Final Report

FIELD TESTING AND IMPLEMENTATION OF DILEMMA ZONE PROTECTION AND SIGNAL COORDINATION AT CLOSELY-SPACED HIGH-SPEED INTERSECTIONS

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16. Abstract

The report presents the details of a study carried out to test and implement a dilemma zone protection technique at three high-speed closely-spaced intersections on Roosevelt Blvd in Middletown, Ohio. Several factors that affect the testing and implementation of the dilemma zone reduction technique were considered as follows: (a) length of dilemma zone, which allowed for vehicular speeds ranging from 45 mph (72.41 kmph) to 60 mph (96.54 kmph) since speeds on these roadways are not uniform and tend to vary within a wide range; (b) detectors, which takes into account the varying speeds that exists on these roadways were located at 300 ft (91.44m) or 600 ft (182.88m), but not both; (c) green extensions, which varied from 1 sec to 5 sec in increments of 1 sec, with the "no green extension" being used as the base case; and (d) vehicle conflicts caused by (i) running red light (ii) stopping abruptly or (iii) accelerating through yellow representing the dilemma zone problem. The traffic data was collected during off peak hours in the morning (9am – 11am) and at night (8pm – 10pm). In all, 288 hours of data were collected on the six intersection approaches. The analysis revealed that that accelerating through yellow was the major conflict for all intersections, followed by running red and stopping abruptly respectively. The study indicated that the three types of conflicts namely, running red light, stopping abruptly and accelerating through yellow can be successfully used to identify vehicles that experience dilemma zone problems at signalized intersections. Overall, this study has shown that, for the roadway segment of Roosevelt Blvd between Highland and Armco, which has a speed limit of 45 mph (72.41 kmph), dilemma zone protection can be effective by placing detectors at 300 ft (91.44m) and providing a green extension of 3 sec on most, but not all, approaches. The effectiveness was more evident during the morning period than during the night period indicating that drivers' speed behavior may be different during daylight and night conditions. The study shows that there is no one "universal" rule for dilemma zone protection that would apply equally to all intersections because each intersection is unique in its geometric and operational characteristics and vehicular speeds on any intersection varies within a wide range. Recommendations for implementing the technique for future improvements of intersections identified with dilemma zone problems were made.

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The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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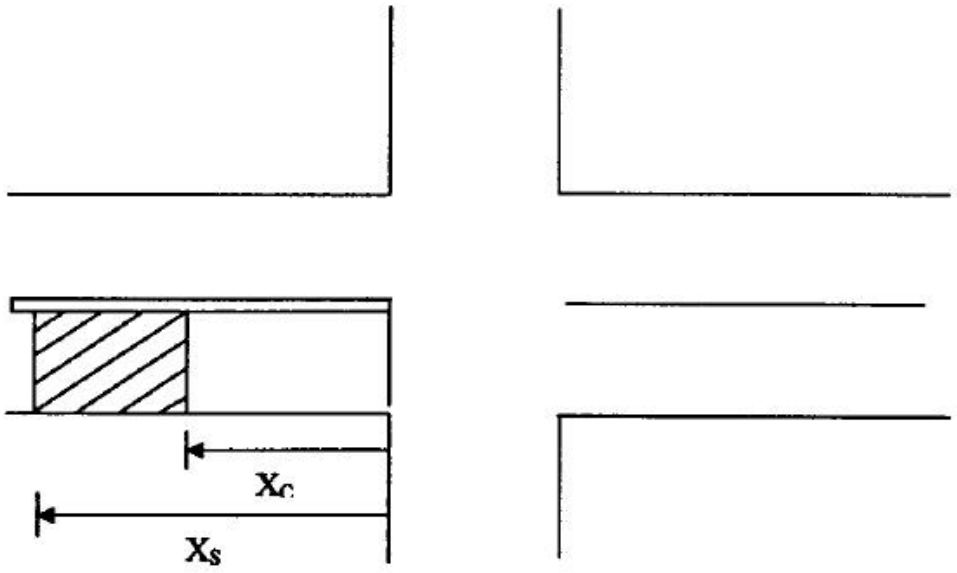
1 INTRODUCTION

Historically, high speed signalized intersections have reported many crashes and have always posed a challenge to traffic engineers for enhancing safety at these intersections. The area close to the intersection, called the dilemma zone, poses a high accident potential for the driver in stopping safely during the yellow interval or in proceeding through the intersection before the beginning of red. The driver is in a potentially hazardous situation whereby, if he tries to cross the intersection at the onset of red interval, he may end up in an angle accident with the cross street traffic or if he accelerates through yellow, he may end up in a rear-end collision. The uncertain situation in a dilemma zone can potentially lead to rear-end or right angle collisions.

Generally, the location of the driver on the intersection approach and the speed of the vehicle influence the driver's decision to stop or proceed when he sees the green signal changing to yellow. The minimum distance the driver requires to stop depends upon the speed of the vehicle, the driver's reaction time, and the deceleration rate. The clearing distance is the distance the vehicle travels between the times the signal changes to yellow to the time the signal changes to red. The stopping distance is the distance traveled by the vehicle between the times the signal changes to yellow to the time when the vehicle actually comes to rest. In Figure 1 the stopping distance is referred to as X_s and the clearing distance as X_c. If X_s is greater than X_c, and the vehicle is placed in

Figure 1. Dilemma Zone



X_S = Minimum Stopping Distance
X_C = Maximum Clearing Distance

between them, a dilemma zone is formed. In this situation, neither the distance to the intersection is adequate for stopping nor is the signal interval adequate for clearing the intersection. An example of clearing distance for a yellow interval of 4 sec is shown in Table 1. The stopping sight distances as suggested by AASHTO are shown in Table 2.

Table 1. Clearing Distance for 4 Sec Yellow Intervals

Speed mph (kmph)	Clearing Distance, ft (m) (Computed)
35 (56.32)	204 (62.18)
40 (64.36)	236 (71.93)
45 (72.41)	264 (80.47)
50 (80.45)	292 (89.00)
55 (88.50)	320 (97.54)
60 (96.54)	352 (107.29)

Some researchers define the dilemma zone as the area on a high speed approach within which 10% of the drivers stop and 90% of the drivers proceed, when they see the signal changing to yellow. It occurs at the end of green phase, which is often associated with rear end and right-angle collisions [2]

In general, a high speed intersection consists of an intersection approach with vehicular speeds of 35 mph (56.32 kmph) or higher. When signalized intersections are located adjacent to each other, then it is always advantageous to coordinate them. It helps to reduce the number of stops, maintain optimum travel speeds, reduce delay and reduce accident potential on roadways. Further, proper coordination can help in reducing vehicle emissions. Signal coordination depends upon the prevailing speed on the main street, spacing of signals, traffic volumes on major and side streets, and number of non–signalized intersections. Among these factors, the traffic engineer can only exert control over the signal timing, at least in the short term. The traffic speed is not constant and varies with the time of day and motorists are heavily constrained in their choice of speeds during congested traffic conditions. Similarly, the traffic volumes are not constant and may be heavy inbound in the mornings and outbound in the evenings. Signal spacing is fixed for all existing systems. The signal timing parameters that are very important in the design of a coordinated system are:

a) Cycle length
b) Offsets
c) Green splits and
d) Phase sequence.

The speed of the vehicles at an intersection is not constant and drivers tend to vary their speeds according to the geometry of the intersection, existence of advance warning signs (if any), signal indicators, and the distance to the stop line. The 85th percentile speed or any variation of the prevailing speeds is normally a basis for fixing the length of the intervals, or the timings for the dynamic signs with flashers, but neither the slow moving vehicles nor other variations are considered in the design. Researchers

Table 2 Stopping Sight Distance (Wet Pavements)

Design Speed mph (Kmph)	Assumed speed for condition mph (Kmph)	Brake Reaction Time (sec)	Brake Reaction Distance ft (m)	Coeff. of friction	Braking distance on level ft (m)	Stopping Sight distance Computed ft (m)	Stopping Sight distance Rounded for design ft (m)
35 (56.32)	32 (51.50) - 35(56.33)	2.5	117.3(35.75) - 128.3(39.11)	0.34	100.4(30.60) - 120.1(36.61)	217.7(66.35) - 248.4(75.71)	225(68.58) – 250(76.20)
40 (64.36)	36(57.94) - 40 (64.37)	2.5	132.0(40.23) - 146.7(44.71)	0.32	135.0(41.15) - 166.7(50.81)	267.0(81.38) - 313.3(95.49)	275(83.82) – 325(99.06)
45 (72.41)	40(64.37) - 45(72.42)	2.5	146.7(44.71) - 165.0(50.29)	0.31	172.0(52.43) - 217.7(66.35)	318.7(97.14) - 382.7(116.65)	325(99.06) – 400(121.92)
50 (80.45)	44(70.81) - 50(80.47)	2.5	161.3(49.16) - 183.3(55.87)	0.3	215.1(65.56) - 277.8(84.67)	376.4(114.73) - 461.1(140.54)	400(121.92) – 475(144.78)
55 (88.50)	48(77.25) - 55(88.51)	2.5	176.8(53.64) - 201.7(61.48)	0.3	256.0(78.03) - 336.1(102.44)	432.0(131.67) - 537.8(163.92)	450(137.16) – 550(167.64)
60 (96.54)	52(83.69) - 60(96.56)	2.5	190.7(58.13) - 220.0(67.06)	0.29	310.8(94.73) - 413.8(126.13)	501.5(152.86) - 633.8(193.18)	525(160.02) – 650(198.12)

(Source: AASHTO Green Book)

have shown that a large number of drivers on high speed signalized intersections increase their speeds when they see yellow light or, even worse, go through red light without stopping. Hence, a large number of vehicles continue to experience dilemma zone problems at high speed signalized intersections. Most of the computer programs used for coordinating signals consider the movement of platoon of vehicles, not of individual vehicles, for optimization of stop, delay, or green bandwidth and hence the measures of effectiveness or performance are given on an aggregate basis. Those programs do not provide any clue whatsoever if an individual vehicle might experience dilemma zone at the intersections. Experiences have shown that, when adjacent intersections are closely spaced (1000 ft (304.8 m)-2000 ft (609.6 m)) it is difficult to achieve the twin operational goals of dilemma zone protection and efficiency maximization (signal coordination) at high speed signalized intersections.

In the past, the researchers at University of Cincinnati developed a method by modifying the NETSIM code to calculate the dilemma zone for each vehicle. They computed optimal signal timings using PASSER II and TRANSYT -7F, and using the modified code they conducted simulation studies and found that the number of vehicles experiencing the dilemma zone can be significantly reduced by providing a green extension of 1 or 2 seconds. This report describes a testing and implementation of the technique, which was performed at several high speed signalized intersections in the City of Middletown, Ohio.

2 OBJECTIVES

The objective of this study is:

a) To field test and implement a dilemma zone protection technique at a high-speed signalized corridor with closely-spaced intersections.
b) To recommend a method for reducing dilemma zone problems that can be implemented by ODOT and cities/municipalities in Ohio.

3 BACKGROUND AND SIGNIFICANCE OF WORK

The problem of dilemma zone has been around for a long time, perhaps as long as traffic signals have existed at high speed intersections. The adequacy of signal change interval has been extensively examined ever since it was formulated by Gazis et al in the early 1960s [1]. It has been shown that dilemma zone protection can help reduce crashes at high speed intersections. Reports have noted a 54% reduction in crash frequency after installation of dilemma zone protection at high speed signalized intersections. Studies have shown an 8% reduction in crashes after installation of dilemma zone protection, and the low percentage was attributed to the poor design of protection [2].

Some of the methods that have been used to address dilemma zone problems are summarized below.

3.1. Adjustment of phase-change interval:

Adjusting the yellow time and "all-red" time has been shown to have reduced crashes at intersections. An onsite field observation of vehicles entering the intersection after the onset of yellow signal conducted in New York, showed that red light violations have been reduced drastically when the yellow signal was increased according to ITE's recommendations. A study conducted in Detroit, Michigan, comparing red light violations at an intersection with all-red time and an intersection without all-red time showed that there was drastic reduction of running red lights at the intersection with all-red time [3].;

The following equation may be used to calculate the duration of the yellow interval [4]:

$$y = t + \frac{V}{2a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where,

y = length of the yellow interval, seconds
t = perception reaction time (usually 1 sec)
V = approach speed, ft/s
a = deceleration rate ft/s^2

If it is desired to provide an additional all-red clearance at the intersection, it may be calculated as follows:

$$r = \frac{(W + L)}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where,

r = length of all–red clearance, seconds
W = width of intersection, ft
L= length of the vehicle, ft
V = approach speed, ft/s

Hence, the total phase-change period is the sum of equations (1) and (2). Table 3 presents some theoretical minimum clearance intervals for various approach speeds and cross street widths [4].

Table 3. Theoretical Minimum Clearance Intervals

Approach Speeds	Yellow Interval	Total Clearance Intervals				
Mph (kmph)	(Sec)	(Yellow plus al-red clearance for crossing street widths, feet (m))				
		30(9.14)	50 (15.24)	70 (21.34)	90 (27.43)	110 (33.53)
20 (32.19)	3.0	4.2	4.9	5.5	6.2	6.9
25 (40.23)	3.0	4.2	4.7	5.3	5.8	6.4
30 (48.28)	3.2	4.3	4.8	5.2	5.7	6.2
35 (56.33)	3.6	4.5	4.9	5.3	5.7	6.1
40 (64.37)	3.9	4.8	5.1	5.5	5.8	6.1
45 (72.42)	4.5	5.1	5.4	5.7	6.0	6.3
50 (80.47)	4.7	5.3	5.6	5.9	6.2	6.4
55 (88.51)	5.0	5.7	5.9	6.2	6.4	6.7

t = 1 sec; a = 10 ft/s^2 (3.05 m/s^2); and L = 20 ft (6.1 m)

However, increased yellow time can pose problems by increasing cycle lengths and delays. When there are closely spaced signalized intersections this may reduce the coordination among the signals.

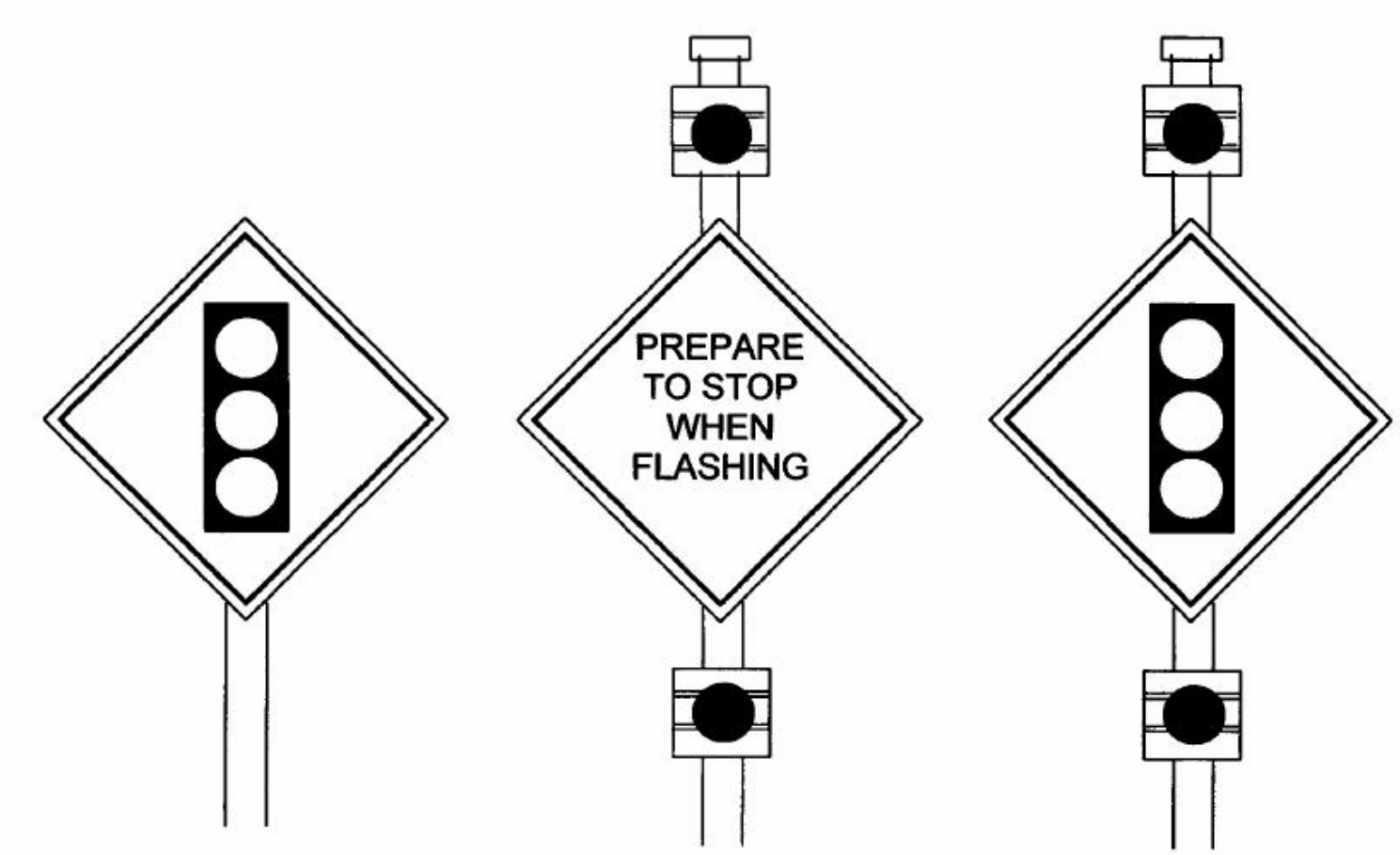
3.2. **Advanced Warning Signs**

There are two broad classes of advance warning signs.

3.2.1.) Passive advance warning signs: These are passive signs just like many other traffic signs and they indicate the presence of an intersection ahead, and alert the drivers.

3.2.2.) Dynamic advance warning signs: These kinds of signs have flashers which start flashing a few seconds before the onset of the yellow interval and continue to flash until the end of the red interval. The most common sign used by the Ohio Department of Transportation (ODOT) is “Prepare to Stop When Flashing” (PTSWF) sign. ODOT also uses a Continuously Flashing Symbolic Signal Ahead (CFSSA) sign at high–speed intersections. The CFFSA sign, as the name suggests, has green, red, and yellow circles and flashers that flash all the time. The flashers are not connected to the signal controller and hence detectors, if any, have no effect on the flashing of the CFSSA sign. An additional sign that has been used by ODOT is the Flashing Symbolic Signal Ahead (FSSA) sign, which is similar to the PTSWF sign except that the texts are replaced by the green, yellow, and red circles. The flashers operate in the same way as the PTSWF sign. The signs are shown in figure 2.

Figure 2 Advance Warning Signs



(a) PSSA sign (b) PTSWF sign (C) CFSSA & FSSA signs

3.3. Advanced Detection

In this system, loop detectors are used to detect approaching vehicles and the green time is extended. The detectors are placed close to the stop line and upstream of the intersection. The detectors are separated with a distance depending upon the location of the dilemma zone. When a vehicle is detected, a signal is sent to the signal controller and the green time is extended by a few seconds to accommodate the vehicle before the signal changes to red. The green time cannot be extended forever, and so the controller shifts the signal when the maximum green time is reached. The shift is abrupt and does not give enough warning to the drivers in the dilemma zone. When the detectors do not detect the vehicle on the major road, the right of way may shift to the minor road. In places of heavy traffic there are high chances for frequent maxouts, and reduce the level of protection of dilemma zone. In places where there are frequent maxouts, advanced warning signs are used in combination with advanced detectors. When the green time reaches a maximum, the controller starts a count down to the yellow signal, and the advanced warning signs are actuated. These help to increase the protection of dilemma zone.

3.4. Dynamic Dilemma Zone Protection

These systems attempt to allocate dilemma zone protection intelligently on the basis of vehicle needs at a particular time rather than as a result of fixed detection scheme. They do not make use of fixed detection near intersections, except for the stop line detection. The speed of each vehicle is measured well ahead of the intersection, and its travel time to the beginning and end of its individual dilemma zone is predicted. Then the green phase is ended when the number of vehicles is at a minimum. Examples of these systems are European systems like MOVA, LHOVRA, [5], SOS or D-CS developed by Texas Transportation Institute [6].

In-vehicle Detection Systems are new advancements in the area of dilemma zone protection. But they provide aid to individual vehicles. Young-Jun Moon et. al developed a system and field tested it and found that it could help eliminate dilemma zone, reduce red light violations and intersection collision. In order to determine whether a vehicle is in dilemma zone, the researchers, installed an antenna near the intersection, which reports number of seconds the light will remain green before the onset of yellow. The onboard device, which receives this information, estimates if the vehicle is in dilemma zone using the warning algorithm developed by the researchers and if so, it activates the visual and audible signs [7].

3.5. Simulation Study by the University of Cincinnati

The literature review has shown that the previous studies were mostly concentrated on determining the extent of dilemma zone, the driver behavior during the signal change interval, the placement of detectors to detect a vehicle in the dilemma zone, and the use of dynamic signs. Most of them were carried out from the point of view of an isolated intersection, and hence the results were not always applicable to a system of coordinated signals on an arterial corridor. Many arterials have several signals that are

closely spaced (1000 ft (304.8 m) -2000 ft (609.6 m)). The researchers at the University of Cincinnati conducted simulated studies for signal systems that consisted of several signalized high-speed intersections. First, the researchers conducted a study of dilemma zone problems by collecting and analyzing traffic flow data at a high-speed intersection using five video cameras covering a stretch of 1400 ft (426.72 m). By figuring out the speeds and locations of the vehicles, when the signal turns yellow, they were able to determine whether a vehicle was in a dilemma zone or not. Their analysis showed that a maximum of green extension or cutback needed to get a vehicle out of the dilemma zone is generally no more than 2 seconds. Next, the researchers modified the NETSIM code, to calculate the dilemma zone for each vehicle. They performed a simulation study using the modified NETSIM code, on five signalized intersections on US 33 in Columbus, Ohio. Using PASSER and TRANSYT-7F programs, they found that if the green time was extended by one second, there would be a decrease of 33 percent for the vehicles experiencing dilemma zone, and by 94% if a maximum extension of five seconds was allowed. They concluded that by implementing a signal timing strategy for green extension, the number of vehicles experiencing dilemma zone could be significantly reduced.

Extending or cutting back green interval may be helpful to keep some vehicles away from the dilemma zone but may affect the following vehicles. Keeping this in mind, the extension (or cutback) must be done with the following vehicles also in mind, and also delay time for the cross traffic. Theoretically, one can keep on extending the green time, but it would affect the delay for cross traffic and the overall speed in the arterial. Hence, it calls for an upper limit for the green extension or cutback, and the overall cycle length must be maintained in order to preserve the coordination of the series of traffic signals. To compensate the extension (or cutback), one can always reduce (or increase) the next green interval on the cross street or the main street.

4 TESTING AND IMPLEMENTATION OF DILEMMA ZONE TECHNIQUE AT CLOSELY-SPACED HIGH-SPEED SIGNAIZED INTERSECTION

4.1. Site Selection, Equipment Installation and Design of Experiment

In consultation with ODOT officials, it was decided to test and implement the technique at three signalized intersections on SR 122 Roosevelt Blvd in the City of Middletown, Ohio. The City had offered to install and maintain the equipment at its own cost if ODOT would allow it to keep the equipment upon the completion of this research project. Upon approval by ODOT, the University of Cincinnati purchased and delivered the equipment to the City for installation at Roosevelt Blvd. and the intersections of Highland, Wicoff, and Armco.

Roosevelt Blvd. is an urban divided highway with a number of closely-spaced signalized intersections and a speed limit of 45 mph (72.42 kmph). The three intersections are closely spaced within a distance of ½ mile. The distance from Highland to Wicoff is about 0.3 miles and the distance from Wicoff to Armco is about 0.2 miles. The equipment installed at the three intersections consisted of video cameras (Iteris) that allowed the setting up of two detectors at 300 ft (91.44 m) and 600 ft (182.88 m) on each intersection approach, thus eliminating the need for permanent installation of loop detectors in the pavement. At each intersection, one camera was installed on Roosevelt Blvd. in each direction, and one camera was installed on each direction of the side street resulting in a total of 12 cameras at the three selected intersections. Necessary cables and wires were provided to carry the signals from the detectors to the 170E type controllers (Safetran) located at the intersections.

The intersection of Roosevelt and Highland is a four-legged intersection with two through lanes and one right turning lane in each direction. The eastbound approach has an exclusive left turn lane. However, left turns are prohibited in the westbound direction.

The intersection of Roosevelt and Wicoff is four-legged intersection with two through lanes, one left turning lane and one right turning lane in each direction.

The intersection of Roosevelt and Armco is a three-legged T-intersection with an opening in the median that allows westbound traffic and northbound traffic to make left turns.

A few photographs of the intersections and the cameras are provided in Figures 3-7. The layouts of the intersections are shown in Figures 1, 2, 3 of the Appendix.

Figure 3. Roosevelt Blvd at Highland St – Eastbound

Figure 4. Roosevelt Blvd at Wicoff –Westbound

Figure 5. Roosevelt Blvd at Armco – Eastbound

Figure 6. Cameras – Roosevelt Blvd at Wicoff

Figure 7. Controller – Roosevelt Blvd at Wicoff

Design of experiment:

The following factors were considered for the testing and implementation of the dilemma zone technique:

(1) Length of dilemma zone

For a yellow time of 3 sec and a vehicle traveling at 45 mph (72.42kmph), we can calculate the clearing distance as follows:

Distance covered in 3 sec (clearing distance) = $\frac{45*5280}{3600}$ x 3 =198 ft (60.35m).

