Change and Clearance Interval Design on Red Light Running and Late Exits

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ABSTRACT

Red light violations (RLV) have been an ongoing concern to many engineering professionals, since a large portion of crashes that occur at signalized intersections involve red light running and such crashes often result in injuries and fatalities. It has been estimated that in the United States, approximately 260,000 traffic crashes occur per year that involve drivers who run red lights, of which 750 are fatal. The purpose of this study was to perform a 'before and after' evaluation of the impacts in terms of red light violations and late exits at signalized intersections when a change and clearance interval is calculated according to the Institute of Transportation Engineers (ITE) guidelines. The study included three signalized intersections located in Oakland County, Michigan. Red light violation data was collected using video cameras at intersection approaches before and after, the implementation of the change and clearance intervals calculated according to the ITE guidelines. The results if the 'before and after' study on RLV indicated mixed results. At one of the study intersections, the RLV rates were reduced after the modified change and clearance intervals were installed. However, at the other two study locations, no significant differences were found in the RLV rates in the 'before' and 'after' periods. The rates of late exits significantly decreased after the installation of the test change and clearance intervals at all three study intersections. Therefore, the effects of implemented all-red clearance intervals were effective in reducing the opportunity and risk of late exiting vehicles being exposed to oncoming traffic at the three study intersections.

INTRODUCTION

A significant portion of crashes that occur at signalized intersections are related to drivers running the red light. Crashes caused by red light violations (RLV) are often associated with injuries and in some instances, fatalities. Many agencies have become aware of the serious consequences of RLV and have implemented a variety of safety initiatives that include stricter enforcement, and various engineering improvements. It has been estimated that in the United States, approximately 260,000 traffic crashes occur per year, that involve drivers who run red lights, of which 750 are fatal *(1)*. The state of Michigan experiences approximately 9,500 crashes per year due to RLV, and 44 percent of these crashes involve injuries and fatalities.

Drivers who run red lights at signalized intersections belong to two groups: deliberate violators and drivers who violate due to a variety of contributing factors (unintentional violators). Both groups of drivers require different safety treatments to alleviate the red light running, and the potential for crashes and injuries. Drivers that deliberately violate red lights at signalized intersections are typically aggressive in nature. In general, law enforcement strategies are usually effective in modifying such driver behavior. However, traditional law enforcement methods to cite red light violators are not very effective. The implementation of such enforcement initiatives lie at the discretion of the police officers, since they must follow the offender through the intersection (during the red signal) in order to cite them. Due to the danger involved in the traditional enforcement method, some agencies began implementing automated enforcement systems at intersections where red light running was identified as a problem. These systems have been effective in mitigating RLV incidents, however they often penalize both deliberate and unintentional violators.

Some of the influencing factors associated with drivers unintentionally violating the red light include: environmental conditions, geometrics, and traffic control features of the intersection. For example, these may include vehicle, road, or pavement condition, sight distance, traffic signal change and clearance intervals, dilemma zones, improper traffic control, signal visibility, traffic signal lens size and placement, signal coordination, excessively long cycle lengths, and others. This paper focuses on the effects of implementing a change and clearance interval calculated according to the ITE guidelines on red light running.

Many traffic engineers follow the design of change and clearance intervals at a signalized intersection as defined in the Institute of Transportation Engineers (ITE) guideline. ITE provides two equations for determining the length of the yellow change interval *(2)*. Equation 1 provides the length of the yellow change interval. Equation 2 provides the length of the yellow interval when all-red clearance intervals are not included in the signal timing *(2)*. Please note that if all-red clearance intervals are not used, the length of the yellow interval will be longer, if someone uses Equation 2 to calculate the yellow time at a signalized intersection.

$$\text{Length of the Yellow Change Interval} = t + \frac{v}{(2a \pm 2Gg)} \qquad \text{Equation 1}$$

$$\text{Length of the Yellow Change Interval (when all-red clearance intervals are not used)} = t + \frac{v}{(2a \pm 2Gg)} + \frac{(W+L)}{v} \qquad \text{Equation 2}$$

