley Avenue observed the highest average crashes of 10 for the after (2011-2015) period. The standard deviation of the intersections in the City of Urbana except Lincoln Avenue and Windsor Road are higher in the before (2006-2010) condition period, thus the crash frequencies were more spread out over 5 years in the before (2006-2010) conditions. In the case of intersections in the City of Champaign and University of Illinois, no uniform trend is observed between before (2006-2010) and after (2011-2015) conditions.

In addition to the crash frequencies, it becomes important to account for traffic volumes at an intersection. Crash rates are the combination of crash frequencies and traffic volumes. It is expressed as "crashes in million entering vehicles (MEV)." The equation to calculate the crash rate is shown below.

$$Crash\ Rate = \frac{Total\ Crashes\ during\ Study\ Period * 1{,}000{,}000}{(Average\ of\ Daily\ Intersection\ Entering\ Volumes) * 365 * Study\ Duration\ (in\ years)} \tag{4.1}$$

The traffic volumes for each intersection were obtained from IDOT, and the year for which the traffic volume data was missing were extrapolated or interpolated as required. **Figure 6** shows the crash rates at all study intersections in the City of Champaign, University of Illinois, and City of Urbana.

In **Figure 6**, there are 8 intersections out of 25 which observed a reduction in crash rates. Mattis Avenue and Olympian Drive, and Galen Drive and Windsor Road are the intersections which observed lower crash rates in the before (2006-2010) and after (2011-2015) periods of study. State Street and Bradley Avenue observed the highest crash rate, followed by Lincoln Avenue and Green Street, Neil Street and Bradley Avenue, and Race Street and Main Street.

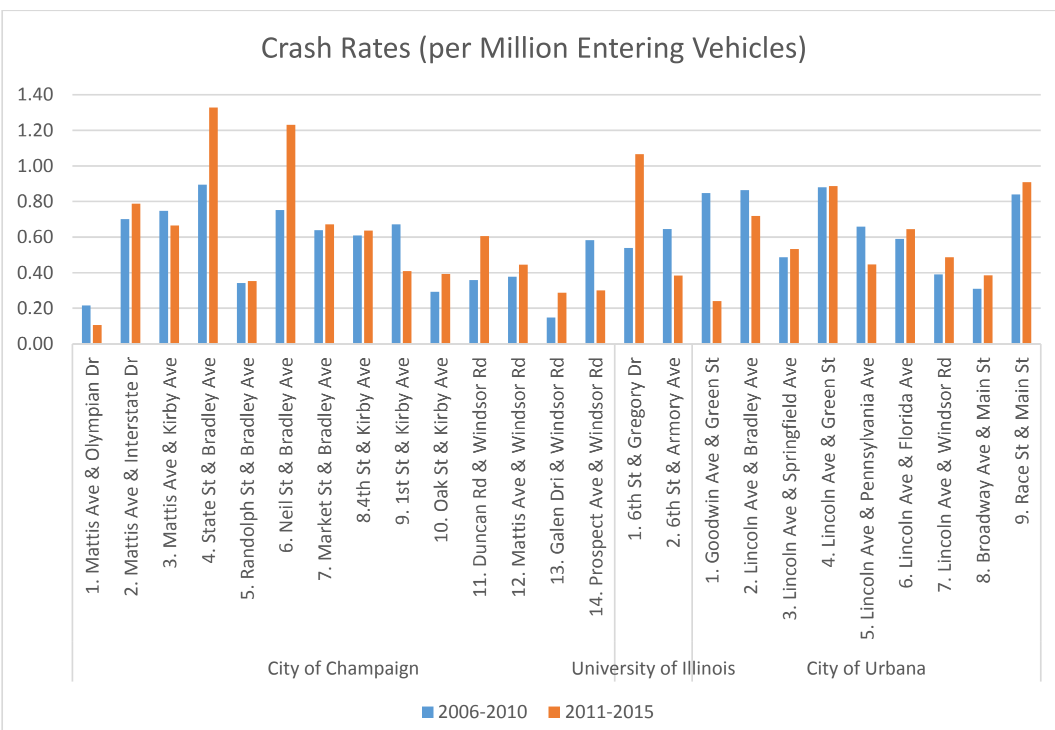

Figure 6: Crash Rates (per MEV) for each Intersection by Jurisdiction

4.1.3 Analysis of Crashes by Collision Types

The type of collision between the vehicles defines the collision type of the crash. For each jurisdiction, collision types were analyzed for before (2006-2010) and after conditions (2011-2015). Rear-end, turning movement, angular, and fixed object type of collisions contribute towards 85% to 95%. Thus, these collision types are compared for the before (2006-2010) and after (2011-2015) conditions. **Figure 7**, **Figure 8**, and **Figure 9** presents the percentage of crashes by collision types for the City of Champaign, City of Urbana, and University of Illinois respectively.

In the City of Champaign (**Figure 7**), the percentage of angular collisions were reduced by 5%, and turning movement were reduced by 6%. On the other hand, an increase in rear-end crashes by 2% and fixed object type crashes by 3% was observed.

In the City of Urbana (**Figure 8**), 7% and 2% reduction in rear-end type collisions and fixed object type crashes respectively was observed, but an increase by 4% and 8% in turning movement and angular type collisions respectively was observed.

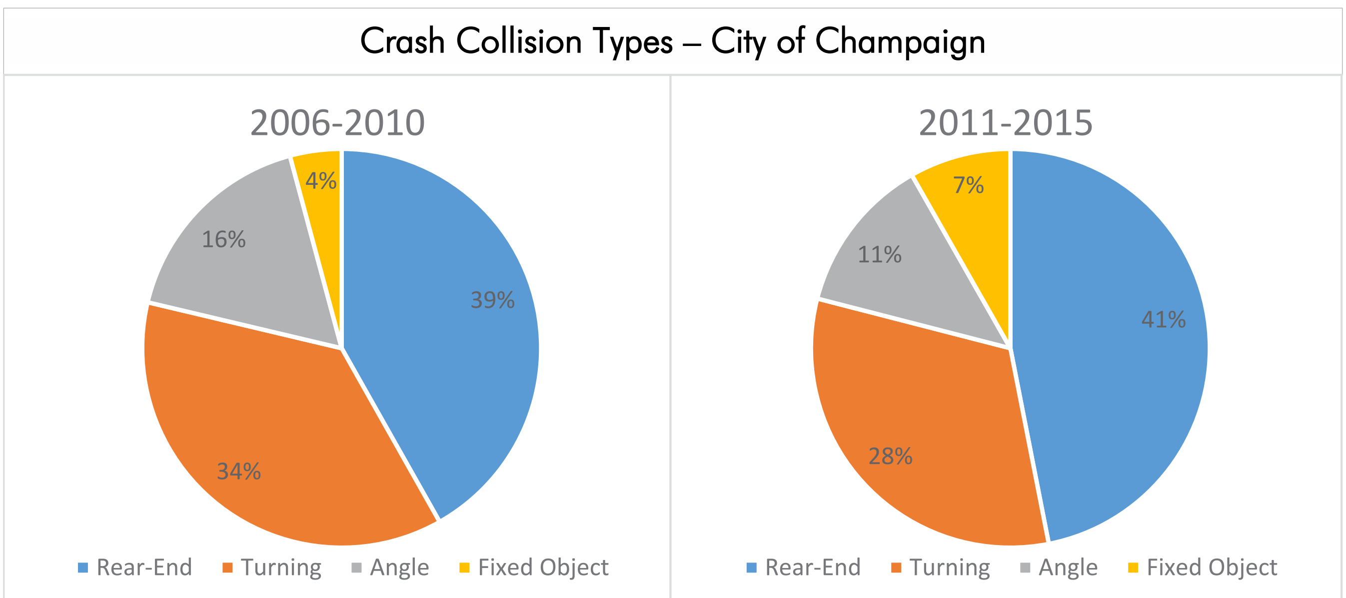

Figure 7: Percentage of Crashes by Collision Type in the City of Champaign for Before (2006-2010) and After Conditions (2011-2015)