Similarly, distance traveled at other speeds can be calculated. Referring to Table 1, the stopping sight distances and clearing distances at different speeds are shown in Table 4.

Table 4. Calculating the stopping and clearing distances

Speed mph (kmph)	Stopping sight distances (X_s) ft (m)	Clearing Distance (X_C) ft (m)
45 (72.41)	319 (97.23) - 383(116.74)	198 (60.35)
50 (80.45)	376 (114.6) - 461(140.51)	219 (66.75
55 (88.50)	432(131.67) - 537(163.68)	240 (73.15)
60 (96.54)	501(152.70) - 633(192.94)	264 (80.47)

Since vehicular speeds vary within a wide range, it was decided to allow for operating speeds between 45 mph (72.42 kmph) and 60mph (96.54).

Hence, the length of dilemma zone = (501 – 198) = 303 ft (92.35 m).

(2) Locations of detectors

In order to allow for the time lag that occurs while detecting vehicles and actually displaying greens, we added 100 ft (30.48 m) to the above distance of 198 ft (60.35 m). Hence it was decided that the first detector would be placed at a distance of 300 ft (91.44m) from the stop line and the second detector would be placed at (300+300) = 600 ft (182.88 m).

(3) Green extensions

It was decided that all testing would be conducted in reference to the "base case", which consisted of no extension of green interval. Tests would be performed by providing green extensions of 1 sec, 2 sec, 3 sec, 4 sec and 5 sec. at the end of current green interval.

(4) Vehicular conflicts

The following vehicular conflicts were observed to determine if a vehicle experienced dilemma zone problem on the intersection approach [4]:

a) Ran red light
b) Stopped abruptly
c) Accelerated through yellow light.

(5) Data collection periods

During peak hours, when traffic volume on the roadway is heavy, vehicular speed tends to be low; motorists tend to travel in platoons and are less likely to experience dilemma zone problems. Hence, the data needed to be collected during off peak hours when speed tended to be high and drivers had the maximum opportunity to experience dilemma zone problems. It was also important to collect data during both daylight and nighttime conditions. Based on a sample of 24-hour volume data provided by the City, it was determined that the hours between 9:00am and 11:00am in the morning had low traffic volumes during daylight hours and hence it was decided to collect data during these hours. Similarly, it was determined that the hours between 8:00pm and 10:00pm at night during the winter months had sufficiently low traffic volumes to allow the researchers collect data for nighttime conditions.

(6) Signal coordination

The signals were coordinated by the City of Middletown, which also developed and implemented the signal timings for the intersections under study. All three intersections had semi-actuated signals. Since the side street traffic volumes were quite low at these intersections, the frequency of vehicles on the side streets activating the

detectors and receiving green light was quite low. Hence, the City decided to set the signals on "recall" during the data collection periods so that the yellow interval would repeat itself during each cycle. Due to the "recall" effects, it was determined that any attempt to conduct delay data would not be meaningful and hence a delay study was not conducted.

The data were collected on weekdays by six graduate students, with each student counting the vehicular conflicts and other traffic counts on each approach. A sample data collection form is shown in the Appendix.

The data was simultaneously collected on all major approaches of the three intersections by six graduate students. At any one time, either the detector at 300 ft (91.44 m) or at 600 ft (182.88 m), but not both, was activated. For the "base case", data was collected for 2 hours in the morning and 2 hours at night without providing any extension of the green time. Then, for each 2-hour period in the morning and at night, data was collected by providing the green extensions of 1, 2, 3, 4, and 5 sec respectively. A pilot study was conducted on the first day to familiarize every one with the data collection method. Based on the experience on the first day, the data collection form was slightly modified. The following is a summary of the number of hours for which data were collected for this project.

Table 5. Total Hours of Data Collection

Intersection	**Number of hours of data collected**	
	Daylight Conditions	**Evening Conditions**
Roosevelt Blvd at Highland (Eastbound Approach)	24	24
Roosevelt Blvd at Highland (Westbound Approach)	24	24
Roosevelt Blvd at Wicoff (Eastbound Approach)	24	24
Roosevelt Blvd at Wicoff (Westbound Approach)	24	24
Roosevelt Blvd at Armco (Eastbound Approach)	24	24
Roosevelt Blvd at Armco (Westbound Approach)	24	24
Total	**144**	**144**
Total hours of observations = 288		

The collected data for 288 hours were tabulated in Excel spreadsheets. The number of right turning vehicles, left turning vehicles, through vehicles and the number of vehicles stopping at red, running through red, passing through green, stopping abruptly on red, and accelerating through yellow were recorded into the spreadsheets. The "total traffic volume" was calculated as the sum of left turning, right turning and through vehicles. The number of vehicles running red, stopping abruptly at red, and accelerating through yellow was summed as "conflict volume". Since the traffic count varied from day to day and according to the time of day, "conflict percentage" was considered a good measure of effectiveness for dilemma zone protection. The "conflict percentage" was calculated as the "total conflict volume" over "total volume" as follows:

$$\text{Conflict Percentage} = \frac{\text{Conflict Volume}}{\text{Total Volume}} * 100$$

Hence the percent reduction in conflicts were calculated as

$$\text{Percentage reduction of conflict percentage} = \frac{(\text{conflict percentage at no green extension} - \text{conflict percentage at given green extension})}{\text{conflict percentage at no green extension}} * 100$$

The results of the data analysis for each approach are discussed in the following sections.

4.2. Analysis of individual approaches

The data collected was tabulated in Excel spreadsheet. The traffic counts included right turning vehicles; left turning vehicles; through vehicles, vehicles running red, abruptly stopping at red, accelerating through yellow, and vehicles that stopped at red. The "total volume" is the sum of left turning, right turning and through vehicles. The "conflict volume" comprised of vehicles that ran red, abruptly stopped at red, and accelerated through yellow. The "total volume" during the morning period ranged from 800 vehicles to 1650 vehicles for two hours of observations, while the "conflict volume" ranged from 8 to 69 vehicles. The "total volume" during the night period ranged from 650 to 1200 vehicles, while the "conflict volume" ranged from 1 to 80. The volume counts for all approaches are tabulated in Tables 6-11.

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Table 6. Summary of volume counts at Roosevelt Blvd at Highland (Eastbound approach)											
Position of detector	**Green time extension**	**Time of day**	**Left turning vehicles**	**Stopped Vehicles**	**Non Stopped Vehicles**	**Run Red Light**	**Stop abruptly**	**Accelerate through Yellow**	**Right turning vehicles**	**Total Volume**	**Conflict volume**
300ft (91.44m)	0 sec	Morning	48	106	1094	3	1	26	218	1496	30
300ft (91.44m)	1 sec	Morning	30	174	764	18	11	36	247	1280	65
300ft (91.44m)	2 sec	Morning	68	136	898	17	0	16	235	1370	33
300ft (91.44m)	3 sec	Morning	56	152	880	5	0	11	192	1296	16
300ft (91.44m)	4sec	Morning	48	117	844	6	1	22	219	1257	29
300ft (91.44m)	5 sec	Morning	28	102	755	4	2	37	145	1073	43
300ft (91.44m)	0 sec	Evening	34	164	509	3	0	10	216	936	13
300ft (91.44m)	1 sec	Evening	29	84	611	1	0	8	221	954	9
300ft (91.44m)	2 sec	Evening	23	95	438	0	0	4	195	755	4
300ft (91.44m)	3 sec	Evening	19	129	520	1	0	1	240	910	2
300ft (91.44m)	4 sec	Evening	18	155	433	5	0	15	235	861	20
300ft (91.44m)	5 sec	Evening	23	132	394	1	0	4	200	754	5
600ft (182.88m)	0 sec	Morning	48	106	1094	3	1	26	218	1496	30
600ft (182.88m)	1 sec	Morning	22	107	882	8	2	40	115	1176	50
600ft (182.88m)	2 sec	Morning	41	138	931	7	2	14	228	1361	23
600ft (182.88m)	3 sec	Morning	65	153	1034	13	0	13	241	1519	26
600ft (182.88m)	4 sec	Morning	41	152	832	6	0	17	179	1227	23
600ft (182.88m)	5 sec	Morning	23	133	814	5	0	31	150	1156	36
600ft (182.88m)	0 sec	Evening	34	164	509	3	0	10	216	936	13
600ft (182.88m)	1 sec	Evening	13	86	400	0	0	5	178	682	5
600ft (182.88m)	2 sec	Evening	20	68	442	4	9	9	167	719	22
600ft (182.88m)	3 sec	Evening	19	71	505	0	0	1	237	833	1
600ft (182.88m)	4 sec	Evening	21	67	467	2	3	27	137	724	32
600ft (182.88m)	5 sec	Evening	17	154	656	2	0	4	262	1095	6

Table 7. Summary of volume counts at Roosevelt Blvd at Highland (Westbound approach)											
Position of detector	**Green time extension**	**Time of day**	**Left turning vehicles**	**Stopped Vehicles**	**Non Stopped Vehicles**	**Run Red Light**	**Stop abruptly**	**Accelerate through Yellow**	**Right turning vehicles**	**Total Volume**	**Conflict volume**
300ft (91.44m)	0 sec	Morning	0	402	665	18	0	27	8	1120	45
300ft (91.44m)	1 sec	Morning	1	281	475	1	3	30	5	796	34
300ft (91.44m)	2 sec	Morning	3	322	661	18	4	19	6	1033	41
300ft (91.44m)	3 sec	Morning	1	294	699	3	8	11	10	1026	22
300ft (91.44m)	4sec	Morning	3	308	532	14	0	16	29	902	30
300ft (91.44m)	5 sec	Morning	0	322	641	19	0	25	16	1023	44
300ft (91.44m)	0 sec	Evening	2	255	491	4	0	7	10	769	11
300ft (91.44m)	1 sec	Evening	1	278	572	9	0	15	29	904	24
300ft (91.44m)	2 sec	Evening	2	185	486	6	3	8	6	696	17
300ft (91.44m)	3 sec	Evening	1	190	495	4	1	4	6	701	9
300ft (91.44m)	4 sec	Evening	0	250	426	4	3	4	5	692	11
300ft (91.44m)	5 sec	Evening	1	180	491	4	1	2	8	687	7
600ft (182.88m)	0 sec	Morning	0	402	665	18	0	27	8	1120	45
600ft (182.88m)	1 sec	Morning	3	212	580	16	2	13	15	841	31
600ft (182.88m)	2 Sec	Morning	0	337	584	1	6	18	32	978	25
600ft (182.88m)	3 sec	Morning	0	317	524	10	4	11	28	894	25
600ft (182.88m)	4 sec	Morning	2	313	671	18	2	23	13	1042	43
600ft (182.88m)	5 sec	Morning	1	284	561	15	3	13	10	887	31
600ft (182.88m)	0 sec	Evening	2	255	491	4	0	7	10	769	11
600ft (182.88m)	1 sec	Evening	3	181	464	7	0	12	24	691	19
600ft (182.88m)	2 sec	Evening	2	192	366	5	1	12	27	605	18
600ft (182.88m)	3 sec	Evening	1	257	525	6	0	18	37	844	24
600ft (182.88m)	4 sec	Evening	2	217	541	4	1	16	11	792	21
600ft (182.88m)	5 sec	Evening	2	369	611	11	2	20	14	1029	33

Table 8. Summary of volume counts at Roosevelt Blvd at Wicoff (Eastbound approach)											
Position of detector	**Green time extension**	**Time of day**	**Left turning vehicles**	**Stopped Vehicles**	**Non Stopped Vehicles**	**Run Red Light**	**Stop abruptly**	**Accelerate through Yellow**	**Right turning vehicles**	**Total Volume**	**Conflict volume**
300ft (91.44m)	0 sec	Morning	51	203	1306	22	1	14	14	1611	37
300ft (91.44m)	1 sec	Morning	23	118	942	20	3	1	12	1119	24
300ft (91.44m)	2 sec	Morning	39	203	1049	11	0	15	16	1333	26
300ft (91.44m)	3 sec	Morning	40	165	1038	12	0	0	17	1272	12
300ft (91.44m)	4sec	Morning	40	185	963	10	1	9	16	1224	20
300ft (91.44m)	5 sec	Morning	33	140	1204	7	2	6	16	1408	15
300ft (91.44m)	0 sec	Evening	34	236	576	8	0	0	2	856	8
300ft (91.44m)	1 sec	Evening	47	56	857	10	2	11	3	986	23
300ft (91.44m)	2 sec	Evening	55	100	540	9	1	12	0	717	22
300ft (91.44m)	3 sec	Evening	39	145	689	5	1	10	2	891	16
300ft (91.44m)	4 sec	Evening	41	171	594	13	0	18	2	839	31
300ft (91.44m)	5 sec	Evening	49	135	516	16	3	20	1	740	39
600ft (182.88m)	0 sec	Evening	34	236	576	8	0	0	2	856	8
600ft (182.88m)	1 sec	Morning	39	106	1068	17	1	17	5	1253	35
600ft (182.88m)	2 sec	Morning	46	111	1155	5	3	2	14	1336	10
600ft (182.88m)	3 sec	Morning	46	162	1269	6	4	0	10	1497	10
600ft (182.88m)	4 sec	Morning	37	168	1086	6	0	12	17	1326	18
600ft (182.88m)	5 sec	Morning	41	132	1077	9	2	8	14	1283	19
600ft (182.88m)	0 sec	Evening	34	236	576	8	0	0	2	856	8
600ft (182.88m)	1 sec	Evening	36	131	534	10	2	19	0	732	31
600ft (182.88m)	2 sec	Evening	41	107	754	15	1	5	1	924	21
600ft (182.88m)	3 sec	Evening	41	118	740	8	1	8	3	919	17
600ft (182.88m)	4 sec	Evening	49	195	506	30	0	27	2	809	57
600ft (182.88m)	5 sec	Evening	46	149	787	14	1	29	7	1033	44

Table 9. Summary of volume counts at Roosevelt Blvd at Wicoff (Westbound approach)											
Position of detector	**Green time extension**	**Time of day**	**Left turning vehicles**	**Stopped Vehicles**	**Non Stopped Vehicles**	**Run Red Light**	**Stop abruptly**	**Accelerate through Yellow**	**Right turning vehicles**	**Total Volume**	**Conflict volume**
300ft (91.44m)	Morning	0 sec	32	447	731	3	7	14	28	1262	49
300ft (91.44m)	Morning	1 sec	31	184	774	11	0	20	41	1061	61
300ft (91.44m)	Morning	2 sec	29	269	900	12	2	11	25	1248	38
300ft (91.44m)	Morning	3 sec	40	261	835	8	2	16	33	1195	51
300ft (91.44m)	Morning	4sec	31	189	680	5	1	12	21	939	34
300ft (91.44m)	Morning	5 sec	20	266	670	10	3	15	19	1003	37
300ft (91.44m)	Evening	0 sec	4	202	711	11	5	27	37	997	69
300ft (91.44m)	Evening	1 sec	14	201	623	5	2	21	48	914	71
300ft (91.44m)	Evening	2 sec	13	204	561	10	3	12	31	834	46
300ft (91.44m)	Evening	3 sec	15	131	603	13	3	21	34	820	58
300ft (91.44m)	Evening	4 sec	6	103	614	10	0	13	28	774	41
300ft (91.44m)	Evening	5 sec	7	167	635	12	1	17	32	871	50
600ft (182.88m)	Morning	0 sec	32	447	731	3	7	14	28	1262	49
600ft (182.88m)	Morning	1 sec	14	213	717	4	1	8	30	987	39
600ft (182.88m)	morning	2 sec	25	254	871	6	0	17	30	1203	47
600ft (182.88m)	morning	3 sec	17	257	905	3	0	6	28	1216	34
600ft (182.88m)	Morning	4 sec	31	299	740	4	0	10	27	1111	37
600ft (182.88m)	Morning	5 sec	21	196	801	2	4	10	44	1078	58
600ft (182.88m)	Evening	0 sec	4	202	711	11	5	27	37	997	69
600ft (182.88m)	Evening	1 sec	7	92	423	4	3	15	25	569	43
600ft (182.88m)	Evening	2 sec	10	151	586	10	7	20	31	815	58
600ft (182.88m)	Evening	3 sec	7	102	665	9	0	43	22	848	65
600ft (182.88m)	Evening	4 sec	5	139	661	6	1	16	55	883	72
600ft (182.88m)	Evening	5 sec	16	153	895	10	3	18	41	1136	62

Table 10. Summary of volume counts at Roosevelt Blvd at Armco (Eastbound approach)											
Position of detector	**Green time extension**	**Time of day**	**Left turning vehicles**	**Stopped Vehicles**	**Non Stopped Vehicles**	**Run Red Light**	**Stop abruptly**	**Accelerate through Yellow**	**Right turning vehicles**	**Total Volume**	**Conflict volume**
300ft (91.44m)	Morning	0 sec	0	308	1185	9	0	2	118	1622	11
300ft (91.44m)	Morning	1 sec	0	195	926	3	0	7	68	1199	10
300ft (91.44m)	Morning	2 sec	0	243	946	16	17	21	73	1316	54
300ft (91.44m)	Morning	3 sec	0	218	850	13	29	24	70	1204	66
300ft (91.44m)	Morning	4sec	0	262	921	8	1	6	59	1257	15
300ft (91.44m)	Morning	5 sec	0	276	1070	7	0	8	55	1416	15
300ft (91.44m)	Evening	0 sec	0	254	607	8	0	18	36	923	26
300ft (91.44m)	Evening	1 sec	0	258	689	3	1	12	20	983	16
300ft (91.44m)	Evening	2 sec	0	137	516	3	10	7	36	709	20
300ft (91.44m)	Evening	3 sec	0	182	652	4	0	10	43	891	14
300ft (91.44m)	Evening	4 sec	0	165	572	21	16	16	36	826	53
300ft (91.44m)	Evening	5 sec	0	155	522	6	12	8	31	734	26
600ft (182.88m)	Morning	0 sec	0	308	1185	9	0	2	118	1622	11
600ft (182.88m)	Morning	1 sec	0	193	975	5	1	6	113	1293	12
600ft (182.88m)	Morning	2 Sec	0	254	904	23	5	25	67	1278	53
600ft (182.88m)	Morning	3 sec	0	349	977	4	2	6	77	1415	12
600ft (182.88m)	Morning	4 sec	0	243	1012	8	0	5	77	1345	13
600ft (182.88m)	Morning	5 sec	0	236	936	6	1	10	91	1280	17
600ft (182.88m)	Evening	0 sec	0	254	607	8	0	18	36	923	26
600ft (182.88m)	Evening	1 sec	0	111	544	12	1	19	27	714	32
600ft (182.88m)	Evening	2 sec	0	179	536	4	0	5	27	751	9
600ft (182.88m)	Evening	3 sec	0	171	715	4	3	8	22	923	15
600ft (182.88m)	Evening	4 sec	0	178	598	5	0	13	41	835	18
600ft (182.88m)	Evening	5 sec	0	220	790	8	0	7	26	1051	15

Table 11. Summary of volume counts at Roosevelt Blvd at Armco (Westbound approach)											
Position of detector	**Green time extension**	**Time of day**	**Left turning vehicles**	**Stopped Vehicles**	**Non Stopped Vehicles**	**Run Red Light**	**Stop abruptly**	**Accelerate through Yellow**	**Right turning vehicles**	**Total Volume**	**Conflict volume**
300ft (91.44m)	0 sec	Morning	70	183	1048	23	4	21	0	1349	48
300ft (91.44m)	1 sec	Morning	56	145	806	7	0	37	0	1051	44
300ft (91.44m)	2 sec	Morning	70	183	1033	5	5	36	0	1332	46
300ft (91.44m)	3 sec	Morning	80	139	988	1	0	17	0	1225	18
300ft (91.44m)	4sec	Morning	53	129	904	16	2	2	0	1106	20
300ft (91.44m)	5 sec	Morning	64	150	982	8	1	12	0	1217	21
300ft (91.44m)	0 sec	Evening	33	166	842	5	2	6	0	1054	13
300ft (91.44m)	1 sec	Evening	32	161	815	4	6	3	0	1021	13
300ft (91.44m)	2 sec	Evening	36	157	671	2	1	12	0	879	15
300ft (91.44m)	3 sec	Evening	23	162	657	1	1	9	0	853	11
300ft (91.44m)	4 sec	Evening	27	119	694	5	0	9	0	854	14
300ft (91.44m)	5 sec	Evening	43	150	701	2	2	16	0	914	20
600ft (182.88m)	0 sec	Morning	70	183	1048	23	4	21	0	1349	48
600ft (182.88m)	1 sec	Morning	57	125	807	14	4	14	0	1021	32
600ft (182.88m)	2 sec	Morning	73	156	959	0	0	16	0	1204	16
600ft (182.88m)	3 sec	Morning	58	175	826	30	17	34	0	1140	81
600ft (182.88m)	4 sec	Morning	41	128	829	15	6	14	0	1033	35
600ft (182.88m)	5 sec	Morning	54	138	803	20	10	39	0	1064	69
600ft (182.88m)	0 sec	Evening	33	166	842	5	2	6	0	1054	13
600ft (182.88m)	1 sec	Evening	44	136	616	2	1	2	0	801	5
600ft (182.88m)	2 sec	Evening	34	132	617	2	0	2	0	787	4
600ft (182.88m)	3 sec	Evening	23	150	614	2	3	9	0	801	14
600ft (182.88m)	4 sec	Evening	29	132	719	6	2	1	0	889	9
600ft (182.88m)	5 sec	Evening	26	152	921	5	3	9	0	1116	17

4.2.1. Roosevelt Blvd at Highland Street (Eastbound Approach)

The analysis for green extension at the intersection of Roosevelt Blvd and Highland (eastbound approach) provided insights into the operation of the traffic signal in relation to dilemma zone problem. The increase or decrease in dilemma zone conflicts was compared with the "base case" where no green extension was provided. During the morning period, when the detector was placed at 300 ft (91.44 m), the green extension of 3 sec reduced dilemma zone conflicts by 94%. In contrast, the dilemma zone conflicts increased by almost 150% with the green extension of 1 sec, by 20% with the green extension of 2 sec, 15% with the green extension of 4 sec and 100% with the green extension of 5 sec. Thus, the green extension of 3 sec gave the best results for reducing dilemma zone conflicts. During the evening period, with detector at 300 ft (91.44 m), there were reductions of dilemma zone conflicts for all green extensions except for the extension of 4 sec. However, the highest reduction in dilemma zone conflicts was seen at 3 sec extension, which provided a reduction of 84%.

During the morning period, with the detector active at 600 ft (182.88 m), the data showed that there were reductions in dilemma zone conflicts when the green extensions were 2 sec, 3 sec, and 4 sec respectively. But the extensions of 1 sec and 5 sec showed increases in dilemma zone conflicts. The 3 sec extension reduced the dilemma zone conflicts by 17%. During the evening period, the detector at 600 ft (182.88 m) showed similar results, with the dilemma zone conflicts reducing for green extensions of 1 sec, 3 sec and 5 sec. An increase in dilemma zone conflicts was noted when the green time was extended by 2 sec and 4 sec. The highest reduction of 91 % occurred when the green extension of 3 sec was provided.

Based on the above results, one could conclude that the green extension of 3 sec was most effective in reducing dilemma zone conflicts on the eastbound approach of Roosevelt Blvd. at Highland Street. The results are presented in the tables and figures below.

Note: In these tables, the positive sign (+) indicates a reduction in dilemma zone conflicts and the negative sign (-) indicates an increase.