Where:
t = driver perception-reaction time for stopping, taken as 1 second
v = approach speed, feet per second (meters per second), taken as 85th percentile speed
a = deceleration rate for stopping, taken as 10 feet per second^2 (3.0 meters per second^2)
g = percent grade, divided by 100
G = acceleration due to gravity taken as 32.2 feet per second^2 (9.8 meters/second^2)
W = width of intersection, in feet (meters), measured from the upstream stop bar to the downstream extended edge of pavement
L = length of clearing vehicle, taken as 20 feet (6.1 meters)

The length of the yellow change and all-red clearance intervals in this study used the following (Equation 3):

$$\text{Length of the Change and Clearance Interval} = \underbrace{t + \frac{v}{(2a \pm 2Gg)}}_{\text{Yellow Change Interval}} + \underbrace{\frac{(W+L)}{v}}_{\text{All-Red Clearance Interval}} \qquad \text{Equation 3}$$

The first two terms of Equation 3, when calculated based on site-specific data provides “enough yellow time for a vehicle to travel, at its initial speed, over the distance it would take to stop at a comfortable average deceleration before entering the intersection” *(2)*. The third term of Equation 3 determines the length of the all-red clearance interval, which provides time for “vehicles to clear the intersection before opposing traffic receives a green indication” *(2)*. This allows vehicles to traverse the intersection without being exposed to opposing traffic, even if they enter the intersection at the tail end of the yellow change interval, irrespective of the length of the yellow time.

The current Michigan Manual of Uniform Traffic Control Devices (MMUTCD) *(3)* suggests that if the calculated yellow change interval is greater than five seconds, then additional time should be allocated to the all-red clearance interval. As per the Michigan Vehicle Code *(4)*, drivers are instructed to do the following when confronted with a steady yellow signal indication at a traffic signal *"shall stop before entering the nearest crosswalk at the intersection or at a limit line when marked, but if the stop cannot be made in safety, a vehicle may be driven cautiously through the intersection"(4)*. Michigan law enforcement officials, like in many other states are reluctant to issue a citation to a motorist for not stopping during a yellow change interval, unless someone is observed to have accelerated, to go through the intersection. Even such a citation is rare, and difficult to prove when contested by the motorist in a court of law.

A study was initiated in Michigan to test the effectiveness of a change and clearance interval calculated as per the ITE guidelines (Equation 3) on red light running, late exits and traffic crashes at three intersections in Oakland County, Michigan using a 'before and after' study plan. The primary focus of this study was to evaluate the effect of introducing all red intervals on red light running and late exits. The traffic crash experience at these intersections were also monitored. The study was conducted, as per the request of the Michigan Traffic Signal Summit, a statewide committee comprised of representatives of state, county and city transportation agencies, private consultants, utility companies, universities and others.

STUDY SITES

Site Description

Three intersections in Oakland County, Michigan were selected to form the study sites and they are as follows:

- Telegraph Road (US-24) and Maple Road
- North Oakland Boulevard and M-59/Highland Road
- Josephine Street and M-59/Huron Road

The basis for selection of the above three sites was to have both highly traveled divided highway intersections, and low volume, suburban intersections included in the study. Traffic volume data including turning counts were collected for the peak periods for the three study intersections during the 'before' period. Table 1 shows a summary of the peak hour approach counts taken on typical weekdays, and the average daily traffic volumes.

Both Telegraph Road and Maple Road carry high traffic volumes. M-59 carries relatively high traffic volumes at both the North Oakland Boulevard and Josephine Street intersections, but much less in comparison to Telegraph Road and Maple Road intersection. The volumes at the intersection approaches of North Oakland Boulevard and Josephine Street are low.

The intersection of Telegraph Road and Maple Road (Figure 1) consists of two major arterial roads and is controlled by a two-phase pre-timed signal and with two sets of traffic signals for Maple Road traffic (referred to as near and far signals) to traverse across the large width of Telegraph Road, which is an eight-lane (total of both directions of travel) divided highway. The existing signal timing at the far signal for Maple Road traffic is different than the timing at the near signal. The green time at the far signal is two seconds longer than at the near signal. As a result, the yellow change interval and the all-red clearance interval between the near and far signal have a time lag of two seconds.