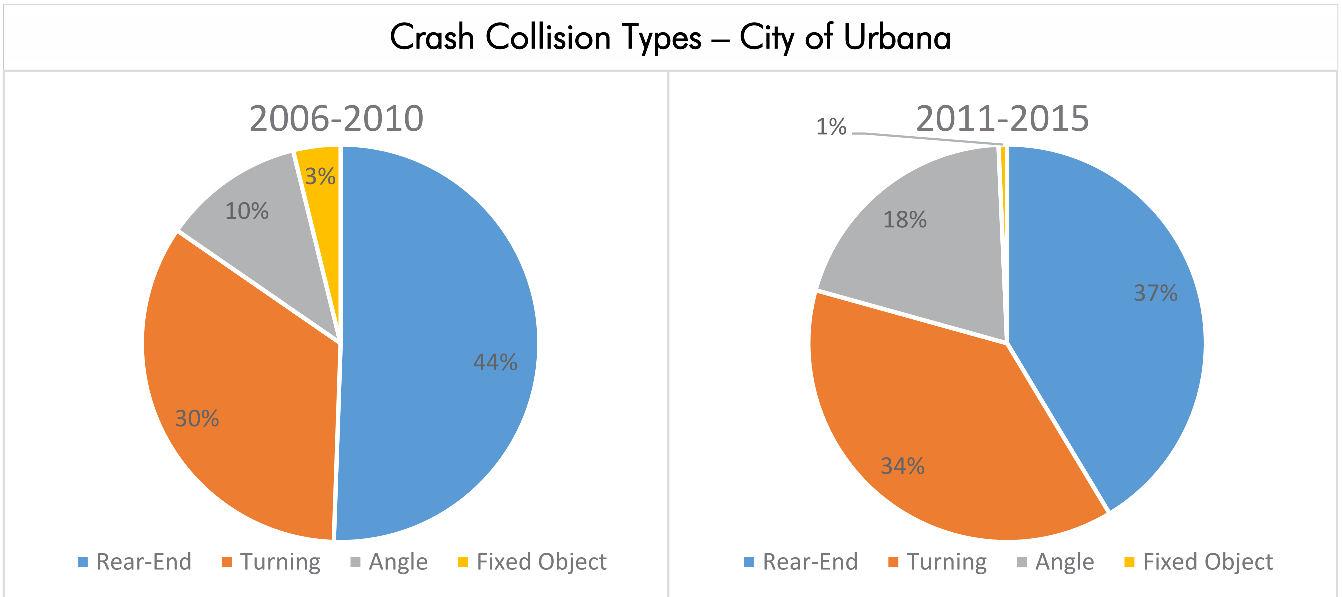

Figure 8: Percentage of Crashes by Collision Type in the City of Urbana for Before (2006-2010) and After Conditions (2011-2015)

On the University of Illinois campus (**Figure 9**), 14%, 15% and 8% reduction in turning movement, rear-end and angular type collisions respectively were observed while an 11% increase of fixed object type collisions was observed.

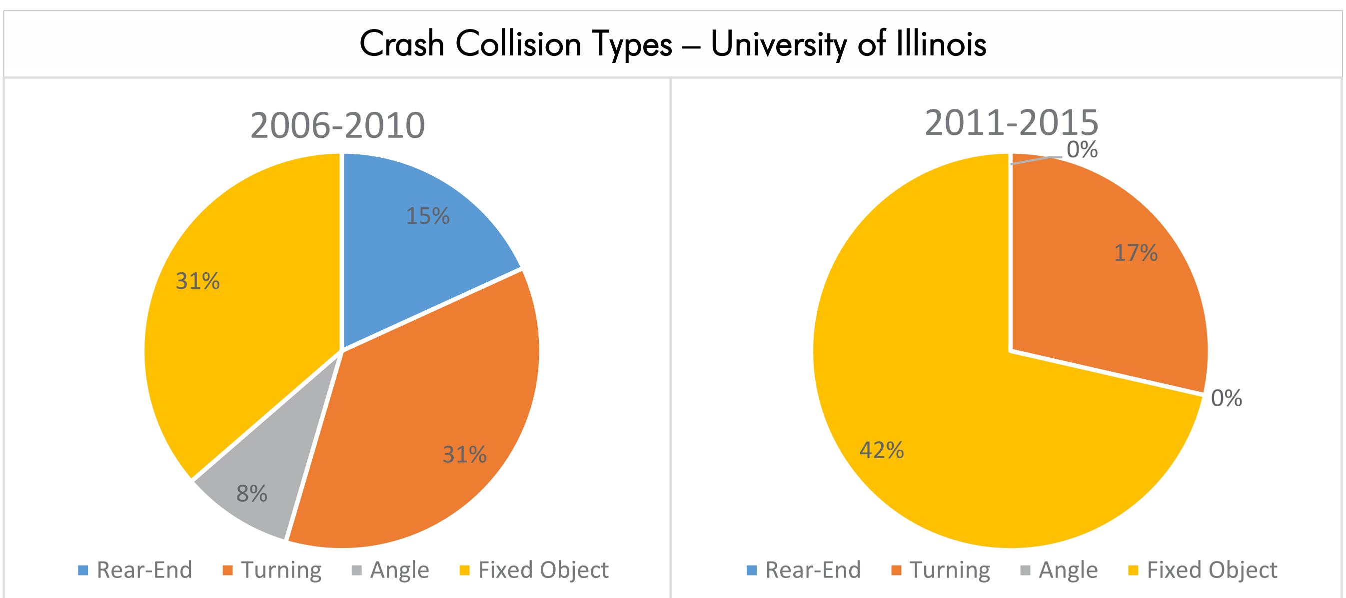

Figure 9: Percentage of Crashes by Collision Type at the Universty of Illinois for Before (2006-2010) and After Conditions (2011-2015)

4.1.4 Analysis of Crashes by Injury Type

The injury type of crashes are classified in KABCO scale. K represents fatal, A as incapacitating injury, B as non-incapacitating injury, C as reported/not evident, and O as no indication of injury and just property damage [15]. The table below presents the summary of crashes by injury type in each jurisdiction for the before (2006-2010) and after (2011-2015) conditions. No fatal crashes were observed at the 25 study intersections during the analysis periods. The numbers represent the total number of crashes considering all the intersections by jurisdiction.

Table 4: Summary of Intersection Crashes in Jurisdictions by Injury Type for Before (2006-2010) and After (2011-2015) conditions

Injury Type	City of Champaign				University of Illinois				City of Urbana			
	Before		After		Before		After		Before		After	
	Crash Frequency	%	Crash Frequency	%	Crash Frequency	%	Crash Frequency	%	Crash Frequency	%	Crash Frequency	%
A-Injury	11	4%	13	5%	1	8%	1	8%	7	3%	13	8%
B-Injury	25	9%	35	13%	3	23%	3	25%	20	10%	19	12%
C-Injury	27	9%	32	12%	0	0%	0	0%	14	7%	15	9%
O-No Injury	222	78%	197	71%	9	69%	8	67%	168	80%	116	71%
Total	285	100%	277	100%	13	100%	12	100%	209	100%	163	100%

As observed in **Table 4**, a major proportion of crashes were of no-injury (O) type ranging from 67% to 78%. The percentage of no-injury type crashes reduced by 11% in the City of Champaign, 11% at the University of Illinois, and 31% in the City of Urbana. The percentage of injury type of crashes in the after condition (2011-2015) increased in the City of Champaign and City of Urbana. At the University of Illinois, the percentage of B-Injury type crashes increased while no change in other types of injuries was observed. Thus, a reduction in no-injury type (O) crashes was observed by change in yellow time and all-red clearance interval. Similar results were observed by Guerin (2012) [7].