Table 12. Conflict analysis – Roosevelt at Highland (Eastbound Approach)

Detector Position	Time of Day	Green Extension	Conflict Percentage	Percentage reduction in conflict percentages
300ft (91.44m)	Morning	0 sec	2.000	Base Case
300ft (91.44m)	Morning	1 sec	5.078	-153.905
300ft (91.44m)	Morning	2 sec	2.400	-20.000
300ft (91.44m)	Morning	3 sec	0.123	93.828
300ft (91.44m)	Morning	4sec	2.307	-15.350
300ft (91.44m)	Morning	5 sec	4.007	-100.350
300ft (91.44m)	Evening	0 sec	1.388	Base Case
300ft (91.44m)	Evening	1 sec	0.943	32.039
300ft (91.44m)	Evening	2 sec	0.530	61.830
300ft (91.44m)	Evening	3 sec	0.220	84.171
300ft (91.44m)	Evening	4 sec	2.322	-67.291
300ft (91.44m)	Evening	5 sec	0.663	52.224
600ft (182.88m)	Morning	0 sec	2.000	Base Case
600ft (182.88m)	Morning	1 sec	4.250	-112.500
600ft (182.88m)	Morning	2 sec	1.688	15.600
600ft (182.88m)	Morning	3 sec	1.711	14.450
600ft (182.88m)	Morning	4 sec	1.874	6.280
600ft (182.88m)	Morning	5 sec	3.114	-55.700
600ft (182.88m)	Evening	0 sec	1.388	Base Case
600ft (182.88m)	Evening	1 sec	0.733	47.190
600ft (182.88m)	Evening	2 sec	3.509	-152.810
600ft (182.88m)	Evening	3 sec	0.120	91.354
600ft (182.88m)	Evening	4 sec	4.410	-217.723
600ft (182.88m)	Evening	5 sec	0.548	60.526

Figure 8. Conflict percentages for 300ft (91.44m) morning - Roosevelt Blvd at Highland (East Bound)

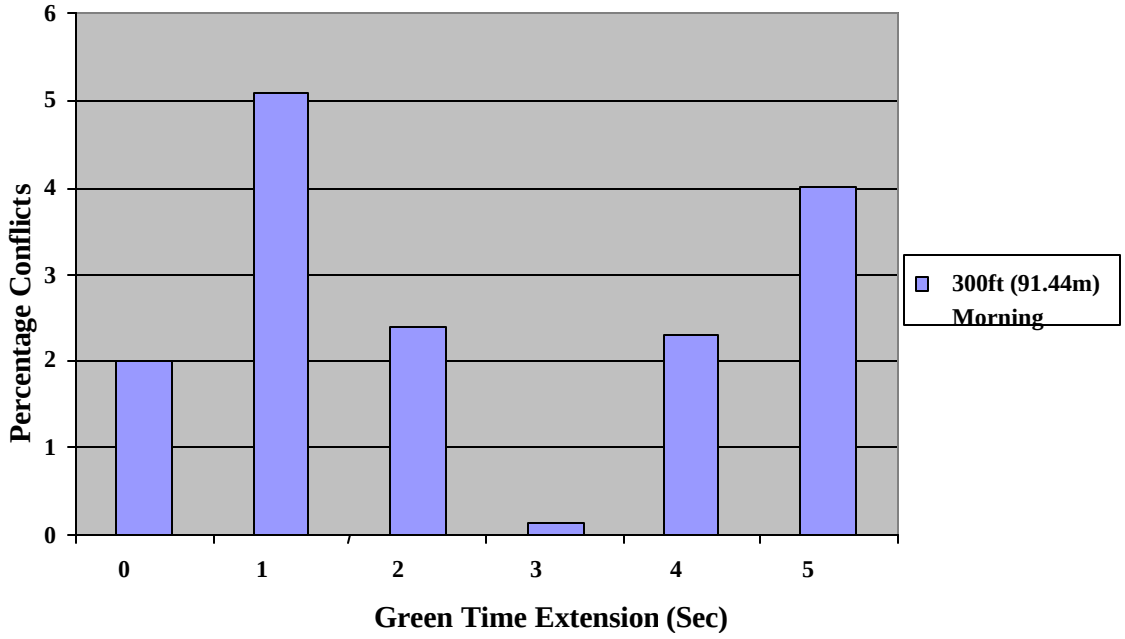


Figure 9. Conflict percentages for 300ft (91.44m) evening - Roosevelt Blvd at Highland (East Bound)

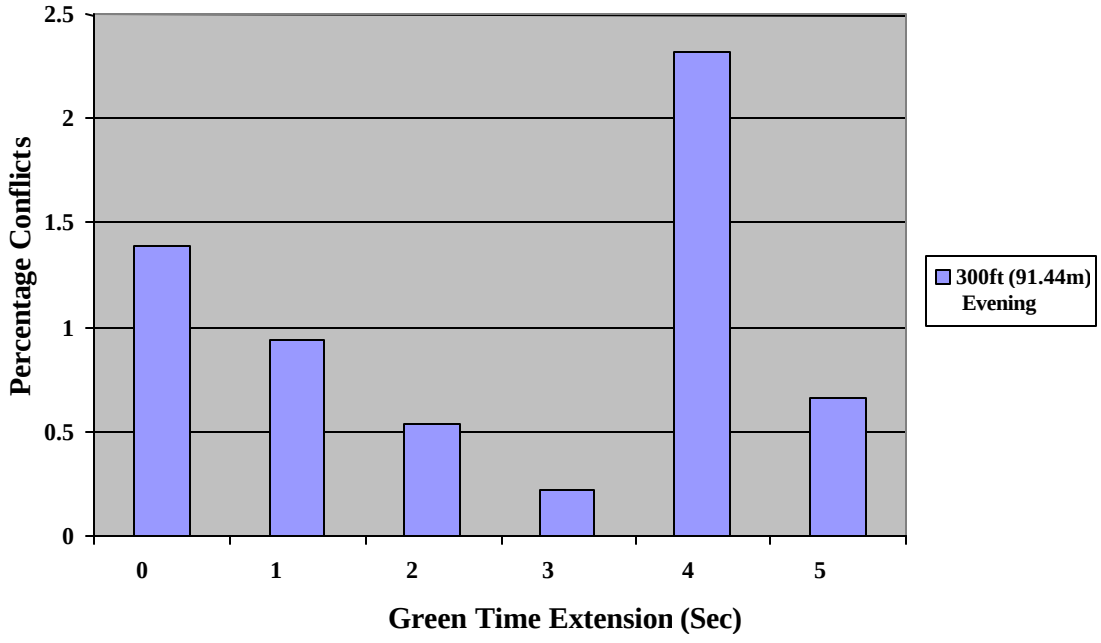


Figure 10. Conflict percentages for 600ft (182.22m) morning - Roosevelt Blvd at Highland (East Bound)

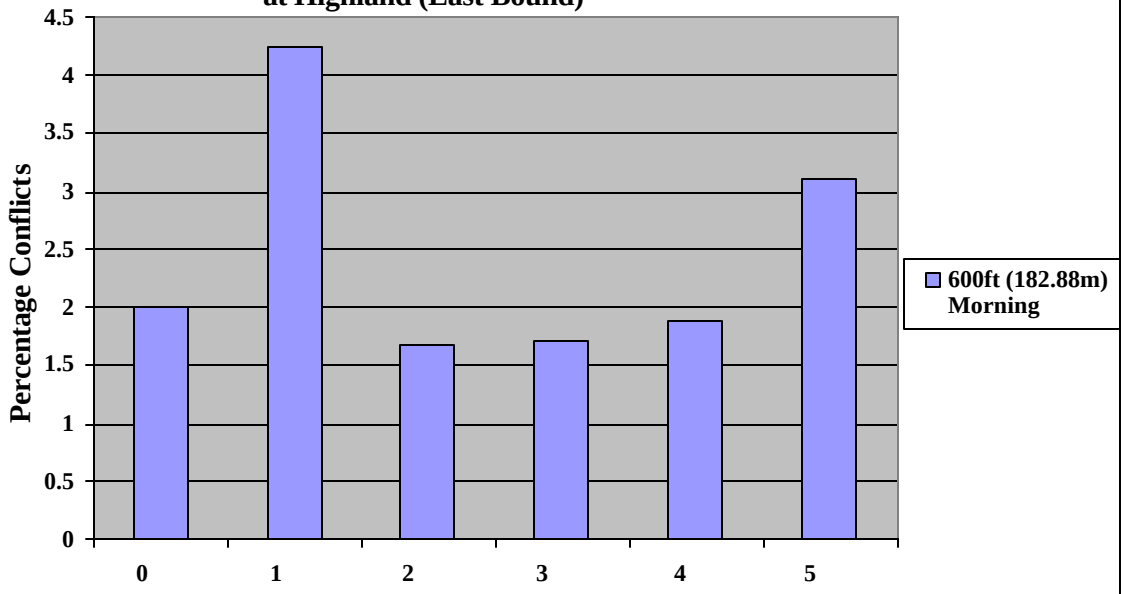


Figure 11. Conflict percentages for 600ft (182.88m) evening - Roosevelt Blvd at Highland (East Bound)

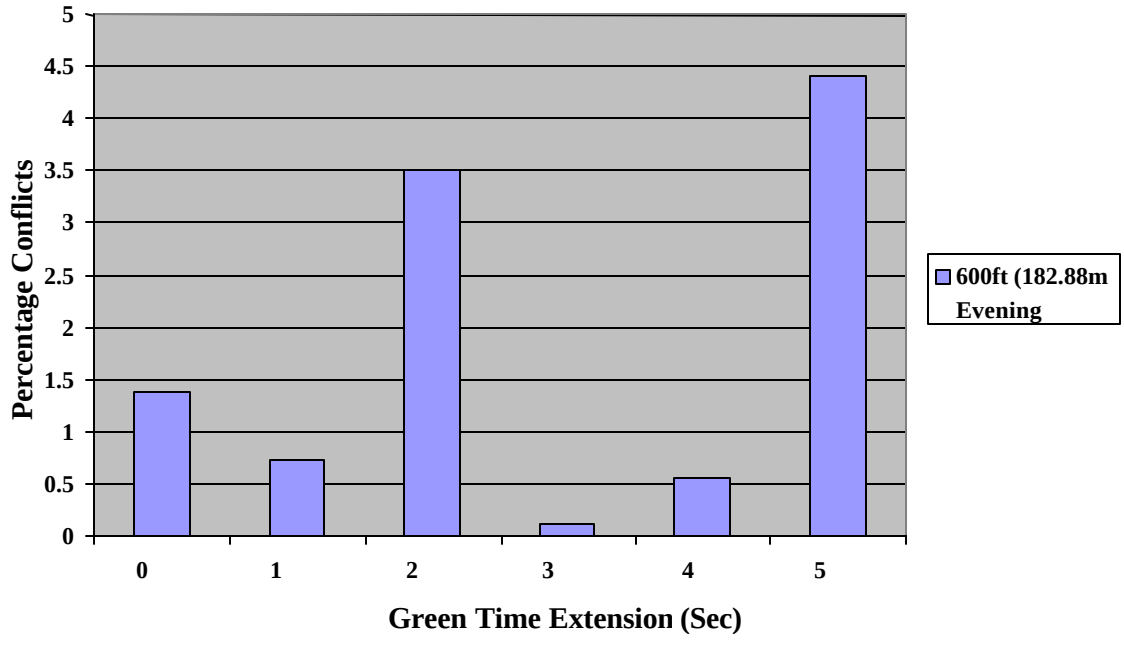
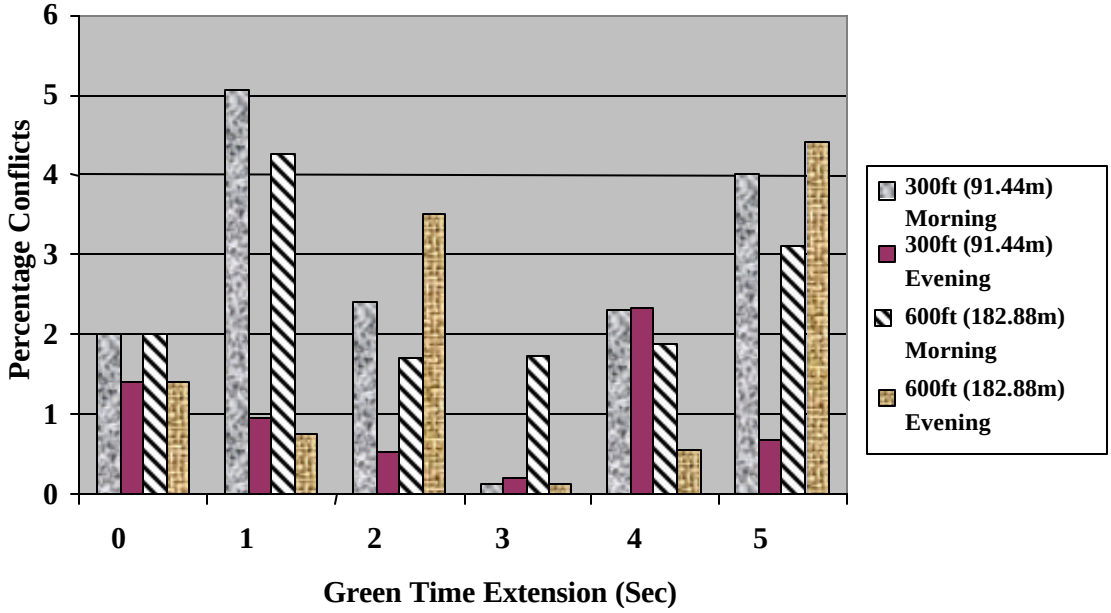


Figure 12 Summary of conflict percentages - Roosevelt Blvd at Highland (East Bound)



Further, an analysis was conducted by excluding the right and left turning traffic and considering the through traffic only (stopping at red, passing through green, running red, accelerating through yellow, abruptly stopping) as the "total volume". The analysis was done for the data collected with the detector at 300 ft (91.44m). It was found that though there was an increase in conflicts for most green extensions, a decrease was observed when the extension of 3 sec was provided during the morning period. The evening period had a different trend; there were reductions in dilemma zone conflicts observed, when the green extensions were provided, except for the 4 sec extension. The highest reduction was obtained when the green extension of 3 sec was provided. The results are shown in the following tables and figures.

Table 13. Conflict analysis (excluding left and right turning traffic) -Roosevelt at Highland (Eastbound approach)

Detector Position	Time of day	Green Extension	Conflict Percentage	Percentage reduction in conflict percentages
300ft (91.44m)	Morning	0 sec	2.44	
300ft (91.44m)	Morning	1 sec	6.48	-165.70
300ft (91.44m)	Morning	2 sec	3.09	-26.80
300ft (91.44m)	Morning	3 sec	1.53	37.40
300ft (91.44m)	Morning	4sec	2.93	-20.10
300ft (91.44m)	Morning	5 sec	4.78	-95.89
300ft (91.44m)	Evening	0 sec	1.90	
300ft (91.44m)	Evening	1 sec	1.28	32.54
300ft (91.44m)	Evening	2 sec	0.74	60.70
300ft (91.44m)	Evening	3 sec	0.31	83.79
300ft (91.44m)	Evening	4 sec	3.29	-73.58
300ft (91.44m)	Evening	5 sec	0.94	50.31

Figure 13 Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) morning Roosevelt at Highland (Eastbound Approach)

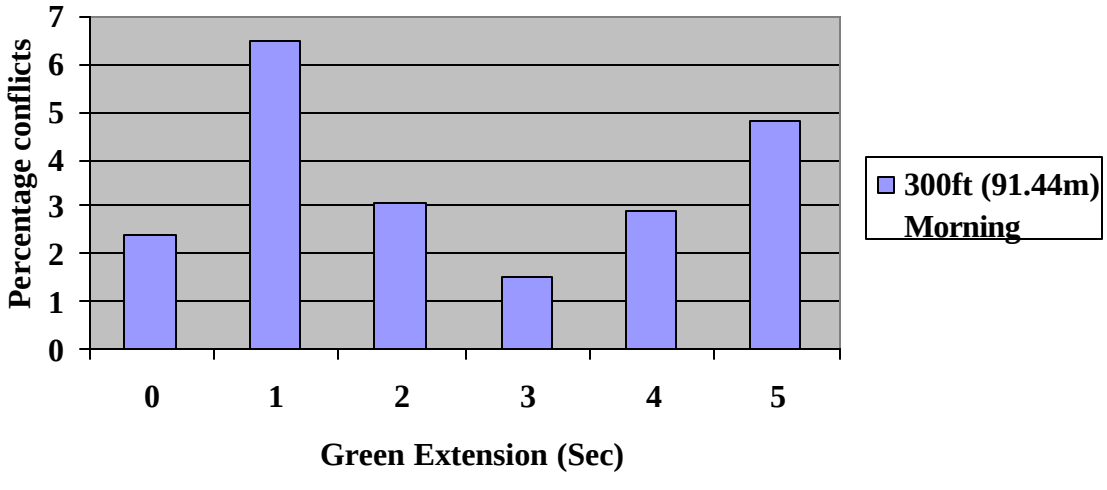
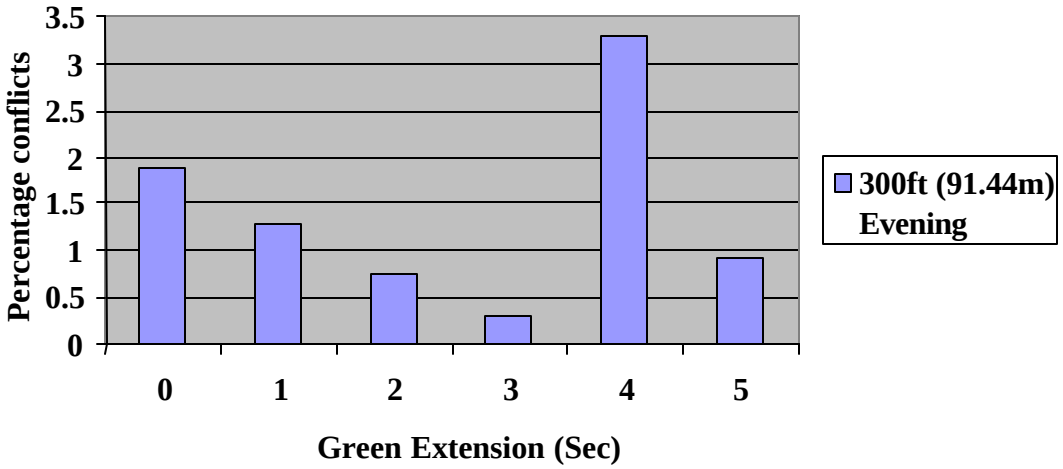


Figure 14 Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) evening -Roosevelt at Highland (Eastbound Approach)



4.2.2. Roosevelt Blvd at Highland Street (Westbound Approach)

The extension of green time at Roosevelt Blvd at Highland Street (westbound approach) showed that, with the detector at 300 ft (91.44 m) during the morning period, there was a reduction in dilemma zone conflicts when the green time extension was 2 sec, 3 sec, 4 sec respectively. However, the highest reduction in dilemma zone conflicts (47%) occurred when the green extension of 3 sec was provided. The data for the evening period showed that though there was an increase in dilemma zone conflicts when the green extensions of 1 sec and 2 sec were provided, and there were reductions in dilemma zone conflicts when the green extensions of 3 sec, 4 sec and 5 sec were provided. There was a reduction of 10% when the extension of 3 sec was provided.

The data collected with the detector at 600 ft (182.88 m) showed similar patterns for the morning period. There was a reduction of dilemma zone conflicts when the green times were extended except that a marginal increase was observed when the 4 sec extension was provided. There was a decrease of 30% in dilemma zone conflicts when the 3 sec green extension was provided. For the evening period, with the detector at 600 ft (182.88 m), the percentage conflicts increased when the green extensions were provided, unlike the other cases. It was observed that there was an increase of almost 90% for each extension.

Table 14. Conflict Analysis – Roosevelt at Highland (Westbound Approach)

Detector Position	Time of Day	Green Extension	Percentage Conflict	Percentage reduction in percentage conflict
300ft (91.44m)	Morning	0 sec	4.018	Base Case
300ft (91.44m)	Morning	1 sec	4.271	-6.309
300ft (91.44m)	Morning	2 sec	3.960	1.439
300ft (91.44m)	Morning	3 sec	2.144	46.637
300ft (91.44m)	Morning	4sec	3.326	17.221
300ft (91.44m)	Morning	5 sec	4.301	-7.049
300ft (91.44m)	Evening	0 sec	1.430	Base Case
300ft (91.44m)	Evening	1 sec	2.655	-85.650
300ft (91.44m)	Evening	2 sec	2.443	-70.804
300ft (91.44m)	Evening	3 sec	1.283	10.280
300ft (91.44m)	Evening	4 sec	1.589	-11.119
300ft (91.44m)	Evening	5 sec	1.109	22.455
600ft (182.88m)	Morning	0 sec	4.018	Base Case
600ft (182.88m)	Morning	1 sec	3.686	8.258
600ft (182.88m)	Morning	2 Sec	2.556	36.383
600ft (182.88m)	Morning	3 sec	2.796	30.410
600ft (182.88m)	Morning	4 sec	4.127	-2.710
600ft (182.88m)	Morning	5 sec	3.495	13.015
600ft (182.88m)	Evening	0 sec	1.430	Base Case
600ft (182.88m)	Evening	1 sec	2.740	-91.608
600ft (182.88m)	Evening	2 sec	2.975	-108.042
600ft (182.88m)	Evening	3 sec	2.840	-98.601
600ft (182.88m)	Evening	5 sec	3.207	-85.420
600ft (182.88m)	Evening	4 sec	2.652	-124.259

Figure 15. Conflict percentages for 300ft (91.44m) morning - Roosevelt Blvd at Highland (West Bound)

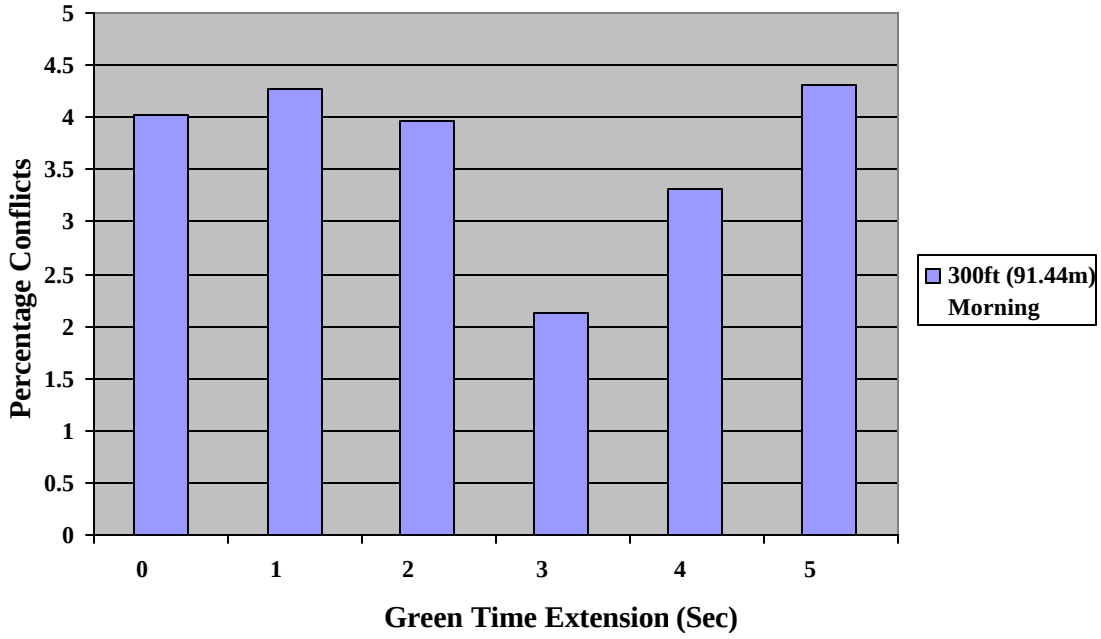


Figure 16. Conflict percentages for 300ft (91.44m) evening - Roosevelt Blvd at Highland (West Bound)

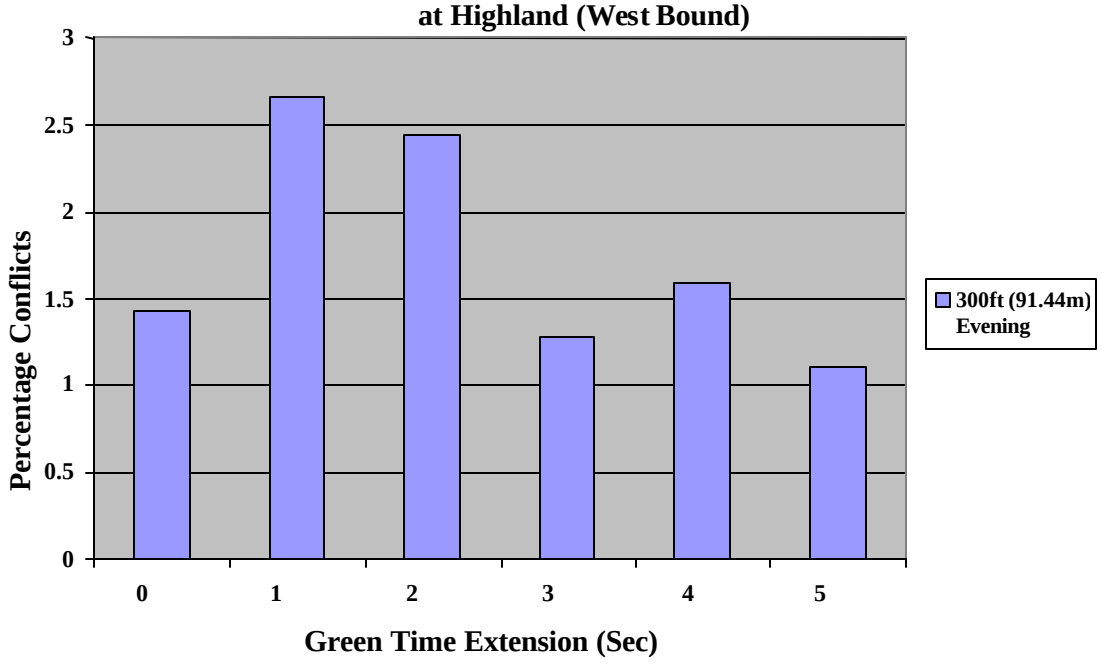


Figure 17. Conflict percentages for 600ft (182.88m) morning - Roosevelt Blvd at Highland (West Bound)