Telegraph Road is a north-south eight lane divided highway with exclusive right-turn lanes at the intersection approaches. The raised median is 44 feet (13.4 meters) wide. No direct left turns are allowed from either roads at the intersection. The speed limit on Telegraph Road is posted as 50 miles per hour (mph), (80 kilometers per hour (km/h)). Maple Road has two lanes of traffic traveling in the east and westbound directions with exclusive right-turn lanes at the intersection approaches. The speed limit on Maple Road is posted as 45 mph (72 km/h).

The intersection of North Oakland Boulevard and M-59/Highland Road (Figure 2) is also controlled by a two-phase pre-timed traffic signal. North Oakland Boulevard is a north-south road with three travel lanes in the northbound direction and two unmarked travel lanes in the southbound direction. The north and southbound directions of traffic are separated by a 20 feet (6.1 meters) wide raised median. The speed limit on North Oakland Boulevard is 35 mph (48 km/h). M-59/Highland Road is a major east-west arterial that has two lanes of traffic traveling in the east and westbound directions with exclusive left and right turn lanes at the intersection approaches. The speed limit on M-59/Highland Road is posted as 45 mph (72 km/h).

The intersection of Josephine Street and M-59/Huron Road (Figure 3) is also controlled by a two-phase pre-timed traffic signal. Josephine Street is a north-south road with one through and right turn lane in each direction, with exclusive left turn lanes at the intersection approaches. The speed limit on Josephine Street is 25 mph (40 km/h).

M-59/Huron Road at Josephine has two lanes of traffic traveling in the east and westbound directions, with exclusive left turn lanes at the intersection approaches. The speed limit on M-59/Huron Road is posted as 35 mph (48 km/h).

Signal Timing

The existing signal timing plans were obtained from the Road Commission for Oakland County for all three study sites. Existing change and clearance intervals and cycle length information were extracted from the signal timing charts. Table 2 shows the pre-implementation (existing) change and clearance intervals for the three sites. It also shows the change and clearance intervals tested in this study.

It is important to note that the traffic signal at the intersection of Telegraph Road and Maple Road uses a two second gap between the near (outside) and far (inside) signals on Maple Road to allow eastbound and westbound vehicles to clear the intersection without stopping in the median area. Both the near and far signals on Maple Road turn green at the same time. However, the green time is extended by two seconds at the far signal. The length of the yellow change intervals for the far and near signals are the same at 4.7 seconds. The signals are offset by two seconds. This offset between signals creates a “pseudo” all-red clearance interval at the near signal, in which only two of the three traffic movements have a red signal indication for two-seconds. The ‘actual’ all-red clearance interval for all the signals was 0.1 seconds for the pre-implementation period.

At the intersection of North Oakland Boulevard and M-59/Highland Road, the existing signal timing for each phase had yellow change intervals of 4.9 seconds and all-red clearance intervals of 0.1 seconds in length.

At the intersection of Josephine Street and M-59/Huron Road, the existing signal timing for each phase had yellow change intervals of 4.4 seconds and all-red clearance intervals of 0.1 seconds in length.

CHANGE AND CLEARANCE INTERVAL DESIGN

Roadway geometry and speed data, 85^{th} percentile speed for each approach during the peak and off-peak periods were collected and used in the calculation of the change and clearance intervals for each of the three sites. The rationale for conducting speed studies for both the peak and off-peak periods is that during congested periods, vehicles may not be able to travel at or near the speed limit and the change and clearance intervals, designed for off-peak period travel speeds, may not function in their intended manner. The change and clearance intervals were calculated using the ITE guidelines, (Equation 3) for peak and off peak periods. However, the same change and clearance intervals were used for both peak and off-peak periods. Table 2 shows the yellow and all-red clearance intervals that were implemented in March 2001. The yellow change intervals, as calculated according to the ITE guidelines (Equation 3), resulted in reduced yellow times ranging from 0.1 seconds to 0.6 seconds on the main arterials of Telegraph Road and M-59, and 0.4 seconds to 1.3 seconds on the main cross-street approaches.