4.1.5 Analysis of Pedestrian and Bike Crashes

This section presents the analysis of crashes involving pedestrians and bikes for the before (2006-2010) and after (2011-2015) conditions. **Table 5** presents the summary of pedestrian and bike crashes at the 25 study intersections.

Table 5: Summary of Pedestrian and Bike Crashes for Before (2006-2010) and After (2011-2015) by Jurisdiction

Location	Pedestrian Crashes			Bike Crashes		
	Crash Frequency			Crash Frequency		
	Before	After	Difference	Before	After	Difference
City of Champaign	2	5	3	7	10	3
University of Illinois	0	3	3	1	1	0
City of Urbana	7	7	0	6	4	-2
Total	9	15	6	14	15	1

The pedestrian crashes increased by 3 in the City of Champaign and University of Illinois, while no change in the City of Urbana was observed. The bike crashes increased by 3 in the City of Champaign, while no change at the University of Illinois was observed. On the other hand, a reduction in bike crashes by 2 was observed in the City of Urbana. The following table presents the summary of pedestrian and bike crashes for before (2006-2010) and after (2011-2015) condition by type of severity.

Table 6: Summary of Pedestrian and Bike Crashes for Before (2006-2010) and After (2011-2015) by Injury Type

Injury Type	Pedestrian Crashes			Bike Crashes		
	Crash Frequency			Crash Frequency		
	Before	After	Difference	Before	After	Difference
A-Injury	0	4	4	1	2	1
B-Injury	1	7	6	1	10	9
C-Injury	2	4	2	1	3	2
O-No Injury	6	0	-6	11	0	-11
Total	9	15	6	14	15	1

In **Table 6**, there were 6 and 11 pedestrian and bike crashes respectively of no-injury type in the before (2006-2010) condition which reduced to 0 in the after (2011-2015) condition. On the other hand, an increase of injury type of pedestrian and bike crashes were observed for the after condition. B-injury type crashes increased by 6 and 9 for pedestrian and bike respectively.

Figure 10: Pedestrian crossing Fourth Street and Kirby Avenue intersection

4.2 Highway Safety Manual Methodology for Estimating Crashes

The Highway Safety Manual (HSM) is a resource that provides information and tools to facilitate improved decision making based on safety performance [16] evaluation of roadway facilities. HSM provides improved methodologies to predict crashes for new and alternate designs. It estimates crashes using rigorous statistical methods based on geometry, operating characteristics, and traffic volumes. It is considered a single national resource for quantitative information about crash analysis and its evaluation [16].

The crash prediction method from the HSM 2010 was used to study the before and after safety impacts of yellow time and all-red clearance interval changes implemented at the 25 study intersections by the City of Urbana, City of Champaign and University of Illinois in 2010-2011. The method used to estimate crashes from HSM 2010 was adopted from the AASHTO Highway Safety Manual (1st Edition) Illinois User Guide [17]. This method was divided in steps, including data collection, selection and calculation of safety performance functions (SPF's), selection and calculation of crash modification factors (CMFs), selection of calibration factors, observed crash data, and finally, expected average crash frequency for the site. These steps were used to estimate crashes for before (2006-2010) and after (2011-2015) conditions. **Figure 12** presents a flowchart of the steps used to estimate crashes.

Figure 11: Highway Safety Manual 2010

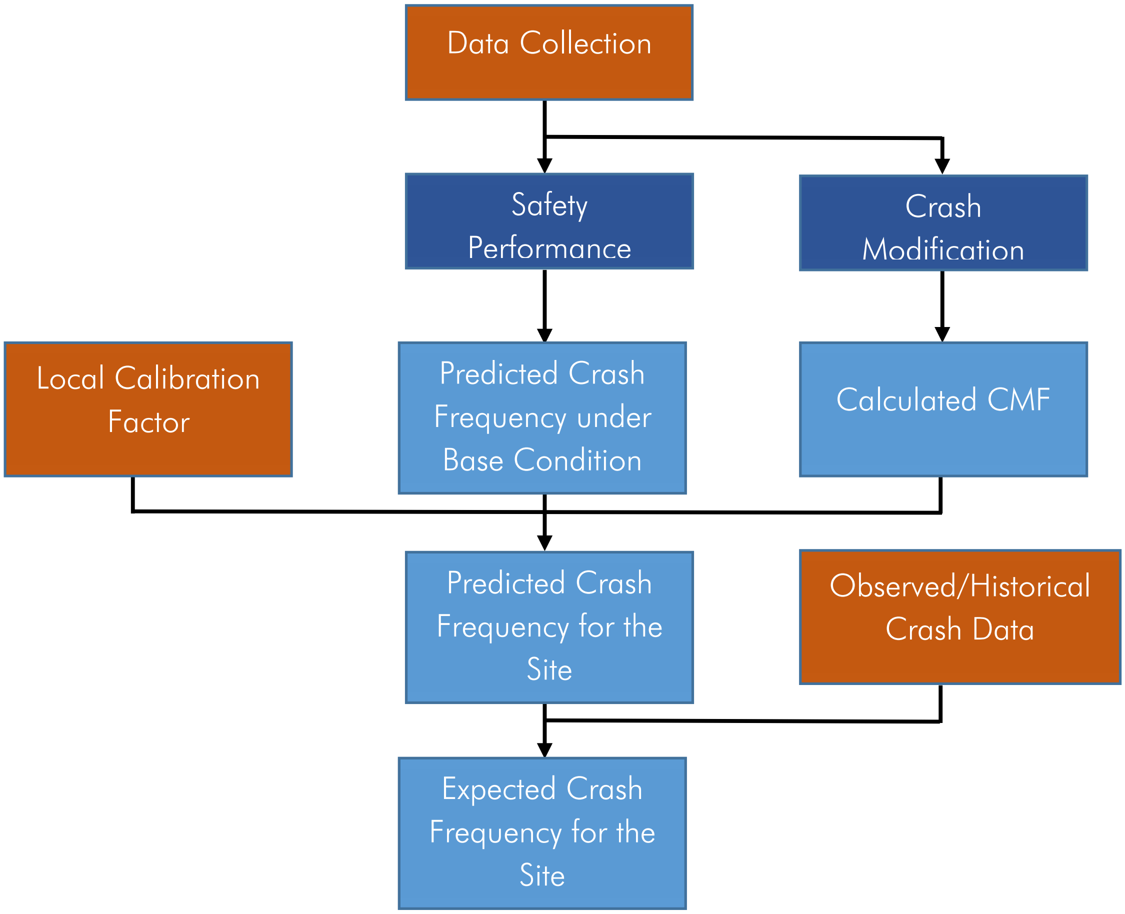

Figure 12: Steps to estimate crashes using HSM 2010

4.2.1 Steps to Calculate Expected Crash Frequency Using HSM 2010

Step 1: Data Collection

All the data required to estimate crashes for before and after conditions was collected in the form of a table, presented in **Table 7** [17]. The Annual Average Daily Traffic (AADT) were obtained from IDOT [18]. The AADT data was available for only 2 years, so using the HSM 2010 methodology, the remaining AADT was calculated by interpolation and extrapolation. For a four-leg intersection, the AADT for the two major legs and the two minor legs may differ, so the AADT of the larger of the two major legs was used for $AADT_{maj}$ and the AADT of the larger of the two minor legs was used as the $AADT_{min}$ (HSM 2010). Data for calculating the crash modification factors (CMFs) were collected by aerial images. The Illinois calibration factor C_i was found from the AASHTO Highway Safety Manual (1st Edition) Illinois User Guide [17].

As an example, this section presents the steps to calculate the expected crashes using the HSM 2010 for a four-leg signalized intersection of Goodwin Avenue and Green Street in the Champaign-Urbana urbanized area using the 2010 data from **Table 7**.