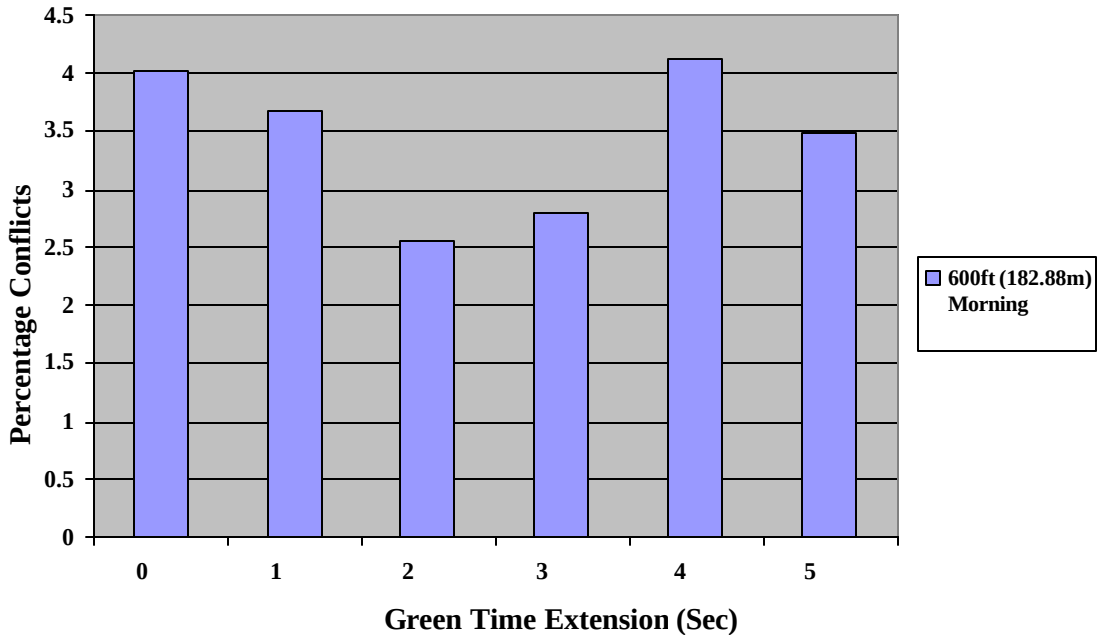


Figure 18. Conflict percentages for 600ft (182.88m) evening - Roosevelt Blvd at Highland (West Bound)

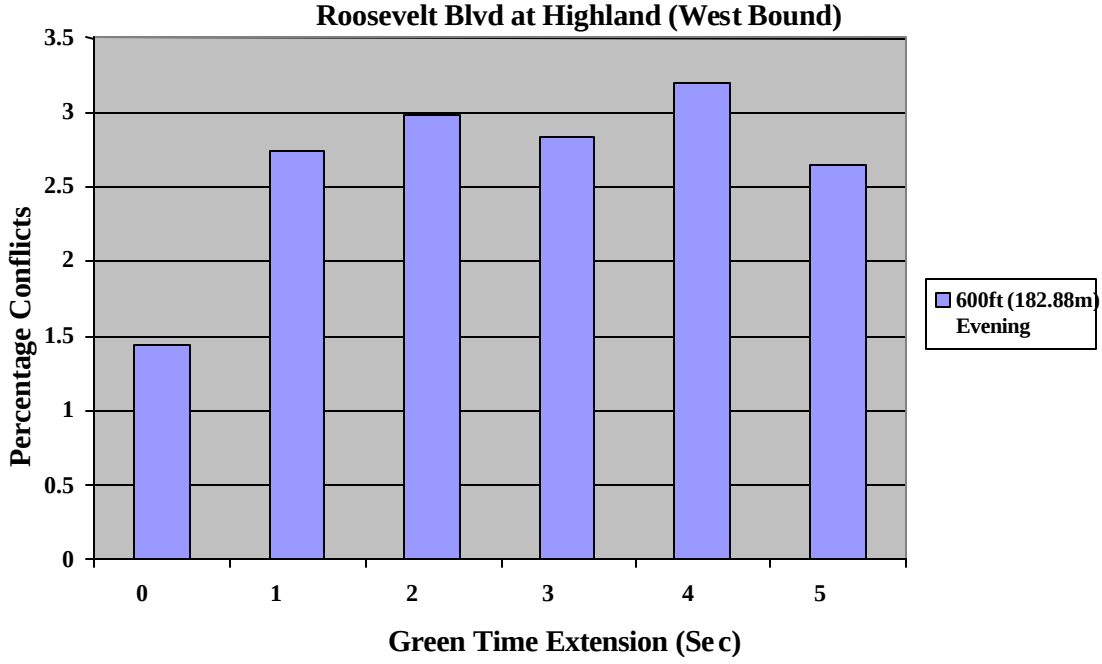
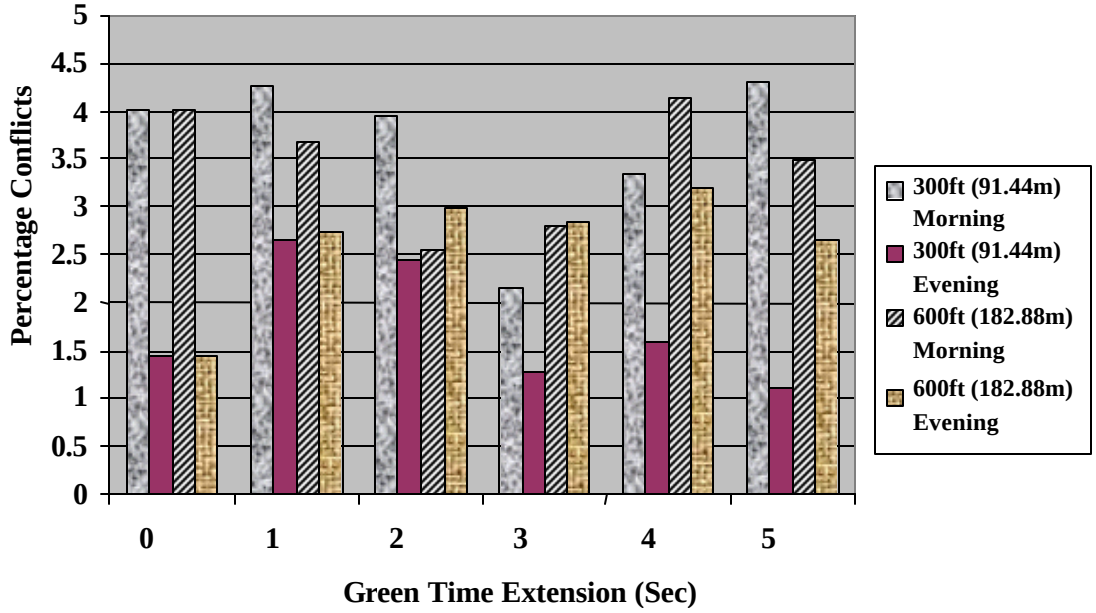


Figure 19. Summary of conflict percentages – Roosevelt Blvd at Highland (Westbound approach)



Further analysis was undertaken with the data collected with the detector at 300 ft (91.44 m), as the data with the detector at 600 ft (182.88 m) did not show consistent results. In this case, the left turning and right turning traffic was excluded from the total volume. The total volume included vehicles passing through green, stopping at red, abruptly stopping on red, accelerating through yellow and running through red. The conflict volume included those vehicles which ran red, stopped abruptly at red or accelerated through yellow. The analysis showed that there was a decrease in dilemma zone conflicts when the green extensions were provided, but the increase was marginal for the green time extensions of 1 sec and 5 sec extension during the morning period. The highest reduction occurred when the green extension of 3 sec was provided. During the evening period, except for the green extensions of 1 sec and 2 sec, there was a reduction in dilemma zone conflicts when the green extension of 3 sec, 4sec and 5 sec were provided. The highest reduction in dilemma zone conflicts occurred when the 3 sec green extension was provided.

Table 15. Conflict Analysis (excluding left and right turning traffic) -Roosevelt at Highland (Westbound approach)

Detector position	Time of day	Green extension	Conflict percentage	Percentage reduction in conflict percentages
300ft (91.44m)	Morning	0 sec	4.0467	
300ft (91.44m)	Morning	1 sec	4.3037	-6.351
300ft (91.44m)	Morning	2 sec	4.0039	1.058
300ft (91.44m)	Morning	3 sec	2.1674	46.440
300ft (91.44m)	Morning	4sec	3.4482	14.790
300ft (91.44m)	Morning	5 sec	4.3694	-7.974
300ft (91.44m)	Evening	0 sec	1.4531	
300ft (91.44m)	Evening	1 sec	2.7459	-88.968
300ft (91.44m)	Evening	2 sec	2.4709	-70.043
300ft (91.44m)	Evening	3 sec	1.2968	10.756
300ft (91.44m)	Evening	4 sec	1.6011	-10.185
300ft (91.44m)	Evening	5 sec	1.0324	28.952

Figure 20. Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) morning Roosevelt at Highland (Westbound Approach)

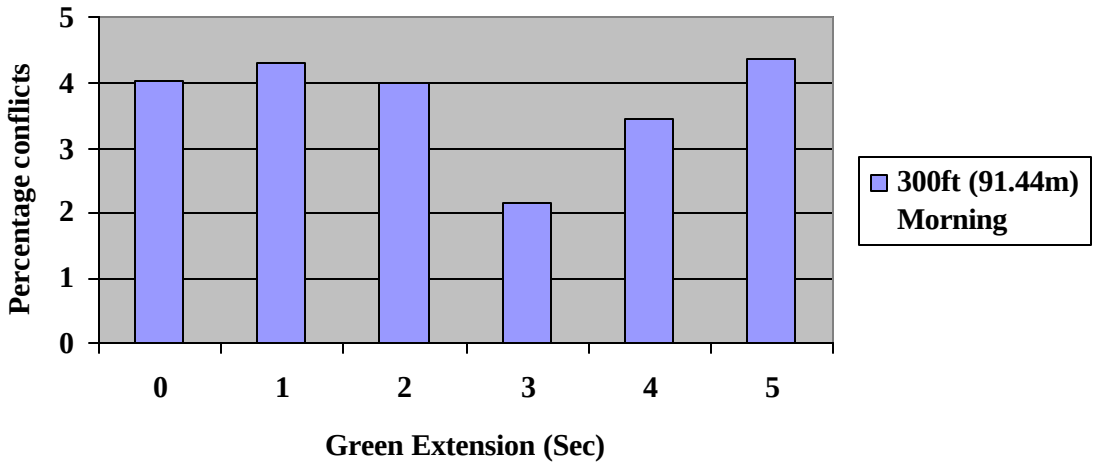
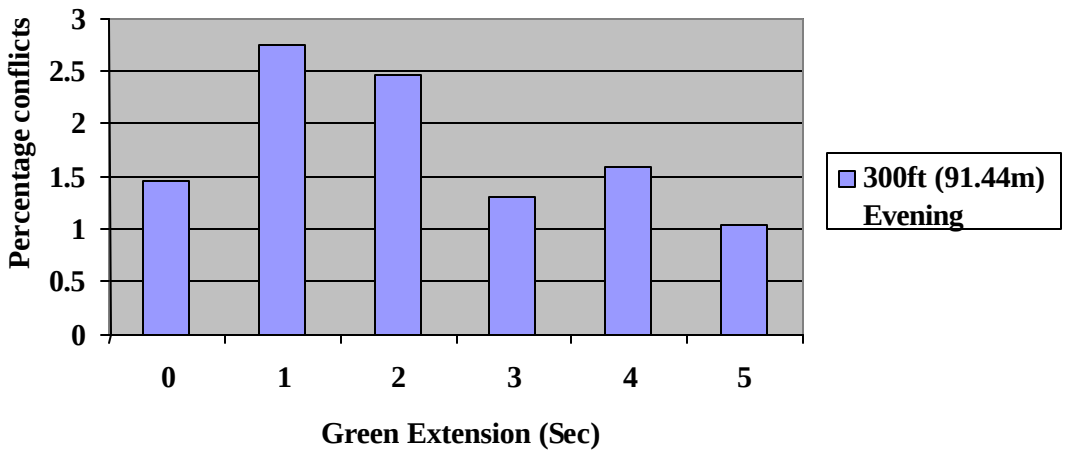


Figure 21. Conflict percentages (excluding left and right turning traffic) 300 ft (91.22m) Evening - Roosevelt at Highland (Westbound Approach)



In summary, the study showed that the 3 sec green extension resulted in the highest reduction of dilemma zone conflicts for this intersection approach.

4.2.3.Roosevelt Blvd at Wicoff (Eastbound Approach)

On analyzing the data collected at the intersection of Roosevelt and Wicoff, with the detector at 300 ft (91.44 m) during the morning period, the researchers found that there was a reduction in dilemma zone conflicts when the green time extensions were provided. A decrease of 59% relative to the base case (with no extension) was observed when the 3 sec extension was provided, and 97% when the extension of 5 sec was provided. During the evening period, with the detector at 300 ft (91.44 m), the collected data showed increase in dilemma zone conflicts when compared to the base case, for all the green extensions. During the morning period, with the detector at 600 ft (182.88 m), the analysis showed that there was reduction of dilemma zone conflicts when green extensions were provided, except for the extension of 1 sec where a small increase was noted. Like in the previous intersection, it was observed that the extension of 3 sec produced the highest reduction of dilemma zone conflicts, where there was a reduction of 70% compared to the base case. On the other hand, with the detector at 600 ft (182.88 m), the evening period did not show such a pattern; instead it recorded an increase in the dilemma zone conflicts when green extensions were provided. The percentages and the relative reduction in conflict percentages are shown in following tables and figures.

Table 16. Conflict analysis – Roosevelt at Wicoff (Eastbound approach)

Detector Position	Time of Day	Green extension	Conflict Percentage	Reduction in percentage conflicts
300ft (91.44m)	Morning	0 sec	2.2967	Base Case
300ft (91.44m)	Morning	1 sec	2.1447	6.618
300ft (91.44m)	Morning	2 sec	1.9504	15.078
300ft (91.44m)	Morning	3 sec	0.9433	58.928
300ft (91.44m)	Morning	4 sec	1.6339	28.859
300ft (91.44m)	Morning	5 sec	0.0653	97.157
300ft (91.44m)	Evening	0 sec	0.9345	Base Case
300ft (91.44m)	Evening	1 sec	2.3326	-149.609
300ft (91.44m)	Evening	2 sec	3.0683	-228.336
300ft (91.44m)	Evening	3 sec	1.7957	-92.156
300ft (91.44m)	Evening	4 sec	3.6948	-295.377
300ft (91.44m)	Evening	5 sec	5.2702	-463.959
600ft (182.88m)	Morning	0 sec	2.2967	Base Case
600ft (182.88m)	Morning	1 sec	2.7932	-21.618
600ft (182.88m)	Morning	2 sec	0.7485	67.410
600ft (182.88m)	Morning	3 sec	0.668	70.915
600ft (182.88m)	Morning	4 sec	1.3574	40.898
600ft (182.88m)	Morning	5 sec	1.4809	35.521
600ft (182.88m)	Evening	0 sec	0.9345	Base Case
600ft (182.88m)	Evening	1 sec	4.2349	-353.173
600ft (182.88m)	Evening	2 sec	2.2727	-143.200
600ft (182.88m)	Evening	3 sec	1.8498	-97.945
600ft (182.88m)	Evening	4 sec	7.0457	-653.954
600ft (182.88m)	Evening	5 sec	4.2594	-355.795

Figure 22 Conflict percentages for 300ft (91.44m) morning - Roosevelt Blvd at Wicoff (East Bound)

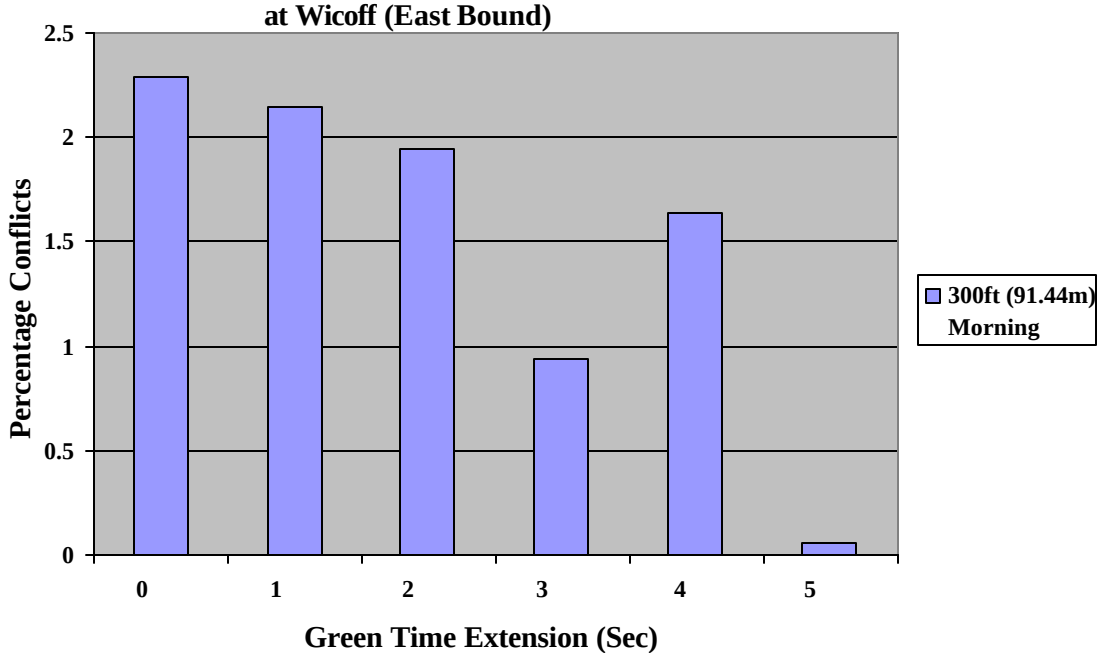


Figure 23 Conflict percentages for 300ft (91.44m) evening - Roosevelt Blvd at Wicoff (East Bound)

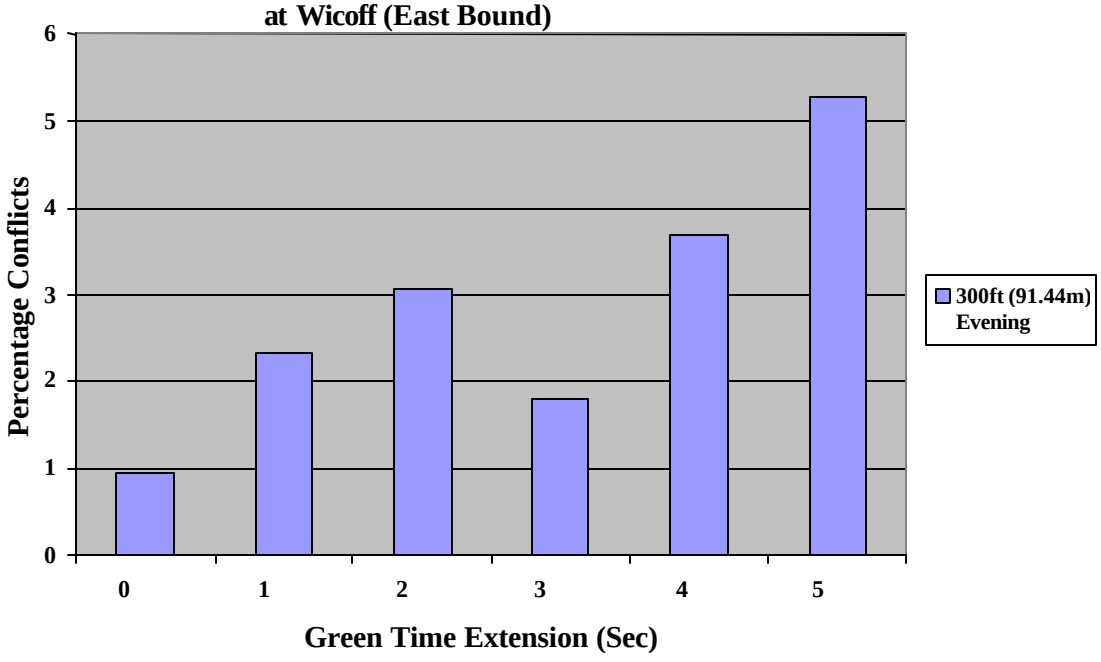


Figure 24 Conflict percentages for 600ft (182.88m) morning - Roosevelt Blvd at Wicoff (East Bound)

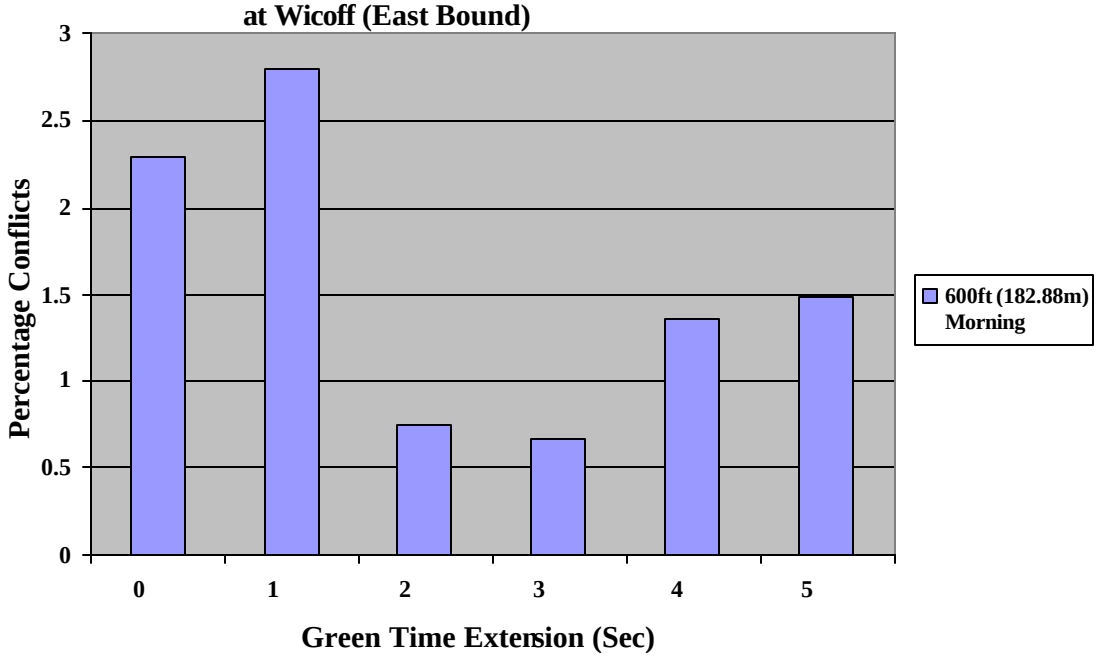
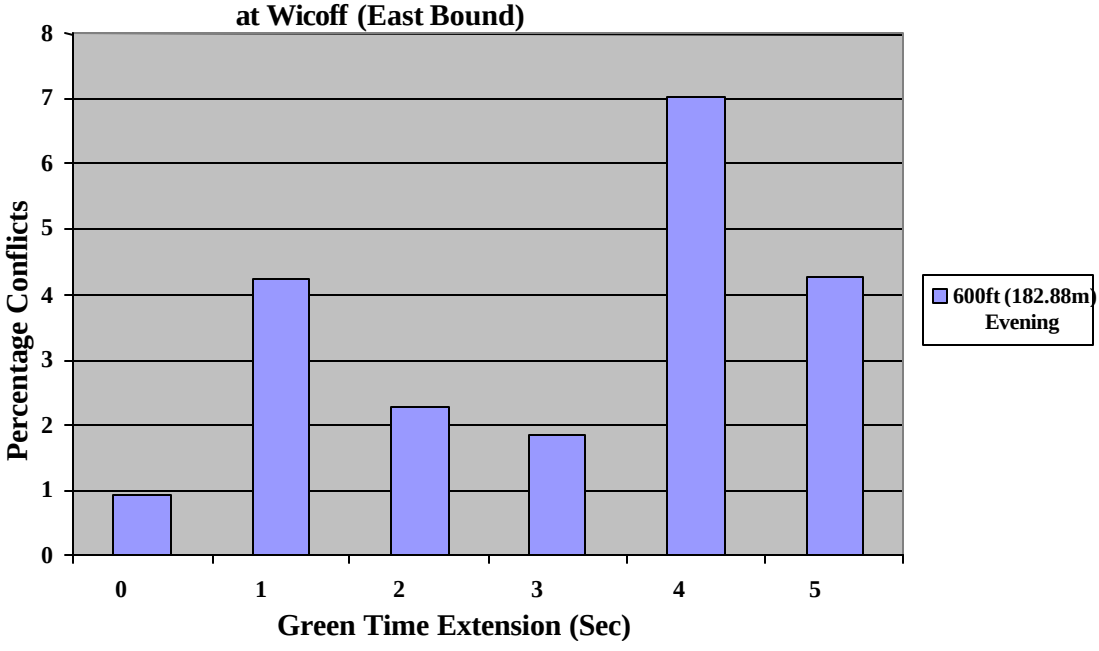
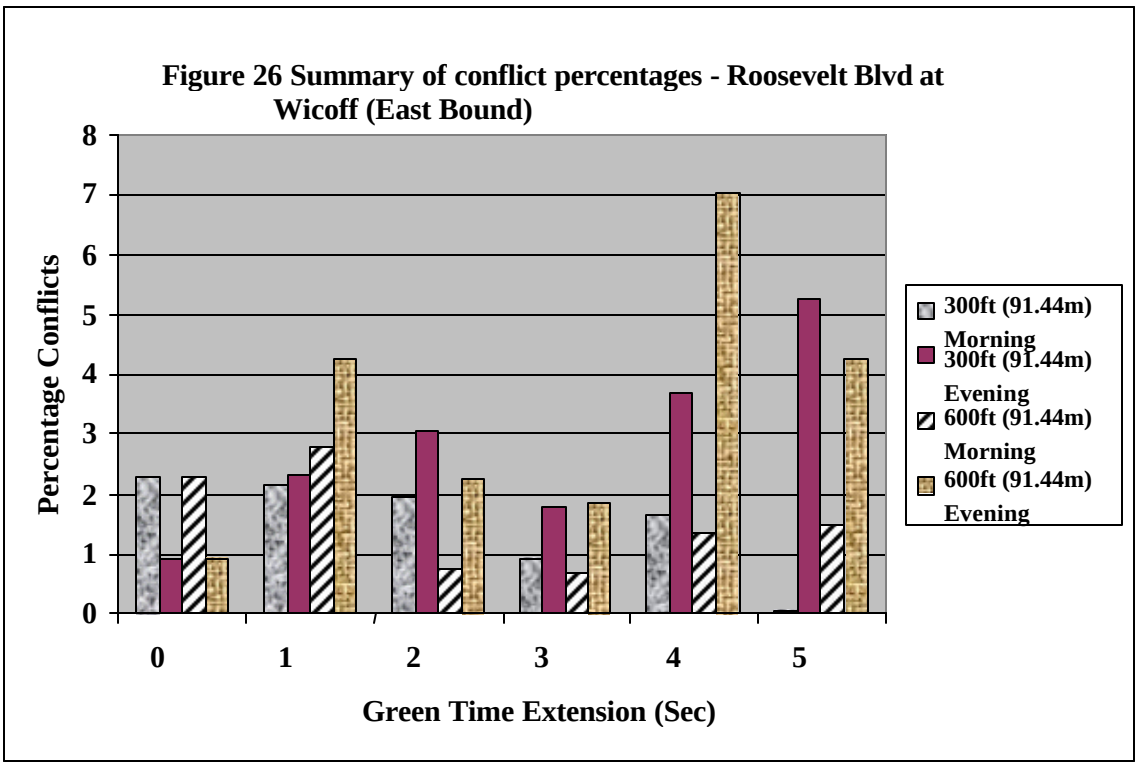


Figure 25. Conflict percentages for 600ft (182.88m) evening - Roosevelt Blvd at Wicoff (East Bound)





An analysis was further carried out by excluding the right turning and left turning vehicles from the "total volume". Further, as the data with the detector at 600 ft (182.88 m) did not show consistent results, the researchers only carried the analysis with the data obtained with the detector at 300ft (91.44m). The results showed that there was a reduction of conflict percentages observed, and highest reduction of 58% in dilemma zone conflicts was observed when the 3 sec green extension was provided, which was a pattern similar to that observed in previous approaches. However, during the evening period, the data showed a different trend, there was an increase in dilemma zone conflicts observed with all green time extensions.