RED LIGHT VIOLATION AND LATE EXIT DATA COLLECTION AND ANALYSIS

Red light violation (RLV) and late exit (LE) data was collected at the approaches of all three intersections using video cameras. In this study, a RLV is defined as a vehicle that crosses the stop bar and continues through an intersection, after the onset of the red light. A late exit (LE) is defined as a vehicle that proceeds through the intersection, and is still in the intersection when the cross street light turns green. For a late exit, drivers may have either entered the intersection at the end of the yellow change interval or during the red signal.

The rationale for including both red light violations and late exits in this study is to test the effectiveness of the designed change and clearance interval on discouraging red light running and to determine the effectiveness of the all-red clearance interval on improving safety for drivers. RLV and LE data was randomly collected on various days of the week and times of the day for the ‘before’ and ‘after’ periods during good weather conditions. Data for the ‘before’ period were collected from October 2000 to February 2001. Data collection for the ‘after’ period began in March 2001 and has been collected through January 2002. In order to accurately collect RLV and LE data, video cameras were carefully positioned at the intersection approaches to record the entire intersection, including the location of the stop bars and the traffic signal lights. The video cameras were positioned unobtrusively, so that most drivers were not aware that their behavior was being monitored. Thus, the location of the video camera did not influence driver behavior, in terms of red light running and late exits. Data was recorded for a minimum of one-half hour per approach, for all the intersection approaches for each day of data collection.

RLV and LE data were only counted for through vehicles and **not** for the turning vehicles, both for the ‘before’ and ‘after’ periods. Red light violations were counted when a vehicle was observed crossing the stop bar after the onset of the red signal. Late exits were counted when a vehicle was observed to be traversing through the intersection when the light for the opposing direction of travel was green.

The late exit data for the intersection of Telegraph Road and Maple Road was counted for both the near and far side signals on Maple Road. It should be noted, however, that all of the late exits for Maple Road traffic occurred at the second signal, which is referred to here as the far signal.

Red light violation and late exit data were collected for the ‘before’ period for a total of 48 hours for all three intersections combined. Data for the ‘after’ period was collected once the new signal timing plans were installed for a total of 60 hours of data.

Statistical analyses were performed to evaluate the difference in RLV and LE data before and after the implementation of the test change and clearance intervals, as per the ITE recommended practice, at the study intersections. The students t-test of significance was used as the statistic to test the effects of the designed change and clearance interval on RLV and LE. The actual observations for RLV and LE, taken at all the intersection approaches, were converted to hourly rates, since each observation period per approach varied from 30 minutes to over an hour. The hourly rates of RLV and LE converted from the actual observations for the three study intersections for the 'before' and 'after' periods are shown in Table 3. The distributions of the observations converted to hourly rates (number of RLV per hour and number of LE per hour) were compared for the 'before' and 'after' periods at all three study locations. Table 4 shows the characteristics of the distribution of the hourly rates of the observed RLV and LE data.

The t-test was selected as the statistical test since the data (hourly rates) is continuous and approximately follows a normal distribution. In the statistical analysis, adjustments were made to account for the unequal variances and unequal sample sizes. The null hypothesis used in this analysis is: The means of the RLV and LE rates in the 'before' period are greater than that in the 'after' period; and thus a one-tailed t-test was used, at a 95 percent significance level ($\alpha = 0.05$). The following are the equations used to calculate the t-statistic and degrees of freedom (k') since unequal sample sizes were used.

$$t_{calculated} = \frac{\overline{X}_B - \overline{X}_A}{\sqrt{\frac{\hat{\sigma}^2_B}{N_B} + \frac{\hat{\sigma}^2_A}{N_A}}} \qquad \text{Equation 4}$$

$$k' = \frac{\left[\hat{\sigma}^2_B / N_B + \hat{\sigma}^2_A / N_A\right]^2}{\frac{\left(\hat{\sigma}^2_B / N_B\right)^2}{N_B} + \frac{\left(\hat{\sigma}^2_A / N_A\right)^2}{N_A}} \qquad \text{Equation 5}$$

The results of the statistical analysis are shown on Table 5.