Table 7: Summary of Pedestrian and Bike Crashes for Before (2006-2010) and After (2011-2015) by Injury Type

Step 1: List of Data for Calculating the Expected Crash Frequency		
Data Item	**Data Collected**	
Data for Calculating Predicted Crash Frequency under Base Condition		
AADT for major road (veh/day)	10,640	
AADT for minor road (veh/day)	5,240	
Sum of Daily Pedestrian Volume (Ped/day)	7,764	
Maximum number of lanes crossed by Pedestrian	5	
Data for Calculating Crash Modification Factors		
Number of approached with left turn lanes	4	
Type of left turn phasing	Approach 1	Prot+perm
	Approach 2	Prot+perm
	Approach 3	Prot+perm
	Approach 4	Prot+perm
	Approach 5	..
Number of approaches with right turn lanes	0	
Number of approaches with right-turn-on-red prohibited	4	
Lighting	Yes	
Red-light camera	No	
Number of bus stops within 1,000 ft of intersection	7	
Presence of schools within 1,000 ft of the intersection	Yes	
Number of alcohol sales establishments within 1,000 ft of the intersection	None	
Illinois Safety Performance Function Calibration Factor and Replaced Default Values		
Illinois calibration factor	2.32	
Bicycle crash adjustment factor	0.015	
Proportion of total crashes for unlightened intersections that occur at night		

Step 2: Selection and Calculation of Safety Performance Functions (SPFs)

To predict crashes for base condition, SPFs are selected based on the type of facility. In this case, the safety performance function for urban and suburban intersections were selected. Among the 25 intersections, two intersections are three-leg signalized and one is a five-leg signalized intersection, while the rest are four-leg signalized intersections. SPFs for five-leg signalized intersections were not present in HSM 2010, thus this intersection was not selected for the before (2006-2010) and after (2011-2015) analysis. The equations for prediction of crash frequencies for base condition in the form of multiple-vehicle collisions, single-vehicle collisions, and vehicle-pedestrian collisions are presented in equation 12-21, 12-24, and 12-29 respectively in the HSM 2010.

Equations for four-leg signalized intersections:

$$N_{bimv} = exp\ (-10.99+1.07\ x\ ln(AADT_{maj})+0.23\ x\ ln(AADT_{min})) \quad (4.2)$$

$$N_{bisv} = exp\ (-10.21+0.68\ x\ ln(AADT_{maj})+0.27\ x\ ln(AADT_{min})) \quad (4.3)$$

$$N_{pedbase}=exp\ (-9.53+0.40\ x\ ln(AADT_{maj}+AADT_{min})+0.26\ x\ ln(AADT_{maj}/AADT_{min})+0.45\ x\ ln(PedVol)+0.04\ x\ n_{lanesx}) \quad (4.4)$$

Equations for three-leg signalized intersections:

$$N_{bimv}=exp\ (-12.13+1.11\ x\ ln(AADT_{maj})+0.26\ x\ ln(AADT_{min})) \quad (4.5)$$

$$N_{bisv}=exp\ (-9.02+0.42\ x\ ln(AADT_{maj})+0.40\ x\ ln(AADT_{min})) \quad (4.6)$$

$$N_{pedbase}=exp\ (-6.60+0.05\ x\ ln(AADT_{maj}+AADT_{min})+0.24\ x\ ln(AADT_{maj}/AADT_{min})+0.41\ x\ ln(PedVol)+0.09\ x\ n_{lanesx}) \quad (4.7)$$

Where

N_{bimv}	= predicted average number of multiple-vehicle collisions for base condition
N_{bisv}	= predicted average number of single-vehicle collisions for base condition
$N_{pedbase}$	= predicted average number of vehicle-pedestrian collisions for base condition
N_{bikei}	= predicted average number of vehicle-bicycle collisions for base condition
$AADT_{maj}$	= Annual Average Daily Traffic (AADT) for major road
$AADT_{min}$	= Annual Average Daily Traffic (AADT) for minor road
$PedVol$	= sum of daily pedestrian volume crossing all intersection legs
n_{lanesx}	= maximum number of traffic lanes crossed by pedestrian

Therefore, for the four-leg signalized intersection of Goodwin Avenue and Green Street example, equations 4.2, 4.3 and 4.4 are used to estimate multiple-vehicle, single-vehicle and vehicle-pedestrian type of collisions respectively.

$N_{bimv}=exp\ (-10.99+1.07\ x\ ln(10{,}640)+0.23\ x\ ln(5{,}240))$ = **2.46 crashes/year**

$N_{bisv}=exp\ (-10.21+0.68\ x\ ln(10{,}640)+0.27\ x\ ln(5.240))$ = **0.20 crashes/year**

$N_{pedbase}=exp\ (-9.53+0.40\ x\ ln(10{,}640+5{,}240)+0.26\ x\ ln(10{,}640/5{,}240)+0.45\ x\ ln(7{,}764)+0.04\ x\ 5)$ = **0.20 crashes/year**

Step 3: Selection and Calculation of Crash Modification Factors (CMFs)

For intersections, there are 6 CMFs for multi-vehicle collisions and single-vehicle crashes and 3 CMFs for vehicle-pedestrian collisions. The CMFs and their references in the HSM 2010 are presented in **Table 8**. Based on the description of the CMFs, aerial images or site visits were used to get the required information to calculate CMFs.

Table 8: Crash Modification Factors (CMF) with HSM 2010 Reference

Applicable SPF	CMF	CMF Description	CMF equation and tables in HSM 2010
Multi-Vehicle collisions and Single-Vehicle Crashes at Intersections	CMF_{1i}	Left-Turn Lanes	Table 12-24
	CMF_{2i}	Left-Turn Signal Phasing	Table 12-25
	CMF_{3i}	Right Turn Lanes	Table 12-26
	CMF_{4i}	Right-Turn-on-Red	Equation 12-35
	CMF_{5i}	Lighting	Equation 12-36 and Table 12-27
	CMF_{6i}	Red-Light Camera	Equation 12-37, 12-38, 12-39
Vehicle-Pedestrian Collisions at Signalized Intersections	CMF_{1p}	Bus Stops	Table 12-28
	CMF_{2p}	Schools	Table 12-29
	CMF_{3p}	Alcohol Sales Establishments	Table 12-30

For the four-leg signalized intersection of Goodwin Avenue and Green Street, the data from **Table 7** and the references from the HSM 2010 presented in **Table 8** and **Table 9** were used to determine the CMFs which are presented in **Table 9**.

Table 9: CMFs for 4-leg Signalized Example Intersection

CMF	CMF Description	CMF equation and tables in HSM 2010	Values
CMF_{1i}	Left-Turn Lanes	Table 12-24	0.66
CMF_{2i}	Left-Turn Signal Phasing	Table 12-25	0.96
CMF_{3i}	Right Turn Lanes	Table 12-26	1.00
CMF_{4i}	Right-Turn-on-Red	Equation 12-35	0.92
CMF_{5i}	Lighting	Equation 12-36 and Table 12-27	0.91
CMF_{6i}	Red-Light Camera	Equation 12-37, 12-38, 12-39	1.00
CMF_{1p}	Bus Stops	Table 12-28	4.15
CMF_{2p}	Schools	Table 12-29	1.35
CMF_{3p}	Alcohol Sales Establishments	Table 12-30	1.00

Step 4: Selection of Illinois Safety Performance Function (SPF) Calibration Factor

The Illinois SPF calibration factor (C_i) for signalized intersection was provided in the AASHTO Highway Safety Manual (1st Edition) Illinois User Guide [3] based on the district and the year. In this project, the intersections are located in District 5 and the analysis was done for before period which was from 2006-2010 and after period from 2011-2015. Thus for a four-leg signalized intersection, before 2009, the calibration factor is 3.22 and after is 2.32. In the case of a three-leg signalized intersection, before 2009 is 2.21 and after is 1.68.

In the four-leg signalized intersection of Goodwin Avenue and Green Street example, a calibration factor of 2.32 was used.