Table 17. Conflict Analysis (excluding left and right turning traffic) -Roosevelt at Wicoff (Eastbound Approach)

Detector position	Time of day	Green time extension	Conflict percentage	Percentage reduction in conflict percentages
300ft (91.44m)	Morning	0 sec	2.393	
300ft (91.44m)	Morning	1 sec	2.214	7.480
300ft (91.44m)	Morning	2 sec	2.034	15.002
300ft (91.44m)	Morning	3 sec	0.988	58.713
300ft (91.44m)	Morning	4sec	1.712	28.458
300ft (91.44m)	Morning	5 sec	1.104	53.865
300ft (91.44m)	Evening	0 sec	0.976	
300ft (91.44m)	Evening	1 sec	2.457	-151.742
300ft (91.44m)	Evening	2 sec	3.323	-240.471
300ft (91.44m)	Evening	3 sec	1.882	-92.828
300ft (91.44m)	Evening	4 sec	3.894	-298.975
300ft (91.44m)	Evening	5 sec	5.652	-479.098

Figure 27. Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) morning Roosevelt at Wicoff (Eastbound Approach)

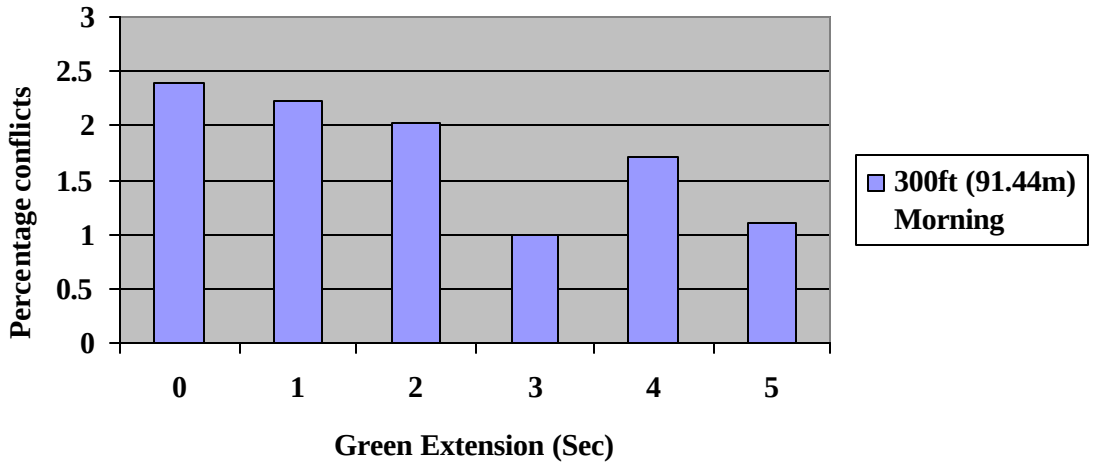
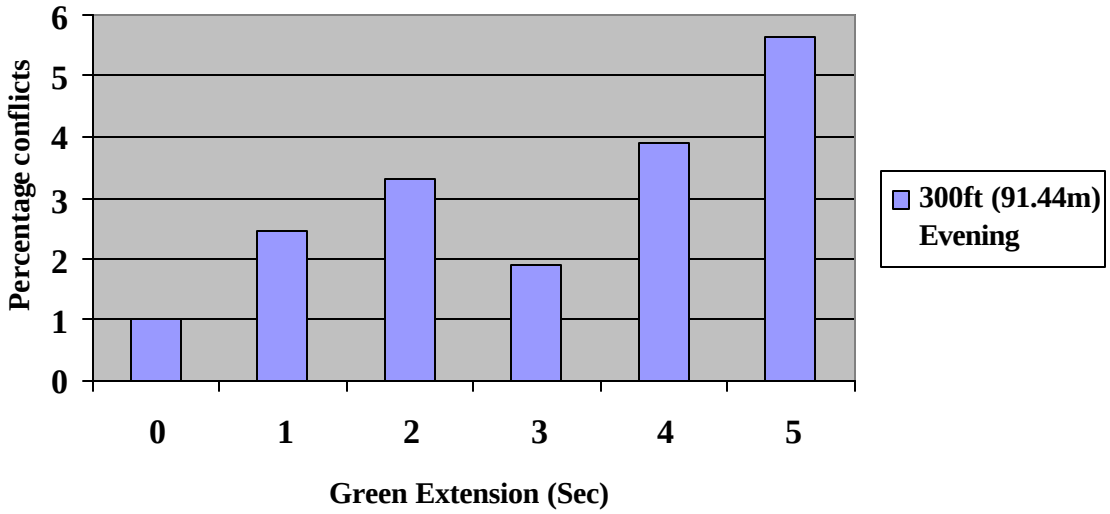


Figure 28. Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) evening Roosevelt at Wicoff (Eastbound Approach)



4.2.4. Roosevelt Blvd at Wicoff (Westbound Approach)

The dilemma zone conflicts observed at the intersection of Roosevelt at Wicoff (westbound approach), for the morning period with the detector at 300 ft (91.44 m), showed an increase for all green extensions when green times were extended. But the observations for the evening period with the detector at 300 ft (91.44 m) showed that there was a decrease in dilemma zone conflicts of 30% except for 3 sec extension that showed a slight increase of 4%. The conflict volumes observed during the morning period with the detector at 600 ft (182.88 m) showed that there was a reduction of dilemma zone conflicts except for a marginal increase for 2 sec green extension. It was noted that there was a 60% decrease of observed dilemma zone conflicts for the green extension of 3 sec. During the evening period, with the detector at 600 ft (182.88 m), it was observed that there was a decrease in dilemma zone conflicts except for the green extensions of 2 sec and 3 sec, where an increase of 5 % and 42 % were recorded. The observations are tabulated below.

Table 18. Conflict analysis – Roosevelt at Wicoff (Westbound Approach)

Detector Position	Time of Day	Green time extension	Conflict percentage	Percentage reduction in conflict percentage compared to base case
300ft (91.44m)	Morning	0 sec	1.902	Base Case
300ft (91.44m)	Morning	1 sec	2.922	-53.636
300ft (91.44m)	Morning	2 sec	2.003	-5.337
300ft (91.44m)	Morning	3 sec	2.176	-14.408
300ft (91.44m)	Morning	4sec	1.917	-0.799
300ft (91.44m)	Morning	5 sec	2.797	-47.074
300ft (91.44m)	Evening	0 sec	4.313	Base Case
300ft (91.44m)	Evening	1 sec	3.063	28.971
300ft (91.44m)	Evening	2 sec	2.998	30.497
300ft (91.44m)	Evening	3 sec	4.512	-4.619
300ft (91.44m)	Evening	4 sec	2.972	31.102
300ft (91.44m)	Evening	5 sec	3.444	20.140
600ft (182.88m)	Morning	0 sec	1.902	Base Case
600ft (182.88m)	Morning	1 sec	1.317	30.741
600ft (182.88m)	morning	2 sec	1.912	-0.531
600ft (182.88m)	morning	3 sec	0.740	61.082
600ft (182.88m)	Morning	4 sec	1.260	33.738
600ft (182.88m)	Morning	5 sec	1.484	21.954
600ft (182.88m)	Evening	0 sec	4.313	Base Case
600ft (182.88m)	Evening	1 sec	3.866	10.353
600ft (182.88m)	Evening	2 sec	4.540	-5.261
600ft (182.88m)	Evening	3 sec	6.132	-42.178
600ft (182.88m)	Evening	4 sec	2.605	39.607
600ft (182.88m)	Evening	5 sec	2.729	36.729

Figure 29. Conflict percentages for 300ft (91.44m) morning - Roosevelt Blvd at Wicoff (West Bound)

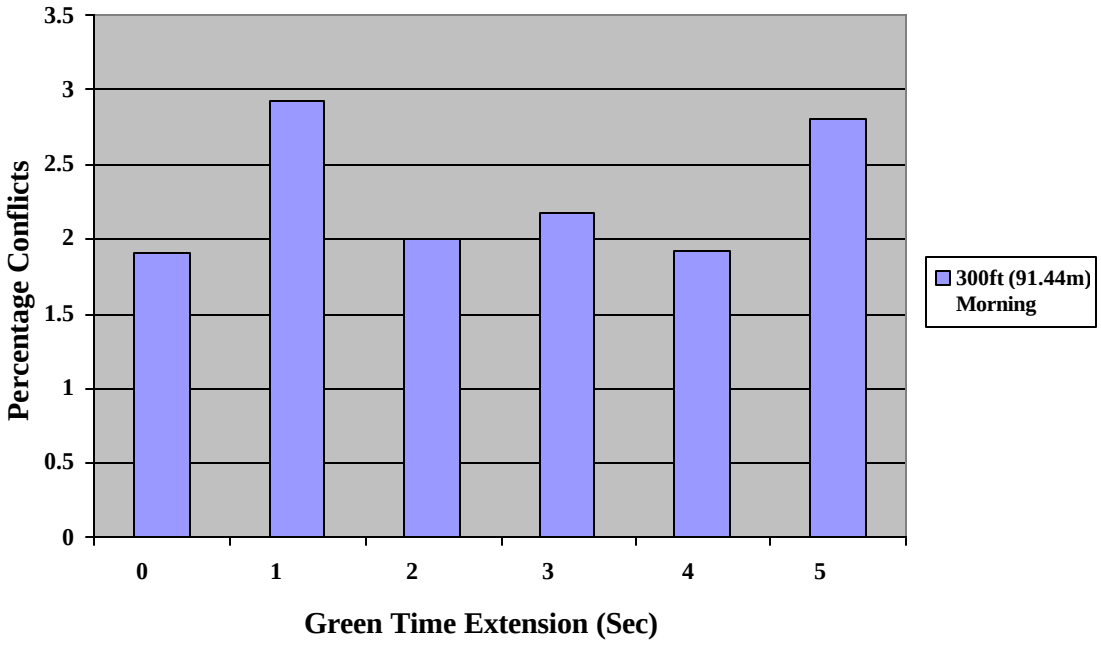


Figure 30. Conflict percentages for 300ft (91.44m) evening - Roosevelt Blvd at Wicoff (West Bound)

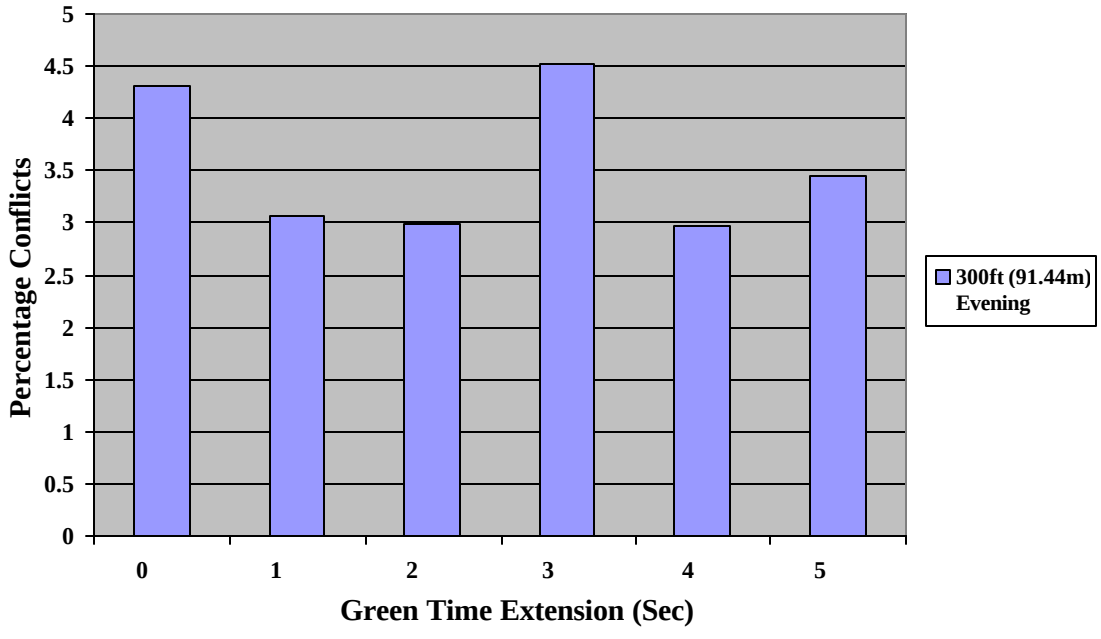


Figure 31. Conflict percentages for 600ft (182.88m) morning - Roosevelt Blvd at Wicoff (West Bound)

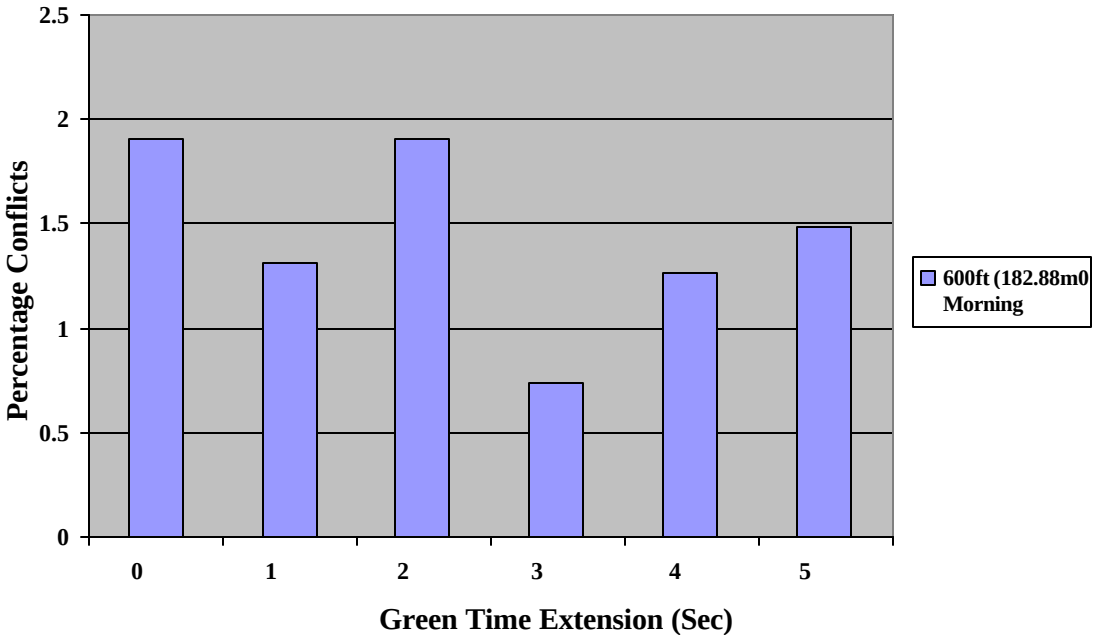
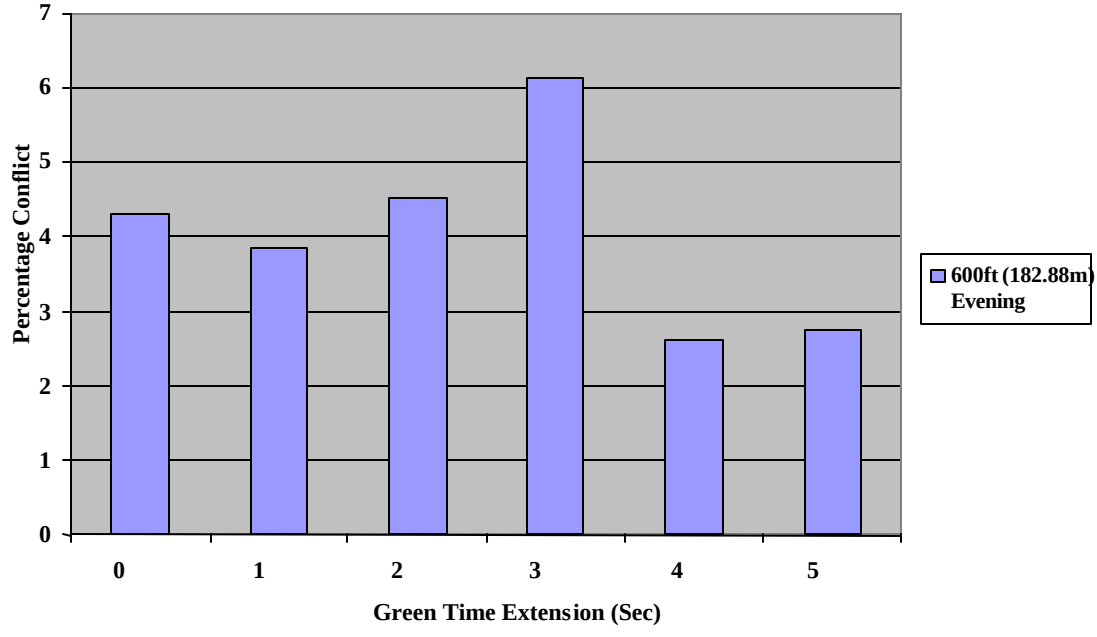
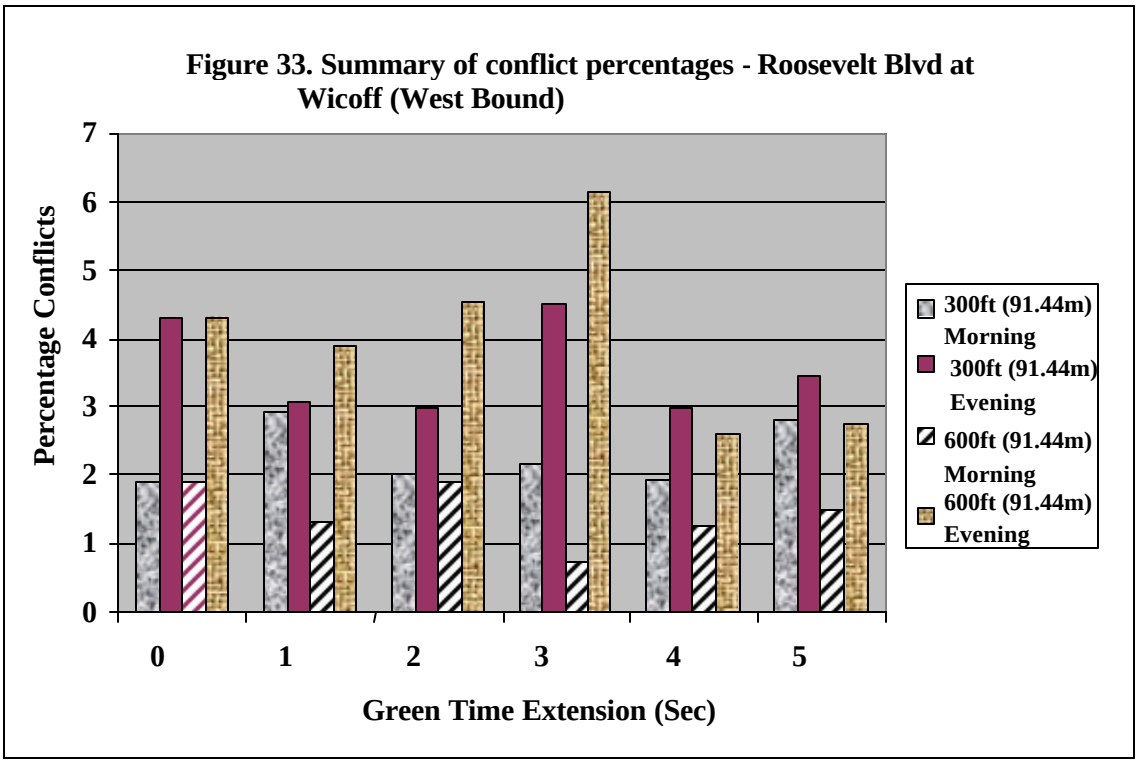


Figure 32. Conflict percentages for 600ft (182.88m) evening - Roosevelt Blvd at Wicoff (West Bound)





A further analysis was performed excluding the left and right turning traffic in the calculation of the total volume. It was observed that there was an increase in conflicts for all green extensions during the morning period. In the case of the evening period, it was observed that there was a decrease in dilemma zone conflicts with the detector at 300 ft (91.44 m), except for the extension of 3 sec.

Table 19. Conflict analysis (excluding left and right turning traffic) -Roosevelt at Wicoff (Westbound approach)

Detector Position	Time of Day	Green Extension	Conflict Percentage	Percentage reduction in conflict percentages
300ft (91.44m)	Morning	0 sec	1.997	
300ft (91.44m)	Morning	1 sec	3.134	-56.935
300ft (91.44m)	Morning	2 sec	2.094	-4.857
300ft (91.44m)	Morning	3 sec	2.317	-16.024
300ft (91.44m)	Morning	4sec	2.029	-1.602
300ft (91.44m)	Morning	5 sec	2.905	-45.468
300ft (91.44m)	Evening	0 sec	4.498	
300ft (91.44m)	Evening	1 sec	3.286	26.945
300ft (91.44m)	Evening	2 sec	3.165	29.635
300ft (91.44m)	Evening	3 sec	4.799	-6.692
300ft (91.44m)	Evening	4 sec	3.108	30.903
300ft (91.44m)	Evening	5 sec	3.606	19.831

Figure 34. Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) morning Roosevelt at Wicoff (Westbound Approach)

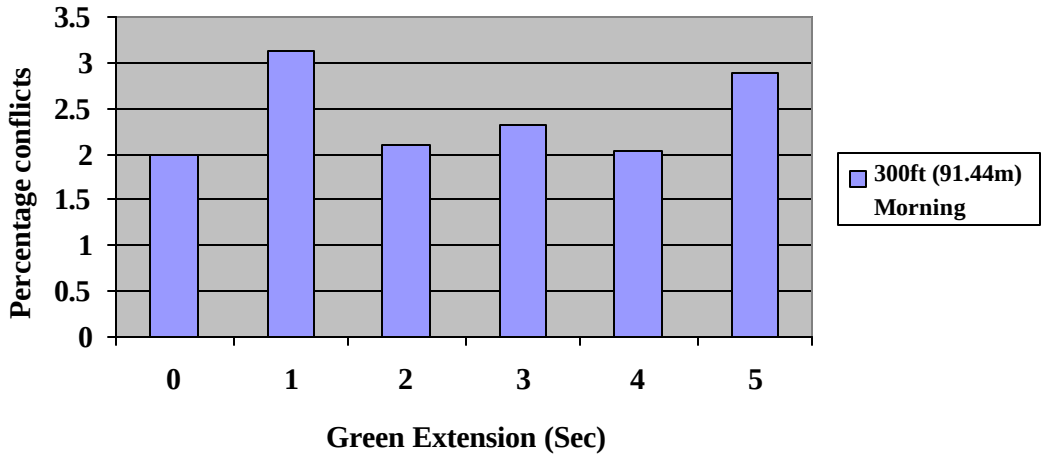
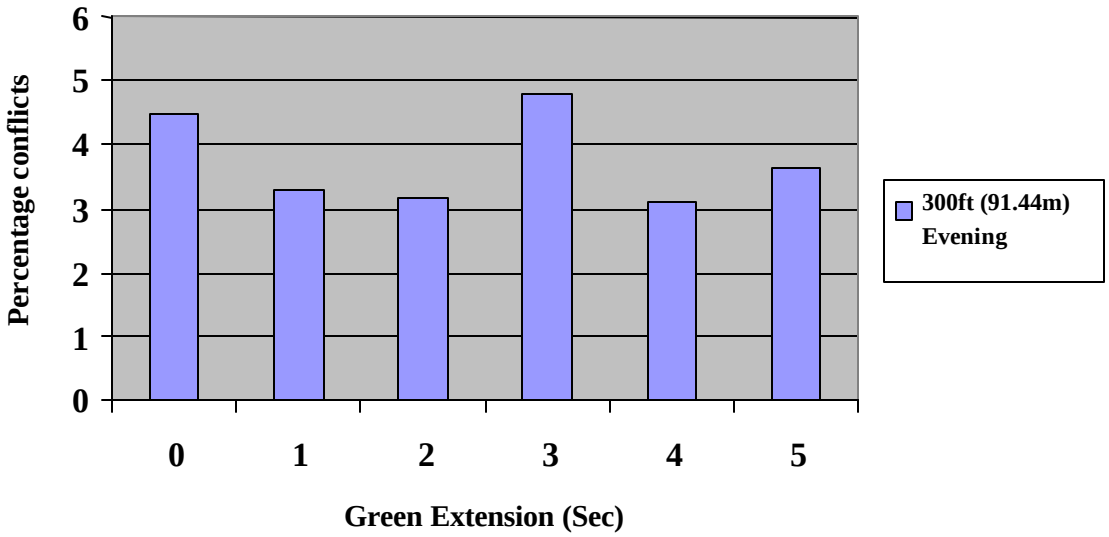


Figure 35. Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) evening Roosevelt at Wicoff (Westbound Approach)



4.2.5. Roosevelt Blvd at Armco (East Bound Approach)

In the base case (where there was no green extension), the dilemma zone conflict was quite low at 0.678% during the morning period, and 2.817% during the evening period. Comparing the morning period, it was noted that the conflicts increased when

different green extensions were provided, for the detector at both 300 ft (91.44 m) and 600 ft (182.88 m). The conflicts were much higher than the base cases when the 2 sec green extension was provided. During the morning period, the dilemma zone conflict was very high (706%) when the 3 sec green extension was provided with the detector at 300 ft (91.44 m). Such an steep increase in conflict cannot be explained and one can only speculate if it was caused by human error on the part of the data collectors or any unusual circumstances on this day. At night, however, the dilemma zone conflicts for 3 sec extension decreased by 44% over the base case.

In general, it was observed that the dilemma zone conflicts during the evening period were lower when compared to the morning period. On the whole, it was observed that the evening conflicts decreased when the detector was placed at 300 ft (91.44 m) and 600 ft (182.88 m) respectively. Further it was noted that by providing a green extension of 3 sec, the conflict rate reduced by 44% and 42% when the detectors were placed at 300 ft (91.44 m) and 600 ft (182.88 m) respectively.

Table 20. Conflict Analysis – Roosevelt at Armco (Eastbound Approach)

Detector position	Time of Day	Green Extension	Conflict Percentage	Percentage reduction of conflict percentages
300ft (91.44m)	Morning	0 sec	0.678	Base Case
300ft (91.44m)	Morning	1 sec	0.834	-23.009
300ft (91.44m)	Morning	2 sec	4.103	-505.206
300ft (91.44m)	Morning	3 sec	5.470	-706.785
300ft (91.44m)	Morning	4sec	1.193	-76.003
300ft (91.44m)	Morning	5 sec	1.059	-56.195
300ft (91.44m)	Evening	0 sec	2.817	Base Case
300ft (91.44m)	Evening	1 sec	1.627	42.241
300ft (91.44m)	Evening	2 sec	2.820	-0.110
300ft (91.44m)	Evening	3 sec	1.571	44.220
300ft (91.44m)	Evening	4 sec	6.416	-127.782
300ft (91.44m)	Evening	5 sec	3.542	-44.579
600ft (182.88m)	Morning	0 sec	0.678	Base Case
600ft (182.88m)	Morning	1 sec	0.928	-36.873
600ft (182.88m)	Morning	2 Sec	4.147	-511.652
600ft (182.88m)	Morning	3 sec	0.845	-24.631
600ft (182.88m)	Morning	4 sec	0.967	-42.552
600ft (182.88m)	Morning	5 sec	1.328	-95.870
600ft (182.88m)	Evening	0 sec	2.817	Base Case
600ft (182.88m)	Evening	1 sec	4.482	-59.100
600ft (182.88m)	Evening	2 sec	1.198	57.471
600ft (182.88m)	Evening	3 sec	1.625	42.312
600ft (182.88m)	Evening	4 sec	2.155	23.497
600ft (182.88m)	Evening	5 sec	1.427	49.341

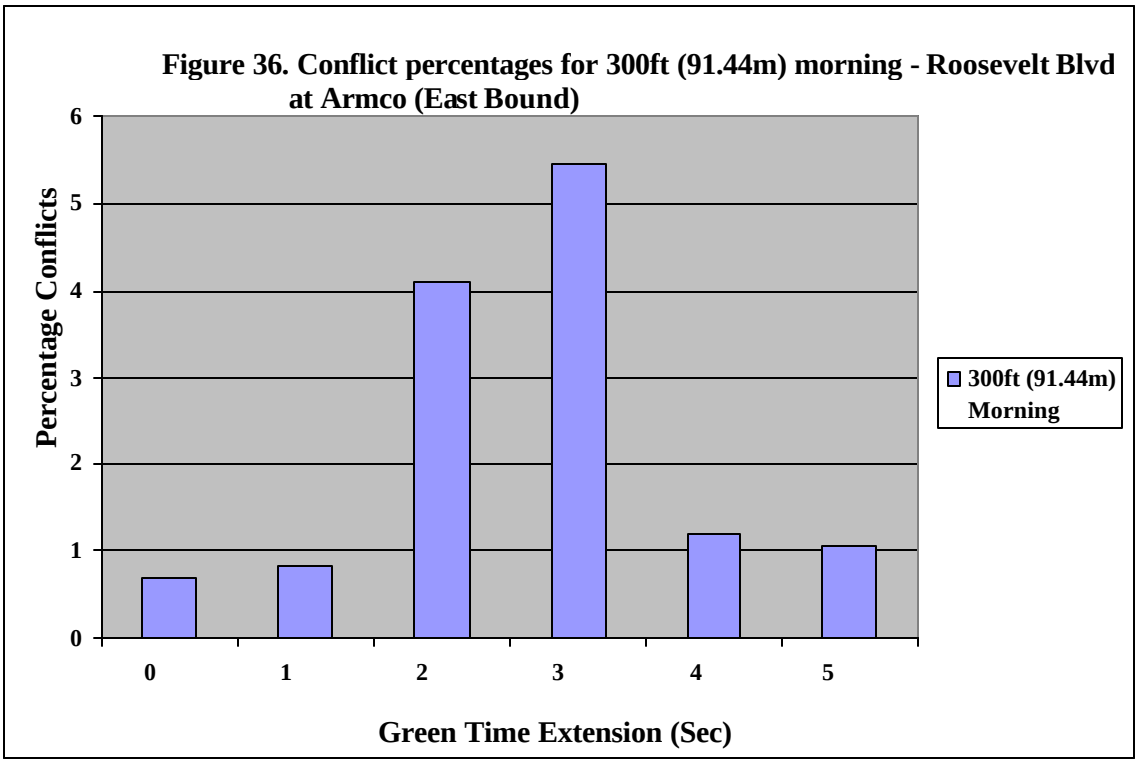


Figure 36. Conflict percentages for 300ft (91.44m) morning - Roosevelt Blvd at Armco (East Bound)
Percentage Conflicts
0
1
2
3
4
5
6
0
1
2
3
4
5
Green Time Extension (Sec)
300ft (91.44m) Morning

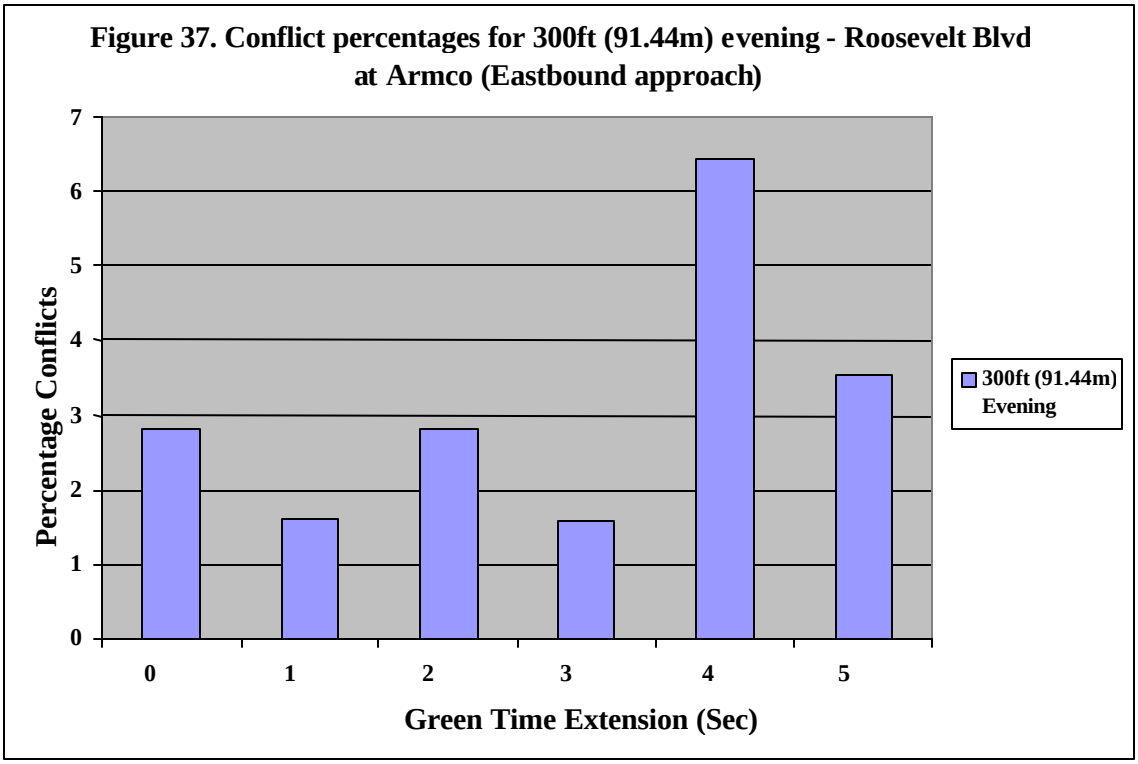


Figure 37. Conflict percentages for 300ft (91.44m) evening - Roosevelt Blvd at Armco (Eastbound approach)
Percentage Conflicts
0
1
2
3
4
5
6
7
0
1
2
3
4
5
Green Time Extension (Sec)
300ft (91.44m) Evening

Figure 38. Conflict percentages for 600ft (182.88m) morning - Roosevelt Blvd at Armco (East Bound)

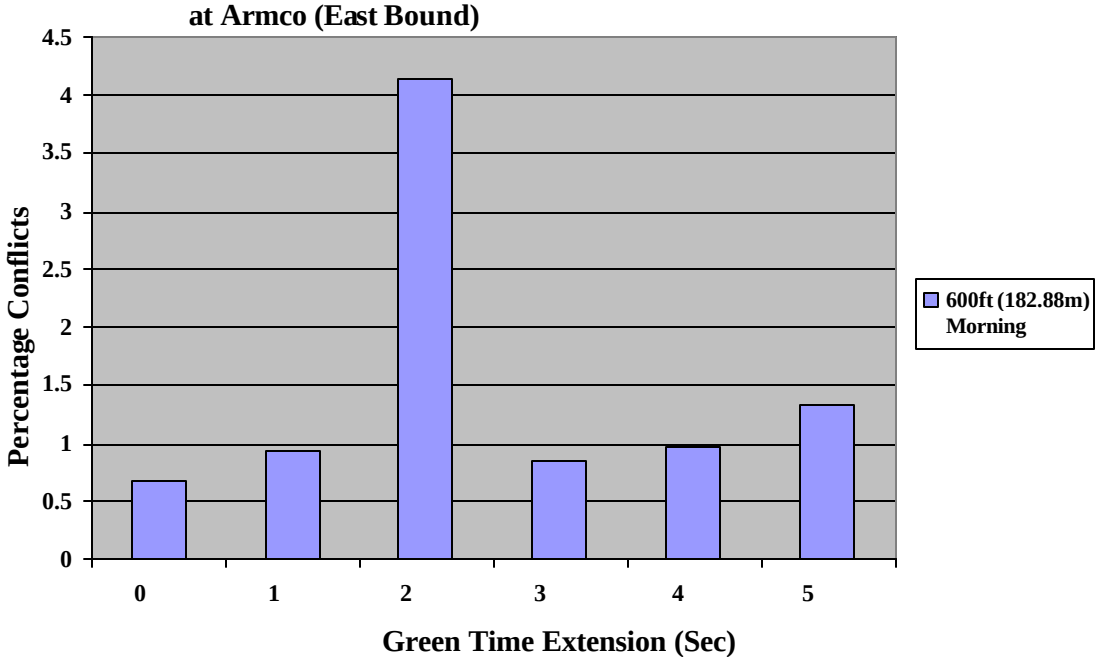
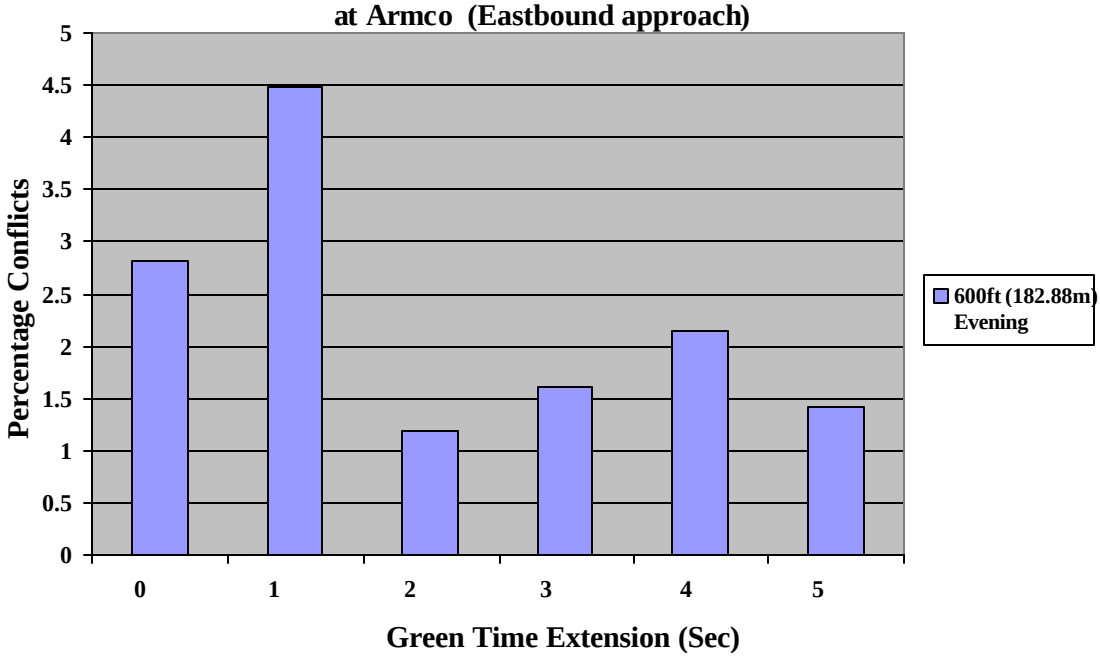
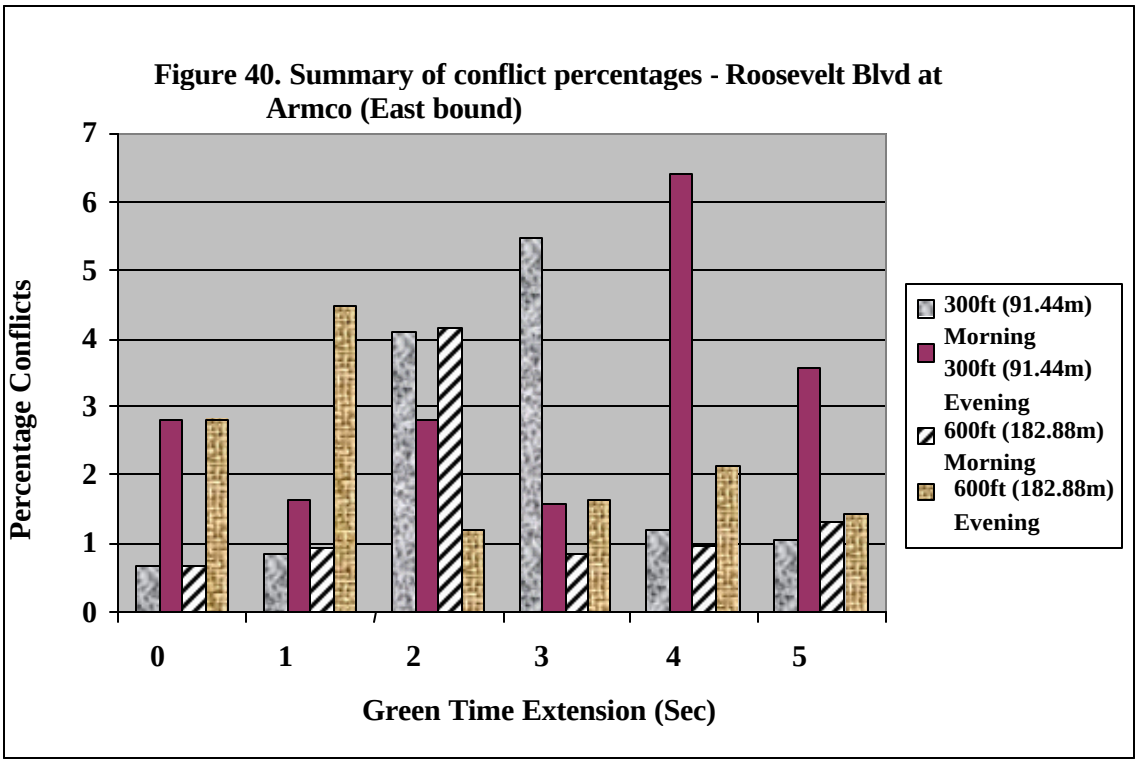


Figure 39. Conflict percentages for 600ft (182.88m) evening - Roosevelt Blvd at Armco (Eastbound approach)





An analysis was carried out by excluding left and right turning vehicles with the detector placed at 300 ft (91.44 m). The analysis showed that an increase in conflicts was observed when the green extensions were provided. As in the previous analysis, there was a very high increase in the percentage of conflict when the green time was extended by 3 sec. The nighttime data showed a different pattern, in contrast to morning data. There was a decrease in dilemma zone conflicts for green extensions of 1 sec and 3 sec. The 3 sec extension had the highest decrease of 46%. There was a marginal increase of 1.3% for the extension of 2 sec. When the green time was extended by 4 sec and 5 sec, there were increases in observed dilemma zone conflicts by 129% and 26 % respectively.

Table 21. Conflict analysis (excluding left and right turning traffic) -Roosevelt at Armco (Eastbound approach)

Detector Position	Time of Day	Green extension	Conflict Percentage	Percentage reduction in conflict percentages
300ft (91.44m)	Morning	0 sec	0.730	
300ft (91.44m)	Morning	1 sec	0.880	-20.548
300ft (91.44m)	Morning	2 sec	4.340	-494.521
300ft (91.44m)	Morning	3 sec	5.820	-697.260
300ft (91.44m)	Morning	4sec	1.250	-71.233
300ft (91.44m)	Morning	5 sec	1.100	-50.685
300ft (91.44m)	Evening	0 sec	2.930	
300ft (91.44m)	Evening	1 sec	1.660	43.345
300ft (91.44m)	Evening	2 sec	2.970	-1.365
300ft (91.44m)	Evening	3 sec	1.650	43.686
300ft (91.44m)	Evening	4 sec	6.710	-129.010
300ft (91.44m)	Evening	5 sec	3.700	-26.280

Figure 41 Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) morning - Roosevelt at Armco (Eastbound Approach)

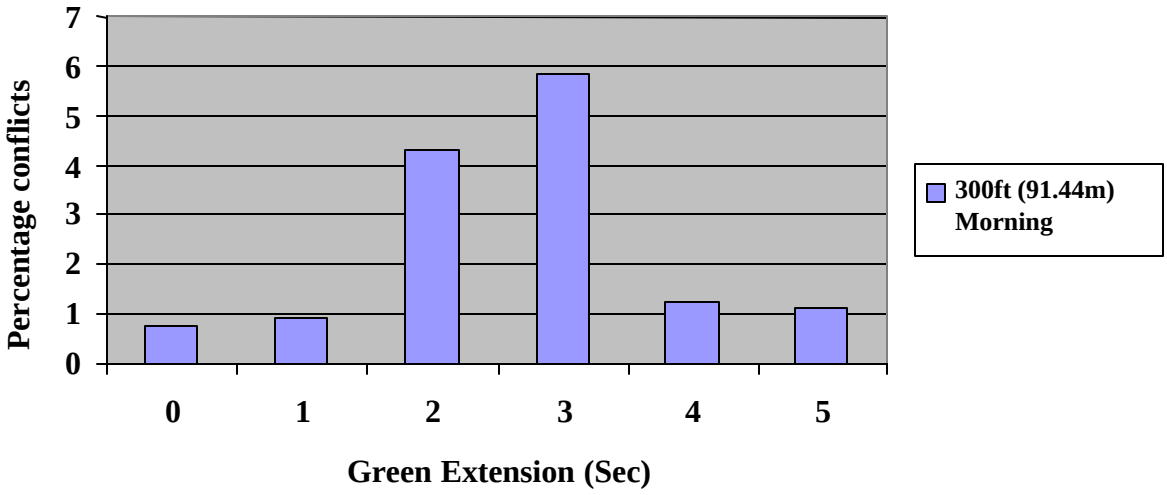
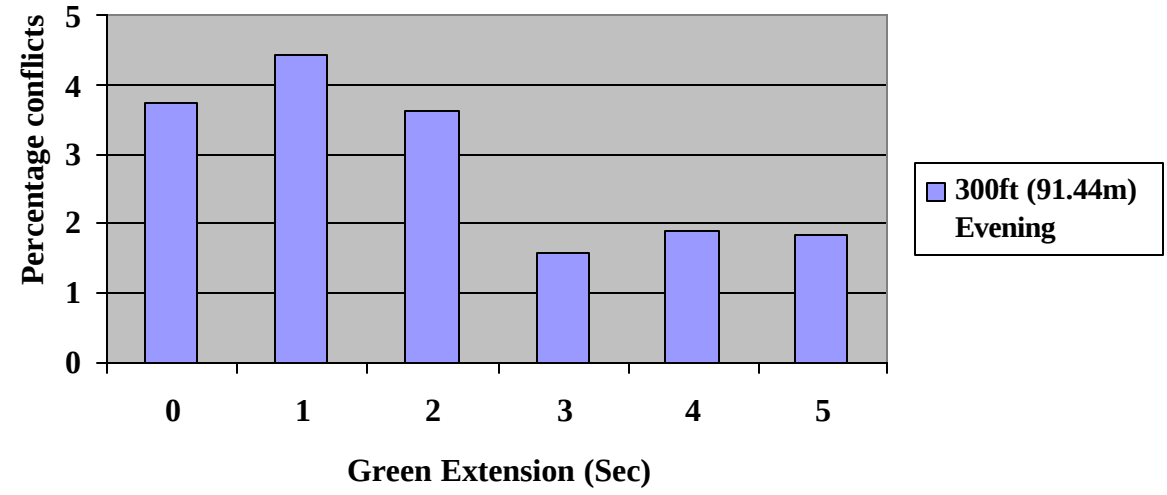


Figure 42 Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) evening -Roosevelt at Armco (Eastbound approach)



4.2.6.Roosevelt Blvd at Armco (Westbound Approach)

An analysis of dilemma zone conflicts at the intersection of Roosevelt Blvd. and Armco showed that there was reduction in dilemma zone conflicts when green extensions were provided during the morning period with the detector at 300 ft (91.44m), except for 1 sec

extension when an increase in dilemma zone conflicts was recorded. The highest reduction of 58% was recorded for the green extension of 3 sec. During the morning period, with the detector at 600 ft (182.88 m), it was observed that there was a decrease in dilemma zone conflicts for green extensions of 1 sec, 2 sec and 4 sec. But it increased by 99% when 3 sec extension was provided and by 88% when 5 sec extension was provided. Analyzing the night period, it was seen that the conflicts were reduced when the detector was placed at 600 ft (182.88m); there was a decrease of 49% when the green extension of 1 sec was provided and a decrease of 58% when the green time was extended by 2 sec. But an increase of around 41% and 23% were observed for the extensions of 3 sec and 5 sec respectively.