Step 5: Calculation of Predicted Crash Frequency under Site Prevailing Conditions

HSM 2010 provides equations to predict crashes under the site prevailing conditions. The base condition crashes as presented in equations from 4.2 to 4.7 are estimated based on collision types, thus the crash frequencies are also estimated by collision types. The following equations presents the predicted crash frequency for four-leg and three-leg signalized intersections.

Multi-vehicle and Single-vehicle Collisions

Where

$$N_{predicted\ mv} = C_i \times N_{bimv} \times (CMF_{1i} \times CMF_{2i} \times \ldots CMF_{6i}) \qquad (4.8)$$

$$N_{predicted\ sv} = C_i \times N_{bisv} \times (CMF_{1i} \times CMF_{2i} \times \ldots CMF_{6i}) \qquad (4.9)$$

Where

C_i = calibration factor for the facility type
N_{bimv} = predicted average number of multiple-vehicle collisions for base conditions
N_{bisv} = predicted average number of vehicle-vehicle collisions for base conditions
CMF_{ni} (n=1,2..6)= CMFs for vehicle-vehicle collisions at signalized intersections

Vehicle and Pedestrian Collisions

Where

$$N_{predicted\ vp} = C_i \times N_{pedbase} \times (CMF_{1p} \times CMF_{2p} \times \ldots CMF_{6p}) \qquad (4.10)$$

Where

C_i = calibration factor for the facility type
$N_{pedbase}$ = predicted average number of vehicle-pedestrian collisions for base conditions
CMF_{np} (n=1,2,3)= CMFs for vehicle-pedestrian collisions at signalized intersections

Vehicle-Bicycle (Vehicle-Bike) Collisions

$$N_{bikei} = N_{bi} \times f_{bikei} \qquad (4.11)$$

Where

N_{bi} = predicted average crash frequency of an intersection (excluding vehicle-pedestrian and vehicle-bicycle collisions)
f_{bikei} = bicycle crash adjustment factor

In the example of four-leg signalized intersection of Goodwin Avenue and Green Street,

Multi-Vehicle and Single-Vehicle Collisions

$N_{predicted\ mv} = 2.32 \times 2.46 \times (0.66 \times 0.96 \times 1.00 \times 0.92 \times 0.91 \times 1.00) = \mathbf{3\ crashes/year}$

$N_{predicted\ sv} = 2.32 \times 0.20 \times (0.66 \times 0.96 \times 1.00 \times 0.92 \times 0.91 \times 1.00) = \mathbf{0\ crashes/year}$

Vehicle-Pedestrian Collisions

$N_{predicted\ vp} = 2.32 \times 0.20 \times (4.15 \times 1.35 \times 1.00) = \mathbf{3\ crashes/year}$

Vehicle-Bicycle Collisions

$N_{bikei} = 0.015 \times (3+0) = \mathbf{0\ crashes/year}$

Step 6: Observed Crash Data

The observed crashes for the intersections were identified in this step. The crashes from 2006 to 2015 were obtained from IDOT. The collision type of the crashes in HSM 2010 are categorized as multivehicle (MV), single vehicle (SV), vehicle-pedestrian (VP) or vehicle-bicycle (vehicle-bike) (VB) type crashes. The crash data from IDOT showed different collision types and it was categorized as MV, SV, VP or VB. **Table 10** presents the IDOT crash data collision types categorized as MV, SV, VP or VB collision types. The collision types presented in **Table 10** are the ones observed from the 2006-2015 crash data at the 25 studied intersections.

Table 10: Categorization of IDOT Crash Collision Types

Collision Type (IDOT)	Category Type	Code (HSM 2010)
Pedestrian	Vehicle-Pedestrian	VP
Pedalcyclists (bikes, bicycle)	Vehicle-Bicycle	VB
Overturned	Single-Vehicle	SV
Fixed Object	Single-Vehicle	SV
Parked Motor Vehicle	Multi-Vehicle	MV
Turning	Multi-Vehicle	MV
Rear End	Multi-Vehicle	MV
Side Swap Same Direction	Multi-Vehicle	MV
Side Swap Opposite Direction	Multi-Vehicle	MV
Head-On	Multi-Vehicle	MV
Angle	Multi-Vehicle	MV

For the four-leg signalized intersection of Goodwin Avenue and Green Street, the number of multi-vehicle crashes are 3, single-vehicle crashes are 0, vehicle-pedestrian crashes are 0 and vehicle-bicycle (vehicle-bike) crashes is 1. These numbers were used in the calculation of expected crash frequency presented in the following section.

Step 7: Calculation of Expected Average Crash Frequency for the Site

The expected crash frequencies were determined by combining the predicted and observed crash frequencies. This was done in two steps using Empirical Bayes method. First, the weighted adjustment (w) was calculated using equation 4.12 based on SPF overdispersion parameter (k). Then, equation 4.13 was used to estimate expected crash frequencies.

$$w = 1/(1 + k \times \textstyle\sum_{\text{all study years}} N_{predicted}) \qquad (4.12)$$

$$N_{expected} = w \times N_{predicted} + (1-w) \times N_{observed} \qquad (4.13)$$

For the four-leg signalized intersection of Goodwin Avenue and Green Street, the calculation of expected crashes was completed as follows:

Expected Multi-Vehicle Crashes
Overdispersion parameter (k) from HSM 2010: 0.39.
$N_{predicted}$ calculated using equation 4.8: 3 crashes/year.

Substituting these values in equation 4.12,

$w = 1/(1 + 0.39 \times 3) = \mathbf{0.46}$

$N_{expected} = 0.46 * 3 + (1 - 0.46) * 3 =$ ***3 crashes/year***

Expected Single-Vehicle Crashes
Overdispersion parameter (k) from HSM 2010: 0.36.
$N_{predicted}$ calculated using equation 4.9: 3 crashes/year.

$w = 1/(1 + 0.36 \times 0) = \mathbf{1}$

$N_{expected} = 1 * 0 + (1 - 1) * 0 =$ ***0 crashes/year***

Vehicle-Pedestrian Crashes
Overdispersion parameter (k) from HSM 2010: 0.24
$N_{predicted}$ calculated using equation 4.10: 3 crashes/year.

$w = 1/(1+0.24 \times 3) = \mathbf{0.58}$

$N_{expected} = 0.58 * 3 + (1 - 0.58) * 0 =$ ***2 crashes/year***

Vehicle-Bicycle Crashes
Overdispersion parameter (k) from HSM 2010: 0
$N_{predicted}$ calculated using equation 4.11: 0 crashes/year.

$w = 1/(1 + 0 \times 0) = \mathbf{1}$

$N_{expected} = 1 * 0 + (1 - 1) * 1 =$ **0 crashes/year**

Step 8: Calculation of Expected Crash Frequency after the Signal Change

This step is performed to estimate crash frequencies for only after (2011-2015) period of analysis that is after the implementation of the new yellow time and all-red clearance interval, i.e. from 2011 to 2015. In this step, an additional crash modification factor (CMF) related to modifying the yellow time and all-red clearance interval was applied to expected crashes calculated from equation 4.13. In HSM 2010, the CMF reference table 14-27 for four-leg signalized intersections is assumed to be the same for three-leg signalized intersections since HSM 2010 does not provide a separate CMF for three-leg signalized intersections. Table 14-27 provides CMF with standard error from which a range of crash frequencies can be estimated. This range was presented in the form of lower limit and upper limit values. Considering a 68% confidence interval, lower limit and upper limit were calculated as follow:

Lower Limit (LL) = $N_{expected}$ x $(CMF-\sigma)$ (4.14)

Upper Limit (UL) = $N_{expected}$ x $(CMF+\sigma)$ (4.15)

For the four-leg signalized intersection of Goodwin Avenue and Green Street example, the CMF for the updated yellow time and all-red clearance interval is 0.92 with standard error of 0.07 (HSM 2010, table 14-27). Thus the range of expected multi-vehicle crashes within 68% confidence interval are