Table 22. Conflict Analysis – Roosevelt at Armco (Westbound Approach)

Detector Position	Time of day	Green Extension	Conflict percentage	Percentage reduction in conflict percentages
300ft (91.44m)	Morning	0 sec	3.558	Base Case
300ft (91.44m)	Morning	1 sec	4.186	-17.650
300ft (91.44m)	Morning	2 sec	3.453	2.940
300ft (91.44m)	Morning	3 sec	1.469	58.713
300ft (91.44m)	Morning	4 sec	1.808	49.185
300ft (91.44m)	Morning	5 sec	1.726	51.504
300ft (91.44m)	Evening	0 sec	1.233	Base Case
300ft (91.44m)	Evening	1 sec	1.273	-3.219
300ft (91.44m)	Evening	2 sec	1.706	-38.360
300ft (91.44m)	Evening	3 sec	1.290	-4.557
300ft (91.44m)	Evening	4 sec	1.693	-37.274
300ft (91.44m)	Evening	5 sec	2.188	-77.410
600ft (182.88m)	Morning	0 sec	3.558	Base Case
600ft (182.88m)	Morning	1 sec	3.134	11.917
600ft (182.88m)	Morning	2 sec	1.329	62.650
600ft (182.88m)	Morning	3 sec	7.100	-99.550
600ft (182.88m)	Morning	4 sec	3.388	4.778
600ft (182.88m)	Morning	5 sec	6.485	-82.263
600ft (182.88m)	Evening	0 sec	1.233	Base Case
600ft (182.88m)	Evening	1 sec	0.624	49.404
600ft (182.88m)	Evening	2 sec	0.508	58.793
600ft (182.88m)	Evening	3 sec	1.747	-41.652
600ft (182.88m)	Evening	4 sec	1.012	17.944
600ft (182.88m)	Evening	5 sec	1.523	-23.490

Figure 43. Conflict percentages for 300ft (91.44m) morning - Roosevelt Blvd at Armco (West Bound)

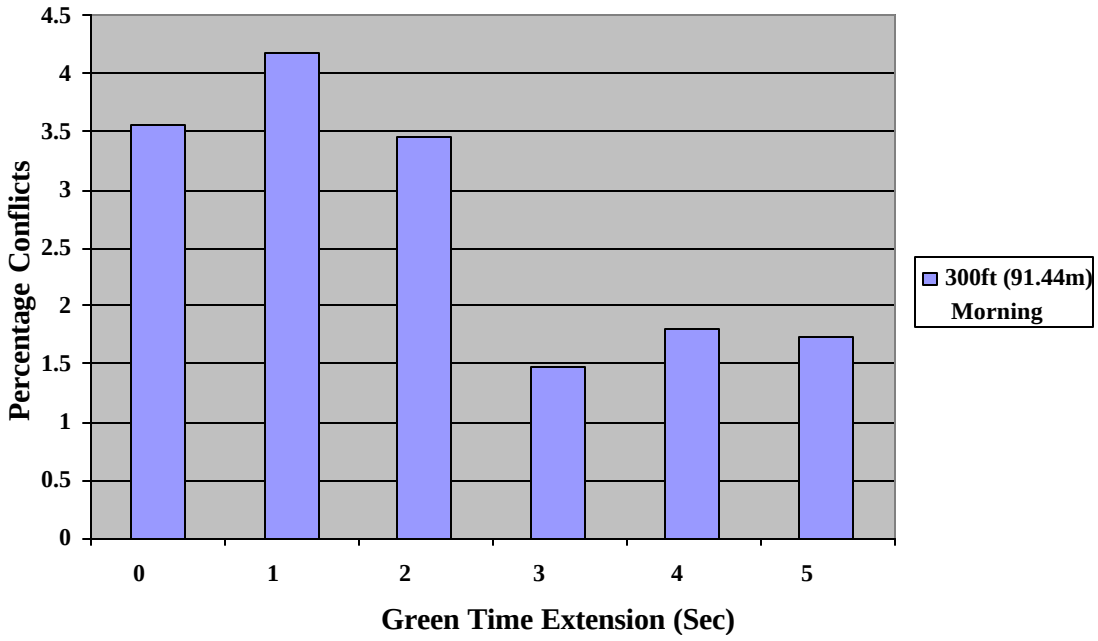


Figure 44. Conflict percentages for 300ft (91.44m) evening - Roosevelt Blvd at Armco (Westbound approach)

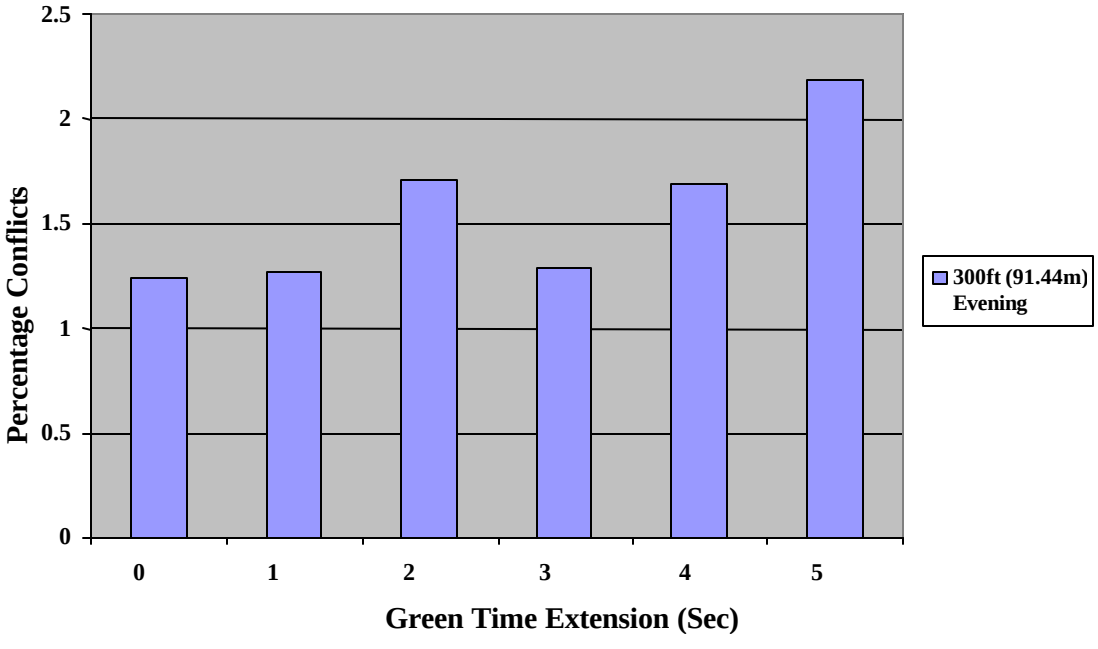


Figure 45. Conflict percentages for 600ft (182.88m) morning - Roosevelt Blvd at Armco (West Bound)

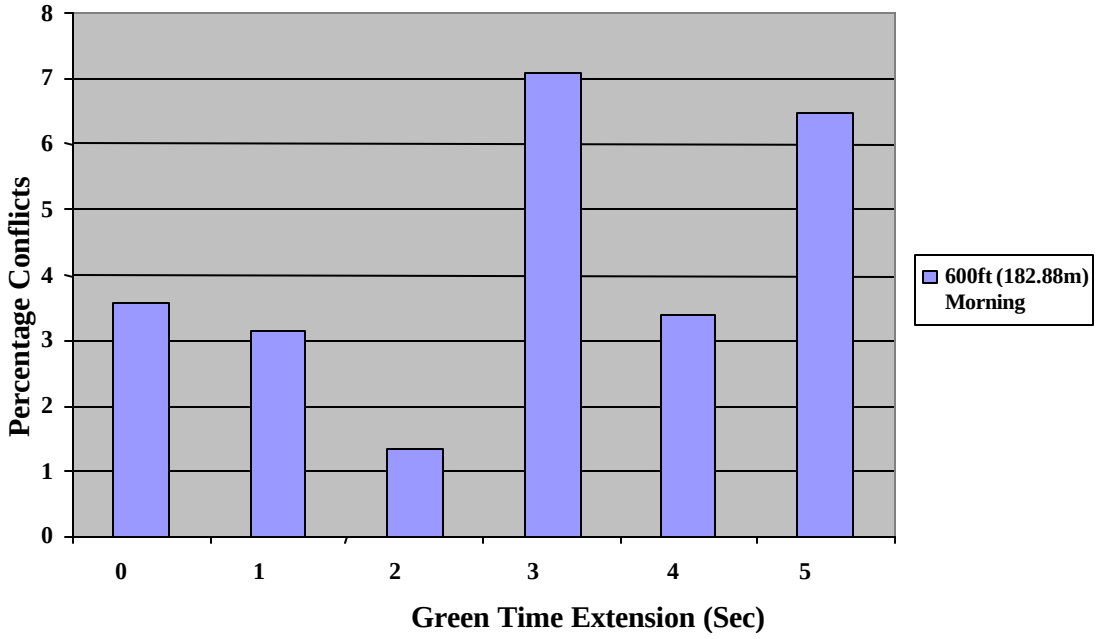
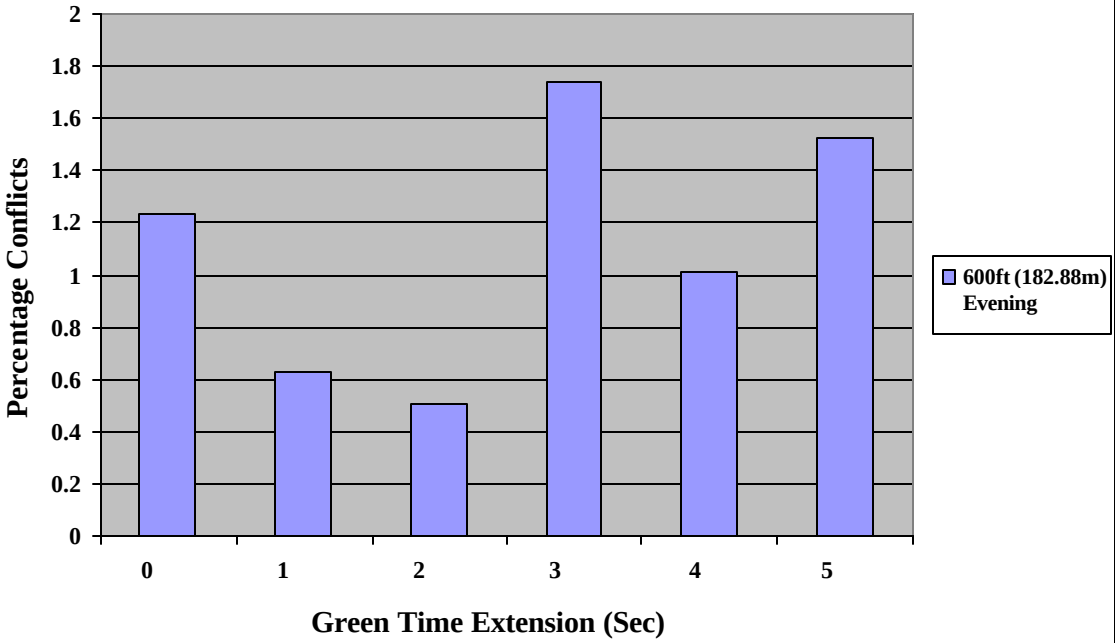
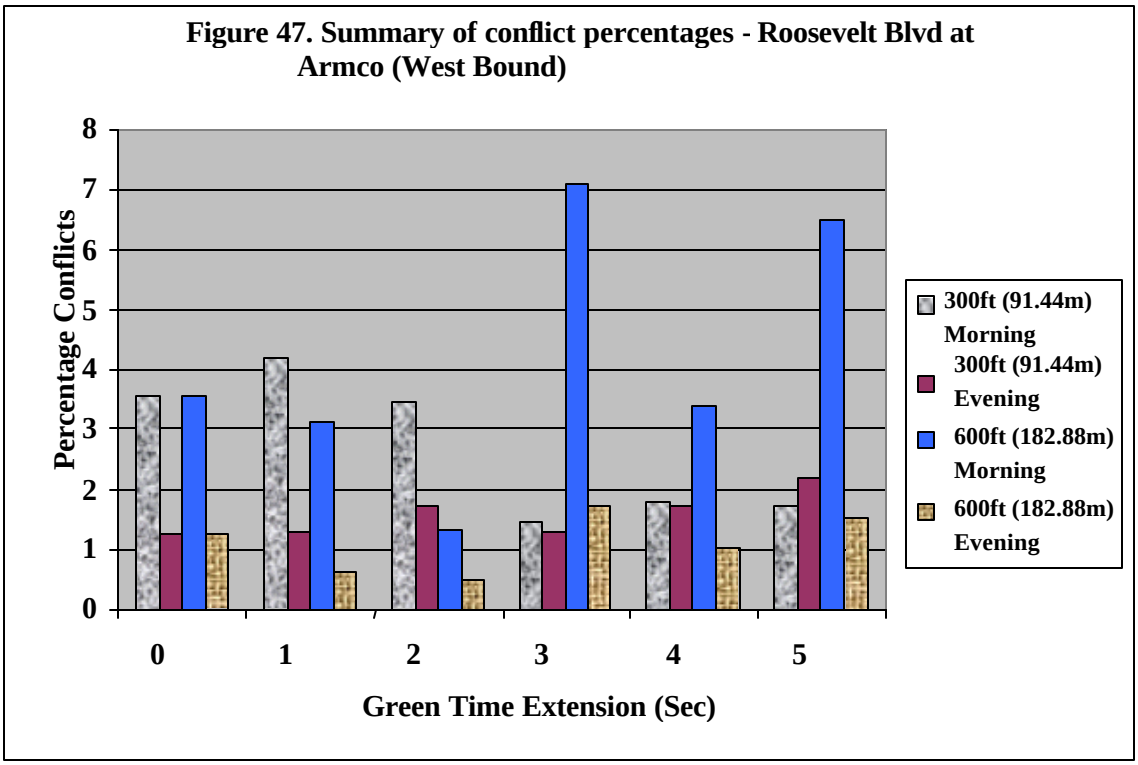


Figure 46. Conflict percentages for 600ft (182.88m) evening - Roosevelt Blvd at Armco (Westbound approach)





Further analysis was carried out by excluding the right turns and left turns, and just considering the through traffic (vehicles running through green, stopping on red, running red, stopping abruptly, accelerating through yellow) as the total volume. The conflict volume was calculated by accounting for those vehicles which ran red, stopped abruptly, or accelerated through yellow. Considering all the intersections, results were more consistent when the detector was present at 300 ft (91.44 m) rather than at 600 ft. So the analysis excluding right turning and left turning vehicles were carried only for the observations with the detector at 300 ft (91.44m). The results are tabulated below.

Table 23. Conflict Analysis (excluding left and right turning traffic) -Roosevelt at Armco (Westbound approach)

Detector Position	Time of Day	Green Extension	Conflict Percentage	Percentage reduction in conflict percentages
300 ft	Morning	0 sec	3.7529	
300 ft	Morning	1 sec	4.4221	-17.832
300 ft	Morning	2 sec	3.645	2.875
300 ft	Morning	3 sec	1.572	58.112
300 ft	Morning	4sec	1.8993	49.391
300 ft	Morning	5 sec	1.8213	51.470
300 ft	Evening	0 sec	1.2732	
300 ft	Evening	1 sec	1.3144	-3.236
300 ft	Evening	2 sec	1.7793	-39.750
300 ft	Evening	3 sec	1.3253	-4.092
300 ft	Evening	4 sec	1.6928	-32.956
300 ft	Evening	5 sec	2.2962	-80.349

It was observed that there was a reduction of dilemma zone conflicts for the morning period, except for 1 sec green extension. Also, the highest reduction of 58% was seen when the green extension of 3 sec was provided. Considering the night period, there was not much reduction in conflicts, and in fact a small rise in conflicts, when green extension was provided, the highest being 80% compared to the base case, when the green extension of 5 sec was provided.

Figure 48. Conflict percentages (excluding left and right turning traffic) 300ft (91.44m) morning – Roosevelt Blvd at Armco (Westbound approach)

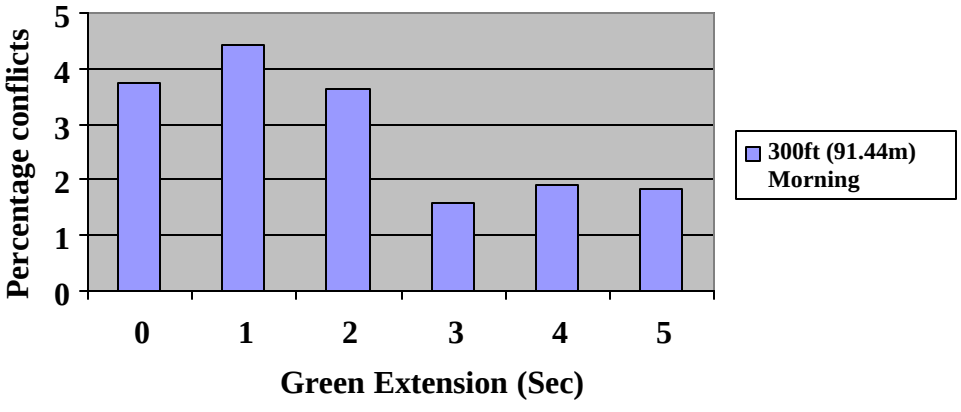
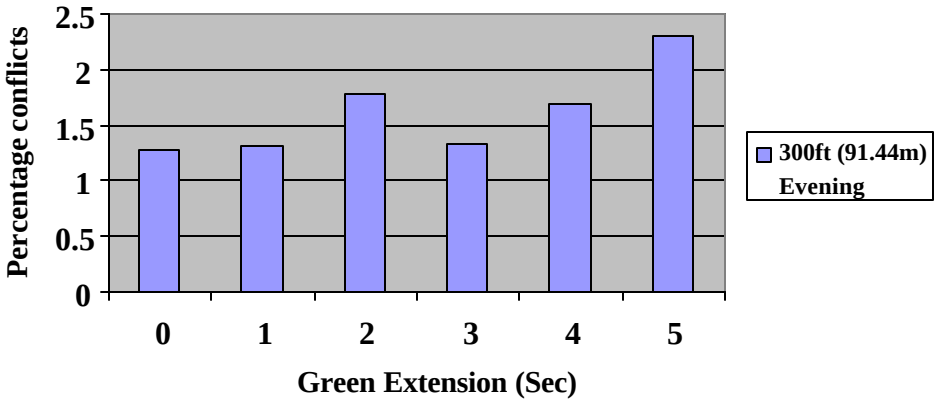


Figure 49. Conflict percentages (excluding left and right turning traffic) 300 ft (91.44m) evening -Roosevelt at Armco (Westbound Approach)



4.3. Analysis of Individual Conflicts

In an attempt to find out which, if any, of the conflicts contributed more significantly then the other conflicts, an analysis was carried out to calculate the individual conflicts (running red light, abruptly stopping, or accelerating through yellow). The individual percentages were found by dividing the volume for the particular conflict by the total volume. The analysis was carried out using the total volumes excluding left and right turning vehicles, and the data collected with the detector active at 300 ft (91.44 m). The results are tabulated below.

Table 24. Individual Conflicts for Roosevelt Blvd at Highland (Eastbound Approach)

Green extension	Time of Day	Run Red light	Stop Abruptly	Accelerate Through Yellow
0 sec	Morning	0.244	0.081	2.114
1 sec	Morning	1.795	1.097	3.589
2 sec	Morning	1.593	0.000	1.500
3 sec	Morning	0.477	0.000	1.050
4sec	Morning	0.606	0.101	2.222
5 sec	Morning	0.444	0.222	4.111
0 sec	Evening	0.437	0.000	1.458
1 sec	Evening	0.142	0.000	1.136
2 sec	Evening	0.000	0.000	0.745
3 sec	Evening	0.154	0.000	0.154
4 sec	Evening	0.822	0.000	2.467
5 sec	Evening	0.188	0.000	0.753

Table 25. Individual Conflicts for Roosevelt Blvd at Highland(Westbound Approach)

Green extension	Time of Day	Run Red light	Stop Abruptly	Accelerate Through Yellow
0 sec	Morning	1.619	0.000	2.428
1 sec	Morning	0.127	0.380	3.797
2 sec	Morning	1.758	0.391	1.855
3 sec	Morning	0.296	0.788	1.084
4sec	Morning	1.609	0.000	1.839
5 sec	Morning	1.887	0.000	2.483
0 sec	Evening	0.528	0.000	0.925
1 sec	Evening	1.030	0.000	1.716
2 sec	Evening	0.872	0.436	1.163
3 sec	Evening	0.576	0.144	0.576
4 sec	Evening	0.582	0.437	0.582
5 sec	Evening	0.590	0.147	0.295

Table 26. Individual Conflicts for Roosevelt Blvd at Wicoff (Eastbound Approach)

Green extension	Time of Day	Run Red light	Stop Abruptly	Accelerate Through Yellow
0 sec	Morning	1.423	0.065	0.906
1 sec	Morning	1.845	0.277	0.092
2 sec	Morning	0.861	0.000	1.174
3 sec	Morning	0.988	0.000	0.000
4sec	Morning	0.856	0.086	0.771
5 sec	Morning	0.515	0.147	0.442
0 sec	Evening	0.976	0.000	0.000
1 sec	Evening	1.068	0.214	1.175
2 sec	Evening	1.360	0.151	1.813
3 sec	Evening	0.588	0.118	1.176
4 sec	Evening	1.633	0.000	2.261
5 sec	Evening	2.319	0.435	2.899

Table 27. Individual Conflicts for Roosevelt Blvd at Wicoff (Westbound Approach)

Green extension	Time of Day	Run Red light	Stop Abruptly	Accelerate Through Yellow
0 sec	Morning	0.250	0.582	1.165
1 sec	Morning	1.112	0.000	2.022
2 sec	Morning	1.005	0.168	0.921
3 sec	Morning	0.713	0.178	1.426
4sec	Morning	0.564	0.113	1.353
5 sec	Morning	1.037	0.311	1.556
0 sec	Evening	1.151	0.523	2.824
1 sec	Evening	0.587	0.235	2.465
2 sec	Evening	1.266	0.380	1.519
3 sec	Evening	1.686	0.389	2.724
4 sec	Evening	1.351	0.000	1.757
5 sec	Evening	1.442	0.120	2.043

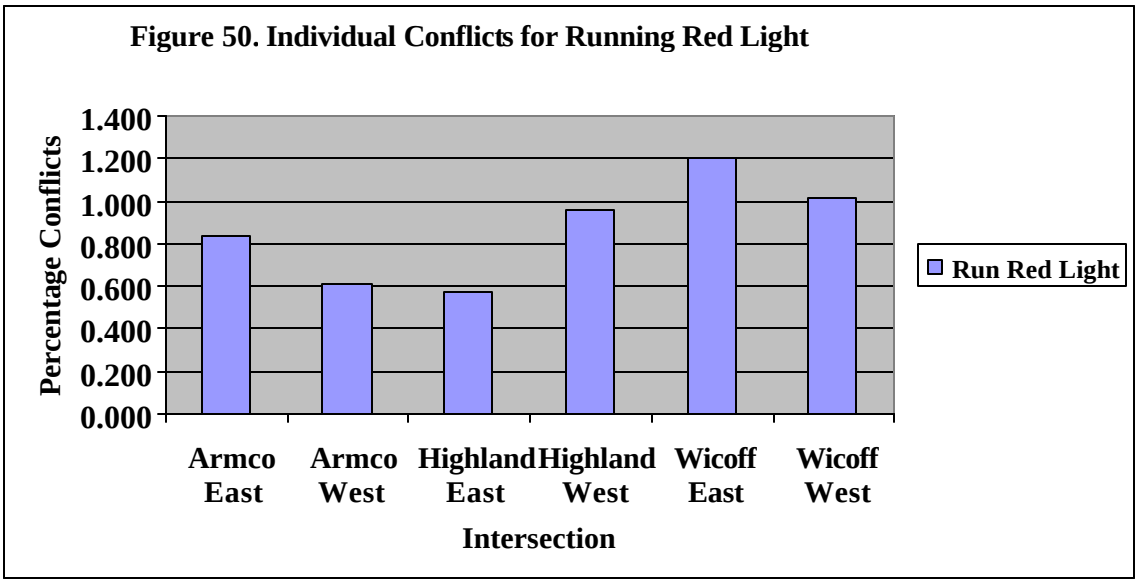
Table 28. Individual Conflicts for Roosevelt Blvd at Armco (Eastbound Approach)

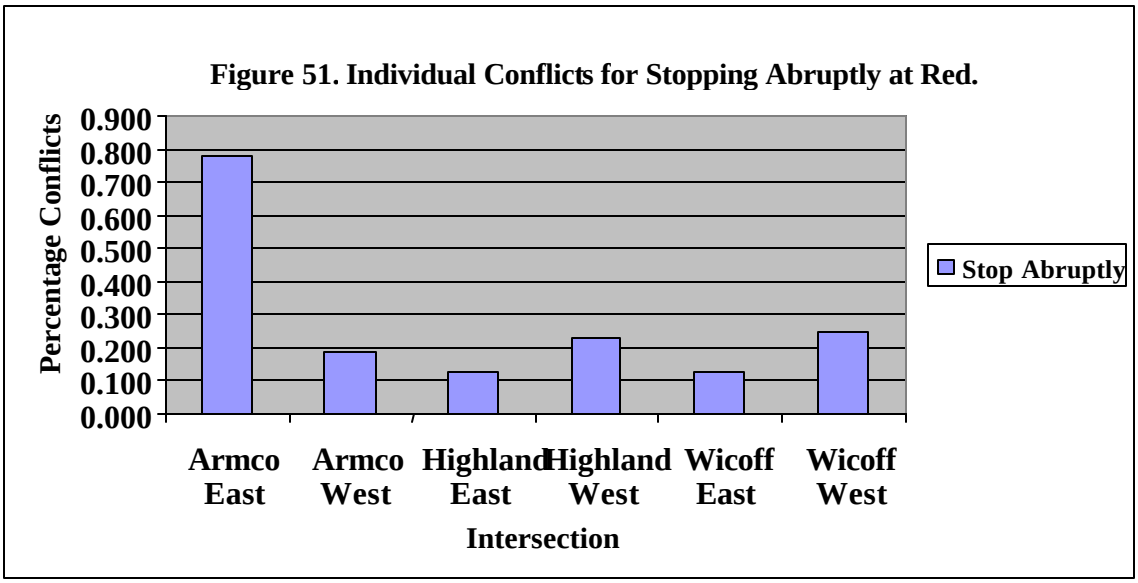
Green extension	Time of Day	Run Red light	Stop Abruptly	Accelerate Through Yellow
0 sec	Morning	0.598	0.000	0.133
1 sec	Morning	0.265	0.000	0.619
2 sec	Morning	1.287	1.368	1.689
3 sec	Morning	1.146	2.557	2.116
4sec	Morning	0.668	0.083	0.501
5 sec	Morning	0.514	0.000	0.588
0 sec	Night	0.867	0.000	1.950
1 sec	Night	0.312	0.104	1.246
2 sec	Night	0.446	1.486	1.040
3 sec	Night	0.449	0.000	1.122
4 sec	Night	2.658	2.025	2.025
5 sec	Night	0.853	1.707	1.138

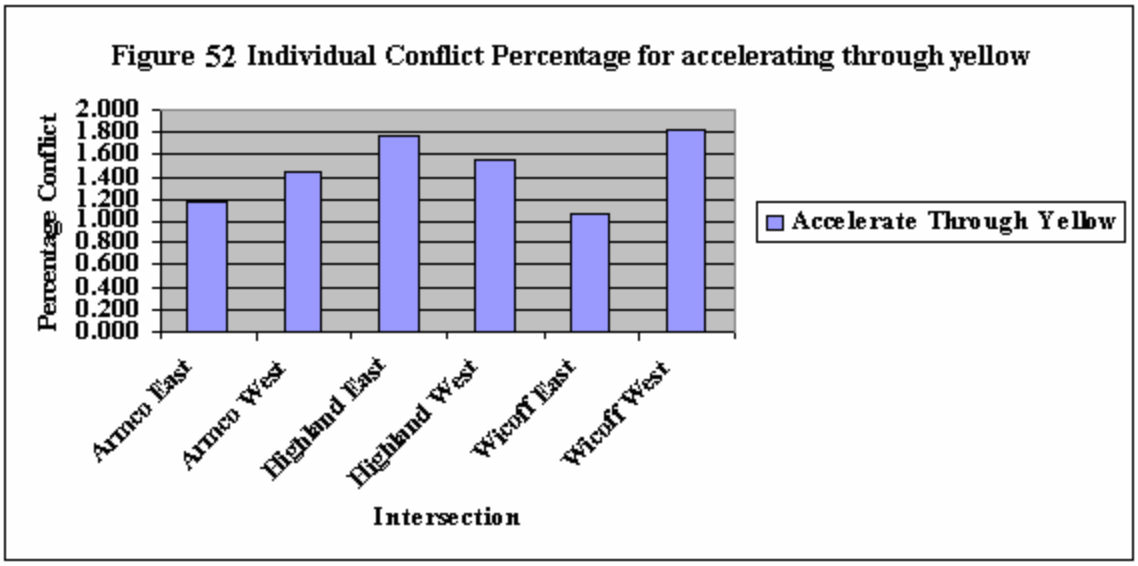
Table 29. Individual Conflicts for Roosevelt Blvd at Armco (Westbound Approach)

Green extension	Time of Day	Run Red light	Stop Abruptly	Accelerate Through Yellow
0 sec	Morning	1.798	0.313	1.642
1 sec	Morning	0.704	0.000	3.719
2 sec	Morning	0.396	0.396	2.853
3 sec	Morning	0.087	0.000	1.485
4sec	Morning	1.519	0.190	0.190
5 sec	Morning	0.694	0.087	1.041
0 sec	Night	0.490	0.196	0.588
1 sec	Night	0.404	0.607	0.303
2 sec	Night	0.237	0.119	1.423
3 sec	Night	0.120	0.120	1.084
4 sec	Night	0.605	0.000	1.088
5 sec	Night	0.230	0.230	1.837

An average of all the percentages were taken at each approach for both the morning and evening periods, and the pattern for each conflict (running red, abruptly stopping on red, and accelerating through yellow) was plotted as shown below.







The results show that accelerating through yellow was most common followed by running through red and abruptly stopping during the change interval.

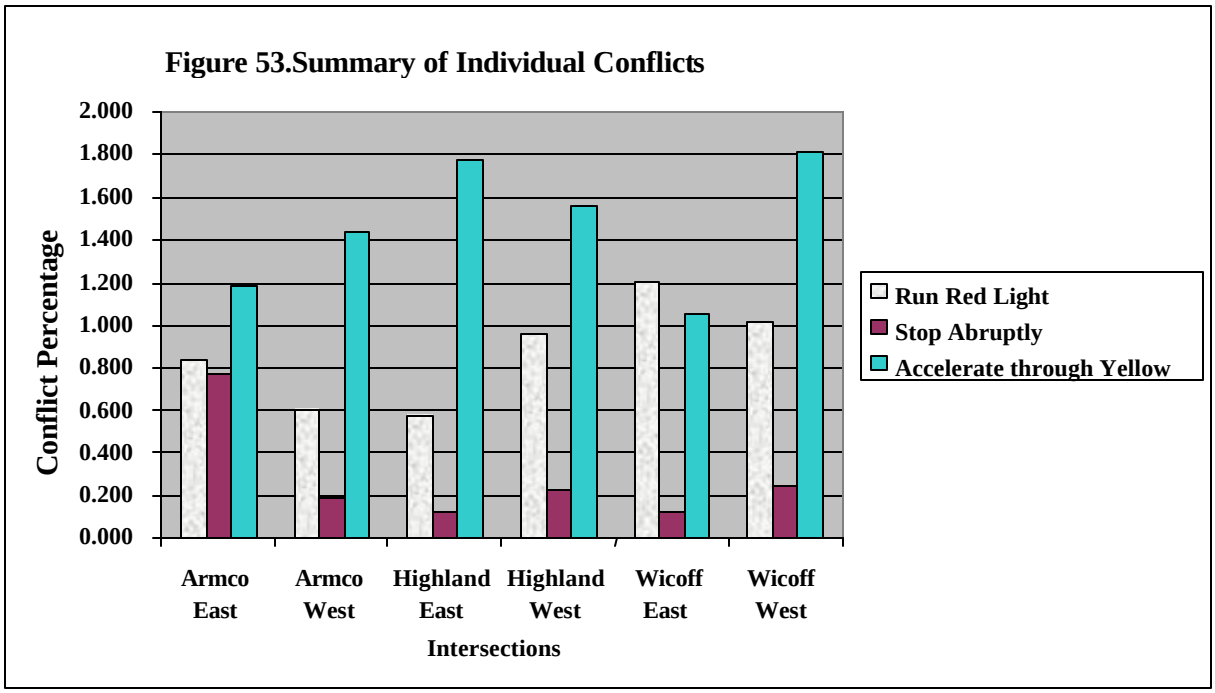


Figure 53.Summary of Individual Conflicts
Conflict Percentage
2.000
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
Armco East
Armco West
Highland East
Highland West
Wicoff East
Wicoff West
Intersections
Run Red Light
Stop Abruptly
Accelerate through Yellow

5. CONCLUSIONS AND RECOMMENDATIONS

The report presents the details of a study carried out to develop a technique for the field evaluation of dilemma zones at high speed intersections in Ohio.

The objective of this study was fulfilled by testing and implementing a dilemma zone protection technique at three high-speed closely-spaced intersections on Roosevelt Blvd in Middletown, Ohio. Several factors that affect the testing and implementation of the dilemma zone reduction technique were considered:

(a) Length of dilemma zone, which allowed for vehicular speeds ranging from 45 mph (72.41 kmph) to 60 mph (96.54 kmph) since speeds on these roadways are not uniform and tend to vary within a wide range;

(b) Location of detectors, which takes into account the varying speeds that exists on these roadways;

(c) Green extensions, which varied from 1 sec to 5 sec in increments of 1 sec, with the "no green extension" being used as the base case;

(d) Vehicle conflicts caused by (i) running red light (ii) stopping abruptly or (iii) accelerating through yellow representing the dilemma zone problem.

(e) Data collection during the hours when traffic volume on the roadway was low and speed tended to be high both during daylight and nighttime conditions;

(f) Signal coordination at semi actuated signals, which required the signals to be set on "recall" for availing the yellow interval during each cycle for maximization of the data collection efforts.

The data was collected at the intersection of Roosevelt Blvd and Highland, Wicoff, and Armco. Two camera detectors (at 300ft (91.44m) and 600 ft (182.88m)) were placed on both approaches of each intersection at Roosevelt Blvd. The number of vehicles in dilemma zone was determined by counting the number of vehicles that ran red, abruptly stopped at red, and accelerated through yellow. The base case consisted of observations where no green extension was provided when the signal changed to yellow. The test cases consisted of green extensions of 1 sec, 2 sec, 3 sec, 4 sec and 5 sec when the vehicles were detected at 300 ft (91.44m) or 600 ft (182.88m), but not both. The traffic data was collected during off peak hours in the morning (9am – 11am) and at night (8pm – 10pm). In all, 288 hours of data were collected on the six intersection approaches. Conflict volumes (vehicles running red, abruptly stopping at red, and accelerating through yellow) were determined and conflict percentages were calculated for all cases of green extensions and detector locations. The analysis revealed that that accelerating through yellow was the major conflict for all intersections, followed by running red and stopping abruptly respectively.

The analysis showed that for both the eastbound and westbound approaches of Highland Street, the detector at 300 ft (91.44m) and the green time extension of 3 sec provided the maximum reduction in dilemma zone conflicts during both morning and night periods. Further analysis was carried out by excluding the left and right turning vehicles from the analysis; however, the dilemma zone reduction pattern did not change.

For the eastbound approach of Roosevelt Blvd at Wicoff, the extension of 3 sec provided a significant reduction in dilemma zone conflicts, except for the night

observations. If the left and right turning traffic was excluded, the results showed that the 3 sec green extension with detector at 300 ft (91.44m)was effective during the morning period, while an increase in conflicts was noted for the night period. On the westbound approach of Roosevelt Blvd at Wicoff, a small increase in conflicts was noted for green extensions in many cases. But the morning period with detection at 600ft (182.88m) showed a decrease in conflicts with a green extension of 3 sec.

On the westbound approach of Roosevelt Blvd at Armco, the 3 sec green extension with the detector at 300 ft (91.44m) showed a reduction in conflicts for the morning period and an increase in conflicts for the night period. On the eastbound approach, the 3 sec green extension with detector at 300 ft (91.44m) showed an increase in conflicts during the morning period, and a decrease during the night period.

The study indicated that the three types of conflicts namely, running red light, stopping abruptly and accelerating through yellow can be successfully used to identify vehicles that experience dilemma zone problems at signalized intersections. The use of these measures in implementing dilemma zone protection techniques in the future is important since currently no other direct measures are available for identifying dilemma zone problems at signalized intersections. Overall, this study has shown that, for the roadway segment of Roosevelt Blvd between Highland and Armco, which has a speed limit of 45 mph (72.41 kmph), dilemma zone protection can be effective by placing detectors at 300 ft (91.44m) and providing a green extension of 3 sec on most, but not all, approaches. The effectiveness was more evident during the morning period than during the night period indicating that drivers' speed behavior may be different during daylight and night conditions. The study shows that there is no one "universal" rule for dilemma zone protection that would apply equally to all intersections because each intersection is unique in its geometric and operational characteristics and vehicular speeds on any intersection varies within a wide range.

The technique used in the present study is simple to implement, and can be used at most of the intersections requiring the use of a detector. Vehicle detection can be provided by using loop detectors, if necessary, instead of video detectors as was done in this study. If the base conflict rate is relatively high, this technique has the potential of reducing dilemma zone problems if it is judiciously implemented.

Recommendations

Improvements to intersections identified with dilemma zone problems may include the following tasks:

(a) Determine the speed limits and location of the detector: Since vehicular speeds on any roadway normally vary within a wide range, it is important for the traffic engineer to decide the speed limits for which dilemma zone protection would be maximized. Once this decision is made, the length of dilemma zone can be calculated and the location of the detector can be determined as shown in Section 4.1 (design of experiments).

(b) Collect sample data for base case: Before implementing the green extension, it is suggested that the traffic engineer collect 2-hour sample data during off-peak hours by counting vehicles that (a) run red light, (b) stop abruptly and (c) accelerate through yellow during the base case, that is, with no green extension.

(c) Implement the green extension: Once the green extension has been implemented, it is important to keep an eye on any abnormalities that might show up during the initial period.

(d) Fine tune the green extension: After allowing a familiarization period of a few weeks, repeat step (b) above for the green extension and make adjustments to the green extension as necessary.

6. REFERENCES

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7. APPENDIX

Figure 1. Roosevelt Blvd at Highland.

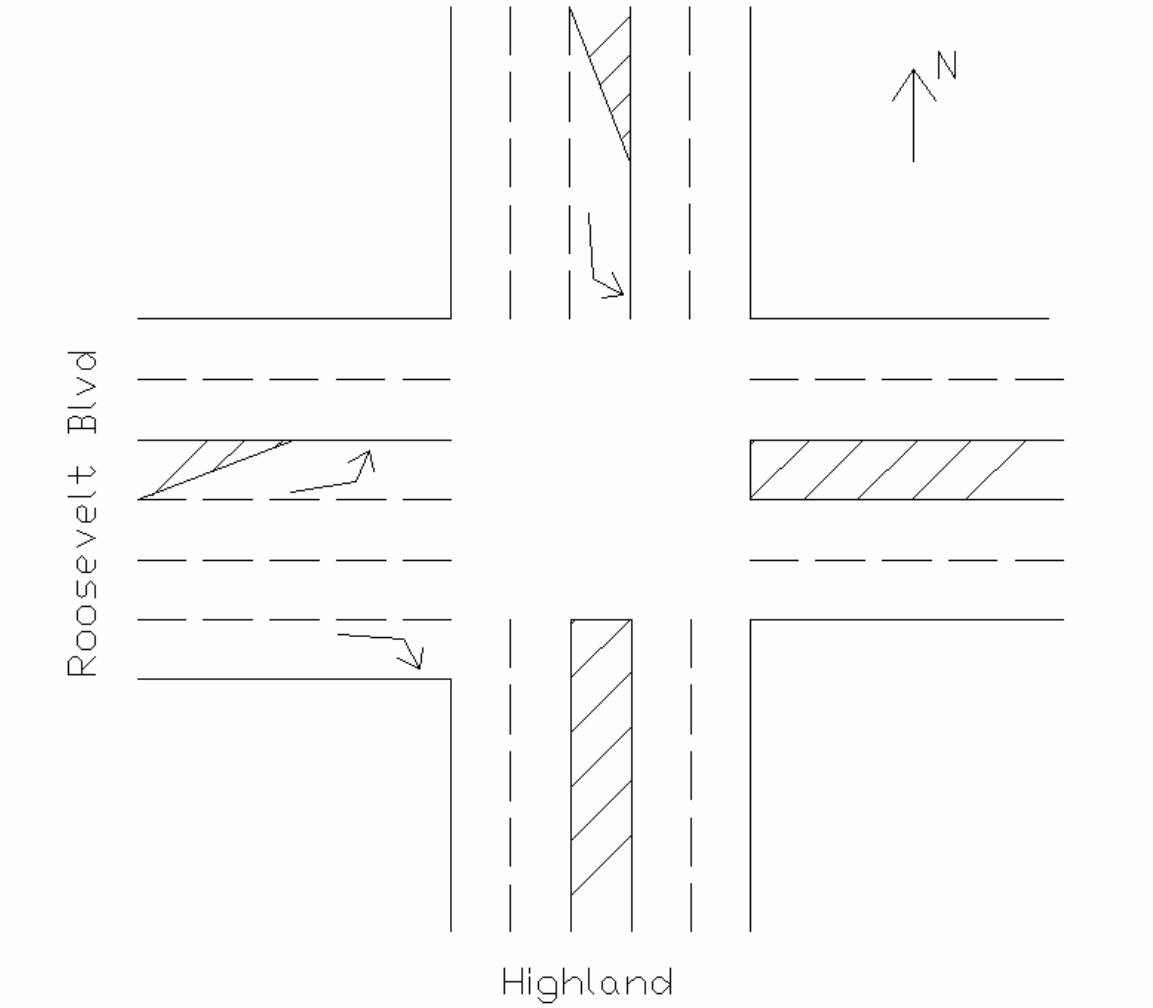

Figure 2. Roosevelt Blvd at Wicoff.

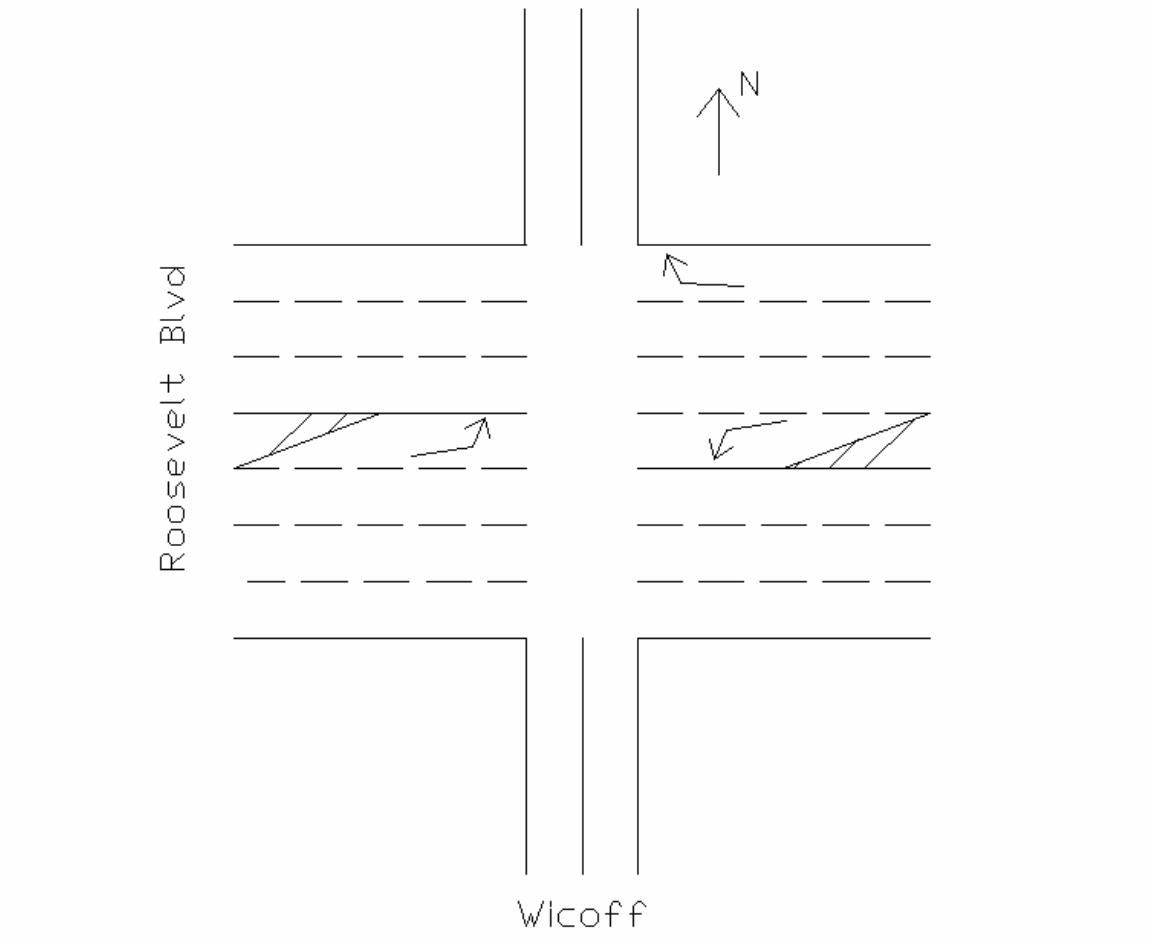

Figure 3. Roosevelt Blvd at Armco.

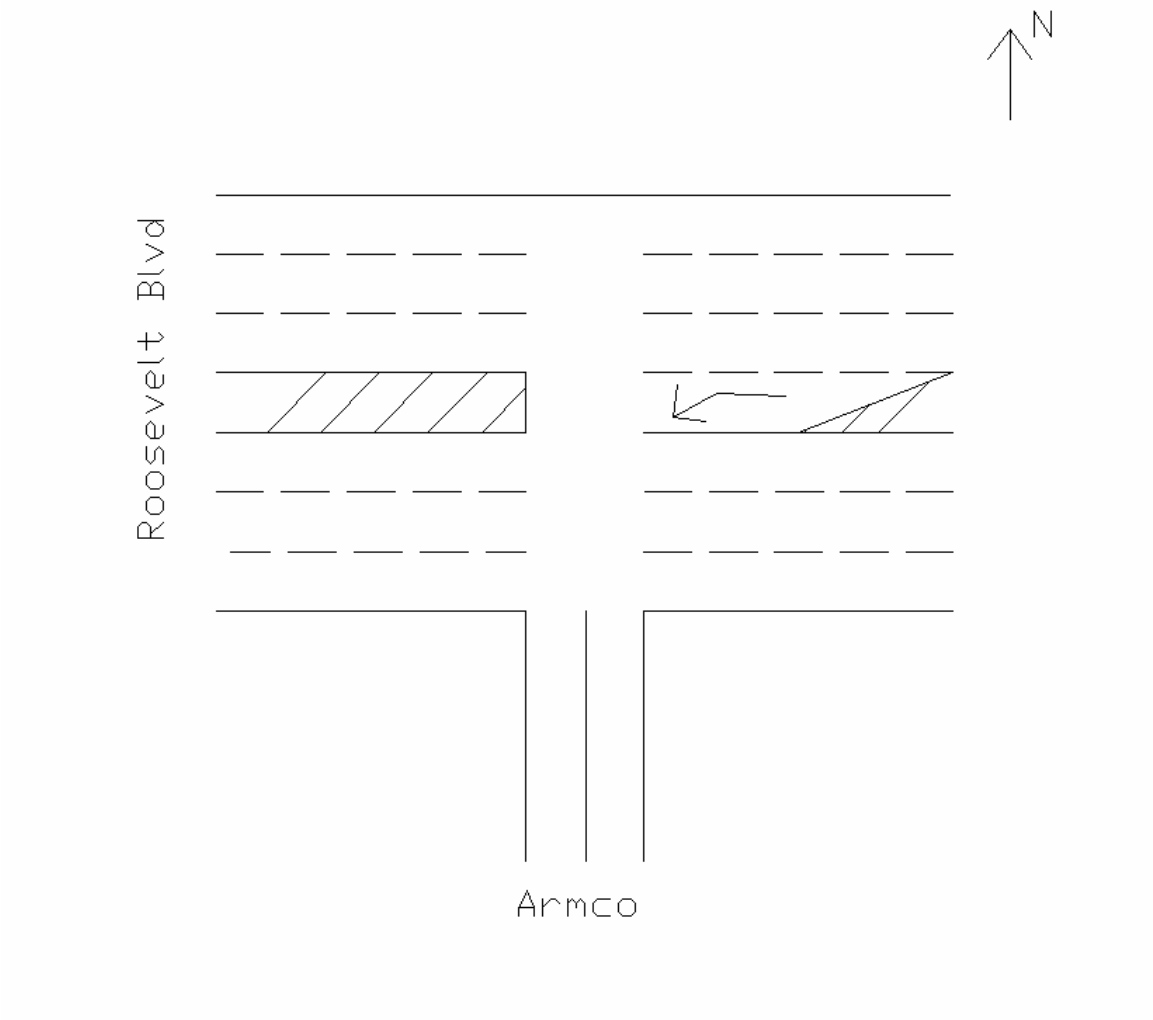

Figure 4. Sample data collection sheet.

Middletown Data Collection – Roosevelt Blvd

Date: ---------- Weather: ---------- Page 1 of _____

Your name: ---------- (Please staple all pages)

Intersection: ---------- Direction: Eastbound/Westbound (circle one)

2 seconds green time extension. The detector at the 600 ft is Active. Data collected from 9am-11am in the Morning.

Begin Time AM/PM (circle one)	Left turns	Through Vehicles					Right turns
		Stopped Vehicles	Non-Stopped Vehicles	Run Red Light	Stop Abruptly	Accelerate Thru Yellow	