Lower Limit (LL) = $N_{expected}$ *x (0.92 - 2 * 0.07) = 3 x 0.78 =* ***2 crashes/year***
Upper Limit (UL) = $N_{expected}$ *x (0.92 - 2 * 0.07) = 3 x 1.06 =* ***3 crashes/year***

The range for single-vehicle crashes are

Lower Limit (LL) = $N_{expected}$ *x (0.92 - 2 * 0.07) = 0 x 0.78 =* ***0 crashes/year***
Upper Limit (UL) = $N_{expected}$ *x (0.92 - 2 * 0.07) = 0 x 1.06 =* ***0 crashes/year***

The range for vehicle-pedestrian crashes are

Lower Limit (LL) = $N_{expected}$ *x (0.92 - 2 * 0.07)=2 x 0.78 =* ***2 crashes/year***
Upper Limit (UL) = $N_{expected}$ *x (0.92 - 2 * 0.07)=2 x 1.06 =* ***2 crashes/year***

The range for vehicle-bicycle (vehicle-bike) crashes are

Lower Limit (LL) = $N_{expected}$ *x (0.92 - 2 * 0.07) = 0 x 0.78 =* ***0 crashes/year***
Upper Limit (UL) = $N_{expected}$ *x (0.92 - 2 * 0.07) = 0 x 1.06 =* ***0 crashes/year***

The summary of the observed and estimated crashes from HSM 2010 is:

Table 11: Summary of Observed and Expected Crashes for Four-Leg Signalized Example

Collision Type	Observed Crashes	Expected Number of Crashes	
		Lower Limit (LL)	Upper Limit (UL)
Multi-Vehicle Crashes	3	2	3
Single-Vehicle Crashes	0	0	0
Vehicle-Pedestrian Crashes	0	2	2
Vehicle-Bicycle Crashes	1	0	0

Thus, from **Table 11**, it is observed that by implementing the yellow-time and all-red clearance interval, the multi-vehicle and single-vehicle crashes for the four-leg signalized intersection are within the expected range calculated from HSM 2010. In reality, this intersection performed better than the expected vehicle-pedestrian crashes. On the other hand, the intersection performed worse than the expected vehicle-bicycle (vehicle-bike) crashes.

4.2.2 Analysis of Expected and Observed Crashes

The expected crashes were calculated from the Highway Safety Manual 2010 using the steps mentioned in the previous section. As mentioned in Step 8 from the previous section, the HSM 2010 provides CMF for change in yellow time and all-red clearance interval along with a standard deviation. Thus, a range of expected crashes were estimated for the after condition from 2011 to 2015. The lower and upper limit of expected crashes within 68% confidence interval were presented for the after (2011-2015) condition only. Equations 4.14 and 4.15 were used. **Table 12** presents the total and average number of crashes estimated and observed. Since the HSM 2010 did not have a crash estimation model for a 5-leg intersection, crashes were not estimated for the intersection of State Street and Bradley Avenue.

In **Table 12**, the total number of intersection crashes in the City of Champaign was observed to be higher than the number of estimated crashes using HSM 2010. Thus, HSM 2010 underestimated crashes for the City of Champaign. On the other hand, the total number of intersection crashes observed at the University of Illinois and City of Urbana intersections was either less than or equal to the total number of estimated crashes using the HSM 2010. If the observed crashes were less than the estimated crashes, then it can be said that the intersection performed better than expected.

Table 12: Observed and Expected Crashes at Intersections for Before (2006-2010) and After (2011-2015) Conditions

Location	Intersection	Observed 2006 to 2010		HSM 2010 Expected Crashes 2006 to 2010		Observed 2011 to 2015		HSM 2010 Expected Crashes Lower Limit (LL) 2011 to 2015		HSM 2010 Expected Crashes Upper Limit (UL) 2011 to 2015	
		Total	Average	Total	Average	Total	Average	Total	Average	Total	Average
City of Champaign	Mattis Avenue and Olympian Drive	4	1	4	1	2	0	1	0	1	0
	Mattis Avenue and Interstate Drive	16	3	15	3	17	3	12	2	13	3
	Mattis Avenue and Kirby Avenue	45	9	48	10	37	7	30	6	35	7
	Randolph Street and Bradley Avenue	14	3	13	3	13	3	11	2	12	2
	Neil Street and Bradley Avenue	39	8	40	8	49	10	35	7	42	8
	Market Street and Bradley Avenue	21	4	21	4	18	4	15	3	17	3
	Fourth Street and Kirby Avenue	23	5	23	5	20	4	15	3	17	3
	First Street and Kirby Avenue	29	6	30	6	16	3	16	3	16	3
	Oak Street and Kirby Avenue	10	2	12	2	12	2	11	2	11	2
	Duncan Road and Windsor Road	10	2	10	2	18	4	13	3	16	3
	Mattis Avenue and Windsor Road	15	3	15	3	17	3	15	3	16	3
	Galen Drive and Windsor Road	5	1	7	1	10	2	10	2	10	2
	Prospect Avenue and Windsor Road	24	5	21	4	12	2	12	2	12	2
	Total	**285**	**57**	**259**	**52**	**277**	**55**	**196**	**39**	**218**	**44**
University of Illinois	Sixth Street and Gregory Drive	7	1	9	2	9	2	6	1	7	1
	Sixth Street and Armory Avenue	6	1	7	1	3	1	0	0	5	1
	Total	**13**	**3**	**16**	**3**	**12**	**2**	**6**	**1**	**12**	**2**
City of Urbana	Goodwin Avenue and Green Street	23	5	27	5	8	2	10	2	10	2
	Lincoln Avenue and Bradley Avenue	36	7	36	7	31	6	27	5	34	7
	Lincoln Avenue and Springfield Avenue	23	5	23	5	22	4	18	4	22	4
	Lincoln Avenue and Green Street	38	8	38	8	22	4	18	4	22	4
	Lincoln Avenue and Pennsylvania Avenue	25	5	25	5	15	3	14	3	15	3
	Lincoln Avenue and Florida Avenue	25	5	28	6	24	5	20	4	24	5
	Lincoln Avenue and Windsor Road	15	3	15	3	21	4	20	4	21	4
	Broadway Avenue and Main Street	6	1	8	2	5	1	5	1	5	1
	Race Street and Main Street	18	4	19	4	15	3	10	2	13	3
	Total	**209**	**42**	**219**	**44**	**163**	**33**	**142**	**28**	**166**	**33**

Table 13 presents the P-values of the statistical t-test for α = 0.05 to determine if the HSM 2010 was able to estimate crashes at intersections within an acceptable range for the Champaign-Urbana region. The t-test was not done for the University of Illinois jurisdiction since only two intersections were available for analysis. The P-values of before (2006-2010) and after (2011-2015) condition for the City of Champaign (14 intersections) are less than 0.05, thus the estimated crashes from HSM 2010 for the intersections in this jurisdiction were significantly different than the observed crashes for the before (2006-2010) and after (2011-2015) conditions. On the other hand, the P-values for the City of Urbana were greater than 0.05, thus there was no significant difference between the mean of observed and estimated crashes. Thus, the HSM 2010 might not be able to capture all the factors required to estimate crashes at intersections for the City of Champaign.

Table 13: P-Values (α = 0.05) of t-Test Between Observed and Expected Average Crashes Across the Intersection by Jurisdictions

Jurisdiction	Before (2006-2010)	After (2011-2015)	
	Observed and Expected	Observed and Lower Limit (LL)	Observed and Upper Limit (UL)
City of Champaign	1.000	0.013	0.027
City of Urbana	0.169	0.081	0.347

The comparison between the average crashes observed and estimated using HSM 2010 by type of collision is presented in **Table 14** and **Table 15**. For the before condition (2006-2010), the observed average number of crashes at the intersection of Prospect Avenue and Windsor Road was higher than expected numbers estimated from HSM 2010. For the after (2011-2015) condition in the City of Champaign, the observed average number of single-vehicle crashes at the intersection of Mattis Avenue and Interstate Drive was higher than the expected. At the intersection of Neil Street and Bradley Avenue, the observed average number of multi-vehicle crashes was higher than expected. At the intersection of Fourth Street and Kirby Avenue, the observed average number of vehicle-bicycle crashes was higher than expected. At the University of Illinois, for after condition (2011-2015), the observed average number of single vehicle crashes at the intersection of Sixth Street and Armory Avenue was higher than expected. In the City of Urbana, the observed average number of crashes were within the expectable range estimated by HSM 2010 for before (2006-2010) and after (2011-2015) conditions.

Table 14: Difference between Observed and Expected Average Crashes including Multi-Vehicle and Single-Vehicle Collision Type at Intersections for Before (2006-2010) and After (2011-2015) Conditions

Location	Intersection	Average Crashes			Average Multi-Vehicle Crashes			Average Single-Vehicle Crashes		
		Before[1]	After[2]	After[2]	Before[1]	After[2]	After[2]	Before[1]	After[2]	After[2]
		Exp[3]-Obs[4]	LL[5]-Obs[4]	UL[6]-Obs[4]	Exp[3]-Obs[4]	LL[5]-Obs[4]	UL[6]-Obs[4]	Exp[3]-Obs[4]	LL[5]-Obs[4]	UL[6]-Obs[4]
City of Champaign	Mattis Avenue and Olympian Drive	0	0	0	0	0	0	0	0	0
	Mattis Avenue and Interstate Drive	0	-1	-1	0	0	0	0	-1	-1
	Mattis Avenue and Kirby Avenue	1	-1	0	0	-1	0	0	0	0
	Randolph Street and Bradley Avenue	0	0	0	0	0	0	0	0	0
	Neil Street and Bradley Avenue	0	-3	-1	0	-2	-1	0	0	0
	Market Street and Bradley Avenue	0	-1	0	0	0	0	0	0	0
	Fourth Street and Kirby Avenue	0	-1	-1	0	0	0	0	0	0
	First Street and Kirby Avenue	0	0	0	0	0	0	0	0	0
	Oak Street and Kirby Avenue	0	0	0	0	0	0	0	0	0
	Duncan Road and Windsor Road	0	-1	0	0	0	0	0	0	0
	Mattis Avenue and Windsor Road	0	0	0	0	0	0	0	0	0
	Galen Drive and Windsor Road	0	0	0	0	0	0	0	0	0
	Prospect Avenue and Windsor Road	-1	0	0	0	0	0	0	0	0
University of Illinois	Sixth Street and Gregory Drive	0	-1	0	0	0	0	0	0	0
	Sixth Street and Armory Avenue	0	-1	0	0	0	0	0	-1	-1
City of Urbana	Goodwin Avenue and Green Street	1	0	0	0	0	0	0	0	0
	Lincoln Avenue and Bradley Avenue	0	-1	1	0	-1	0	0	0	0
	Lincoln Avenue and Springfield Avenue	0	-1	0	0	-1	0	0	0	0
	Lincoln Avenue and Green Street	0	-1	0	0	-1	0	0	0	0
	Lincoln Avenue and Pennsylvania Avenue	0	0	0	0	0	0	0	0	0
	Lincoln Avenue and Florida Avenue	1	-1	0	0	-1	0	0	0	0
	Lincoln Avenue and Windsor Road	0	0	0	0	0	0	0	0	0
	Broadway Avenue and Main Street	0	0	0	0	0	0	0	0	0
	Race Street and Main Street	0	-1	0	0	-1	0	0	0	0

1. Before: 2006-2010
2. After: 2011-2015
3. Expected (Exp) Average Crashes (HSM 2010)
4. Observed (Obs) Average Crashes
5. Expected Lower Limit (LL) of Estimated Crashes from HSM 2010
6. Expected Upper Limit (UL) of Estimated Crashes from HSM 2010

Avg Obs Crashes > Avg Exp Crashes
Avg Obs Crashes < Avg Exp Crashes
Avg Obs Crashes = Avg Exp Crashes

Table 15: Difference between Observed and Expected Average Crashes including Multi-Vehicle and Single-Vehicle Collision Type at Intersections for Before (2006-2010) and After (2011-2015) Conditions

Location	Intersection	Average Vehicle-Pedestrian Crashes			Average Vehicle-Bicycle Crashes		
		Before[1]	After[2]	After[2]	Before[1]	After[2]	After[2]
		Exp[3]-Obs[4]	LL[5]-Obs[4]	UL[6]-Obs[4]	Exp[3]-Obs[4]	LL[5]-Obs[4]	UL[6]-Obs[4]
City of Champaign	Mattis Avenue and Olympian Drive	0	0	0	0	0	0
	Mattis Avenue and Interstate Drive	0	0	0	0	0	0
	Mattis Avenue and Kirby Avenue	1	0	0	0	0	0
	Randolph Street and Bradley Avenue	0	0	0	0	0	0
	Neil Street and Bradley Avenue	1	0	0	0	0	0
	Market Street and Bradley Avenue	0	0	0	0	0	0
	Fourth Street and Kirby Avenue	1	0	0	0	-1	-1
	First Street and Kirby Avenue	1	0	0	0	0	0
	Oak Street and Kirby Avenue	0	0	0	0	0	0
	Duncan Road and Windsor Road	0	0	0	0	0	0
	Mattis Avenue and Windsor Road	0	0	0	0	0	0
	Galen Drive and Windsor Road	0	0	0	0	0	0
	Prospect Avenue and Windsor Road	0	0	0	0	0	0
University of Illinois	Sixth Street and Gregory Drive	1	0	0	0	0	0
	Sixth Street and Armory Avenue	1	0	1	0	0	0
City of Urbana	Goodwin Avenue and Green Street	1	1	1	0	0	0
	Lincoln Avenue and Bradley Avenue	1	0	1	0	0	0
	Lincoln Avenue and Springfield Avenue	0	0	0	0	0	0
	Lincoln Avenue and Green Street	0	0	0	0	0	0
	Lincoln Avenue and Pennsylvania Avenue	0	0	0	0	0	0
	Lincoln Avenue and Florida Avenue	1	0	0	0	0	0
	Lincoln Avenue and Windsor Road	0	0	0	0	0	0
	Broadway Avenue and Main Street	0	0	0	0	0	0
	Race Street and Main Street	1	0	0	0	0	0

1. Before: 2006-2010
2. After: 2011-2015
3. Expected (Exp) Average Crashes (HSM 2010)
4. Observed (Obs) Average Crashes
5. Expected Lower Limit (LL) of Estimated Crashes from HSM 2010
6. Expected Upper Limit (UL) of Estimated Crashes from HSM 2010

Avg Obs Crashes > Avg Exp Crashes
Avg Obs Crashes < Avg Exp Crashes
Avg Obs Crashes = Avg Exp Crashes

5. Study Findings

This report presents the before (2006-2010) and after (2011-2015) analysis of crashes at signalized intersections to study the effect of yellow time and all-red clearance interval in Champaign-Urbana urbanized area. This section presents the findings from literature review, performance level of the 25 studied intersections, analysis of crash data of the studied intersections and comparison with crashes estimated using HSM 2010.

In the literature review, the following observations were made:

- The increase in yellow time reduced the red light violations. On the other hand, excessive long yellow time might encourage the drivers to not wait and hence disregard the yellow time.
- The yellow timing followed by all-red clearance reduced the red light violations, right angle crashes and property damage crashes.
- A positive safety effect of yellow time and all-red clearance was observed for short term from 6 months to 1 year but no long term benefits were observed.

The performance level of the 25 study intersections were studied using a microsimulation software Synchro®. It is observed that 9 out of 14 intersections in the City of Champaign, 2 out of 2 intersections in the University of Illinois and 4 out of 9 intersections in the City of Urbana observed reduction in peak hour volumes and level of service (LOS).

The observations from the before (2006-2010) and after (2011-2015) condition analysis of crashes are:

- No statistically significant difference in the number of intersection crashes by jurisdiction over the five years of before (2006-2010) and after (2011-2015) periods was observed after updating the yellow time and all-red clearance interval at intersections.
- The intersection of Neil Street and Bradley Avenue observed the highest number (10) of average crashes in the after period (2011-2015).
- The intersection of State Street and Bradley Avenue observed the highest crash rate, followed by the intersection of Lincoln Avenue and Green Street; while lower crash rates were observed for the intersections of Mattis Avenue and Olympian Drive, and Galen Drive and Windsor Road.
- The predominant types of crashes in the before (2006-2010) and after (2011-2015) conditions at the studied intersections were rear-end, turning, angular and fixed object ranging from 85% to 95%.
- At the University of Illinois, the percentage of fixed object type of collisions in the after (2011-2015) period are higher (31%) than rear-end, turning movement, and angle type. In the after (2011-2015) condition, fixed object type of collisions increased by 11%.
- In the before (2006-2010) and after (2011-2015) periods, the percentage of rear-end type of collisions are higher, ranging from 37% to 44% in the City of Champaign and City of Urbana as compared to the turning, angular and fixed object type. In the City of Champaign, rear-end movement collisions increased by 2%, while a 7% reduction was observed in City of Urbana for the after (2011-2015) period.
- From the literature review, the yellow time and all-red clearance interval affect the angular collision crashes. In the after (2011-2015) period, 15% and 5% reduction in angular crashes was observed at the University of Illinois and City of Champaign respectively, while an 8% increase was observed in the City of Urbana.
- The predominant percentage of injury type of crashes are no-injury/property damage type. In the after period (2011-2015). The percentage of property damage type crashes decreased by 46%, 8%, and 1% in City of Urbana, City of Champaign and University of Illinois respectively. Also in the after (2011-2015) period, the percentage of

higher injury crashes increased, excluding the University of Illinois where only B-type injury crashes increased.
- The pedestrian crashes in the after (2011-2015) period increased by 3 in the City of Champaign and City of Urbana, while no change was observed for the University of Illinois.
- The bike crashes in the after (2011-2015) period increased by 3 in the City of Champaign, no change at the University of Illinois, and a reduction of 2 crashes was observed in City of Urbana.
- The no-injury type of pedestrian and bike crashes reduced to zero in the after (2011-2015) condition, while an increase in injury type of crashes was observed.

The Highway Safety Manual 2010 (HSM) was used to estimate the expected number of crashes for before (2006-2010) and after (2011-2015) conditions. HSM 2010 provides a crash estimation model taking into account the yellow time and all-red clearance interval. Following are the observations from comparing the estimated crashes with observed crashes for before (2006-2010) and after (2011-2015) conditions.

- A significant difference between the observed and estimated crashes at the studied intersections in the City of Champaign was observed for the after (2011-2015) condition. HSM 2010 underestimated the total number of crashes at the studied intersections (13 intersections) in the City of Champaign.
- In the City of Urbana, no significant difference between the intersection crashes and the estimated crashes using HSM 2010 was observed for before (2006-2010) and after (2011-2015) conditions. The total of studied intersection (9 intersections) crashes are within the expected range of crashes estimated by HSM 2010.
- The total number of crashes at the studied intersections (2 intersections) at the University of Illinois were within the expected number of estimated crashes from HSM 2010 for before (2006-2010) and after (2011-2015) conditions.
- In the after (2011-2015) condition, the Neil Street and Bradley Avenue intersection observed a higher average number of multi-vehicle crashes than expected. Also in the after (2011-2015) condition, the Mattis Avenue and Interstate Drive plus the Sixth Street and Armory Avenue intersections observed a higher than average number of single-vehicle crashes than expected. The intersection of Fourth Street and Kirby Avenue observed a higher than average number of vehicle-bicycle (vehicle-bike) crashes than expected. In the City of Urbana, the observed crashes at intersections were within the expected range of crashes estimated using HSM 2010.

Figure 13: Neil Street and Bradley Avenue Intersection

6. Conclusion and Recommendations

CUUATS yellow time and all-red signal clearance policy guidelines were implemented at City of Champaign, University of Illinois, and City of Urbana intersections in 2010-2011. To study the effect of this policy, 25 intersections were selected for the before (2006-2010) and after (2011-2015) condition analysis. 14 study intersections in the City of Champaign, 2 at the University of Illinois, and 9 in the City of Urbana were considered. This section summarizes the findings and conclusion.

In the year 2010, the lowest number of crashes were observed at the 25 studied intersections which was when the implementation of yellow time and all-red signal clearance had started and continued in 2011. There is no significant difference in the number of intersection crashes before (2006-2010) and after (2011-2015) by jurisdiction. This means no long term effect of yellow time and all-red clearance was observed in the City of Champaign, City of Urbana nor at the University of Illinois.

The predominant collision types at the 25 studied intersections in the before (2006-2010) and after (2011-2015) conditions were rear-end, turning movement, angular and fixed object ranging from 85% to 95%. Since the University of Illinois has different socio-economic and demographic characteristics than the rest of Champaign-Urbana, the trends of crashes for before (2006-2010) and after (2011-2015) conditions were different between the three jurisdictions. At the University of Illinois, the fixed object type of collisions are higher as opposed to the City of Urbana and City of Champaign. The percentage of rear end and turning movement types of collisions became zero after the implementation of yellow time and all-red signal clearance. Since only 2 intersections from the University of Illinois were considered for this study, more intersections are required for study to confirm these findings.

The injury type of crashes have either increased or remained the same in the after (2011-2015) period except for the property damage crashes. As discussed in section 1.1, Guerin (2012) [11] observed a significant reduction of property damage crashes and rear-end crashes by implementing the yellow time and all-red signal clearance. In the after (2011-2015) period, the City of Champaign, City of Urbana and University of Illinois observed a reduction in property damage crashes, with a significant reduction of 46% observed in the City of Urbana. On the other hand, a reduction in rear-end crashes was observed only in the City of Champaign and at the University of Illinois.

The only improvement in terms of pedestrian and bike crashes was seen in the City of Urbana where the bike crashes reduced by 2 in the after (2011-2015) period. Overall, the pedestrian crashes and bike crashes increased in the after (2011-2015) period, and the severity of these types of crashes also increased. Since pedestrians and bicyclists have less protection in a crash as compared to a driver in a car, they are more likely to have higher severity injury.

The HSM 2010, was used to estimate the before (2006-2010) and after (2011-2015) condition regarding intersection crashes in the City of Champaign and City of Urbana. The estimation of crashes for the City of Urbana closely matched the number of crashes observed; however, for the City of Champaign, the number of estimated crashes did not reflect the observed number of crashes for the after period (2011-2015). The intersection crashes at the University of Illinois and City of Urbana are within the expected range of crashes estimated from the HSM 2010 for the before (2006-2010) and after (2011-2015) conditions. Thus the HSM 2010 is a good tool to determine if the observed crashes are within the expected range, but the crash estimation model needs to be calibrated to be applied for a particular region.

Some intersections like Neil Street and Bradley Avenue, Mattis Avenue and Interstate Drive, Sixth Street and Armory Avenue, and Fourth Street and Kirby Avenue observed more crashes than expected, thus it is recommended to do a safety study at these intersections to determine the type of safety countermeasures needed to address safety problems at these intersections.

Overall, this study did not find any significant safety improvements due to the implementation of updated change and clearance intervals at the 25 study intersections. However, it is important to note that traffic safety improvements depend on many factors including road users' behaviors, traffic enforcement activities, roadway geometric conditions, weather, time of day, and many other factors.

Figure 14: Sixth Street and Armory Avenue Intersection

Figure 15: Sixth Street and Gregory Drive Intersection

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