The results were mixed for RLV. The RLV rates significantly reduced during the 'after' period at the intersection of Telegraph Road and Maple Road. At the intersection of North Oakland Boulevard and M-59/Highland Road, the RLV rates slightly increased in the 'after' period; however were not statistically significant. At the Josephine Street and M-59/Huron Street intersection, the RLV rates reduced slightly during the 'after' period, however this reduction was not statistically significant.

In terms of late exit rates, the results of the statistical analysis indicated that the late exit rates significantly decreased after the installation of the all-red clearance intervals at all three study intersections. Therefore, the effects of implemented all-red clearance intervals, which ranged from 2.0 to 3.0 seconds, were effective in reducing the opportunity and risk of late exiting vehicles being exposed to oncoming traffic at the three study intersections.

TRAFFIC CRASH ANALYSIS

The main objective of the study was to determine the effect of the change and clearance interval on RLV and LE. In addition, the traffic crash experience was also monitored. Traffic crash data was analyzed from the police report forms for the 'before' period for two years of data for all three of the study intersections for the same time periods as the 'after' period.

A 'before and after' crash analysis was conducted in order to test the effectiveness of the test change and clearance intervals on traffic crashes. The 'before' crash history of the sites for the previous two years (1999-2000) were selected and compared with the same time periods (months of an year) as the 'after' period. The 'after' improvement period for the sites began on various dates in March 2001 and the data has been collected through for just over one year for all three of the study intersections. The results of the 'before and after' traffic crash analysis is based on thirteen to fifteen months of 'after' data. Table 6 shows the traffic crash comparison of all three intersections based on the data available (intersection-related crashes within 150 foot radius). Please note that all crashes directly or indirectly related to driveways were excluded from this analysis. Since the signal change and clearance intervals were implemented, (March 2001) the traffic crashes appear to be reducing at all three of the study intersections.

The traffic crash comparison at the Telegraph Road and Maple Road intersection revealed that some right angle and rear end crashes were still occurring in the 'after' period. It was expected that these types of crashes, especially the right angle crashes, would be mitigated by implementing the calculated yellow and all red intervals. Each traffic crash that occurred in the 'after' period was thoroughly examined in order to determine the causal factors of the crash. It was observed that some of the traffic crashes at the Telegraph Road and Maple Road intersection were related to the two-sets of traffic signals. The effective green time for the far signal is extended by two-seconds in order to allow vehicles to clear the intersection safely. This time lag or offset between the near side and far side signals may not be properly designed for the travel speed of the cross street traffic during the peak hours. This was evidenced through the crash patterns in the median area and also, at the far sides of the intersection. The distance between the two signals is not large enough to allow vehicles to stop safely and thus, drivers are expected to travel through. By providing inappropriate offsets between the two sets of signals, drivers may be forced to violate the far signal and sometimes get involved in traffic crashes.

CONCLUSIONS

Red light running has been an ongoing concern to many safety engineering professionals since the proportions of crashes that occur due to such driver behavior represent a majority of crashes at urban and suburban signalized intersections. Many initiatives to discourage red light running have been implemented throughout the United States, including public awareness campaigns, automated enforcement programs and various engineering countermeasure strategies. These efforts have affected the overall crash statistics in the nation, which show a reduction in RLV related crashes over the past several years.

A 'before and after' evaluation study was conducted to test the effects of a change and clearance intervals calculated according to ITE guidelines on RLV and late exits at three signalized intersections in Oakland County, Michigan. The risk associated with vehicles that have not cleared the intersection when the cross-street light turns green (late exit) was also evaluated. Vehicles were considered to exit late, regardless of whether they ran the red light or not. One of the three sites intersects with a highly traveled divided highway, and the other two sites are typical intersections carrying moderate traffic volumes. This study was conducted, as per the request of the 'Michigan Traffic Signal Summit' in order to aid the committee in making policy recommendations regarding the design of a change and clearance interval to the Michigan Department of Transportation.

The results if the 'before and after' study on RLV indicated mixed results. At the intersection of Telegraph Road and Maple Road, where the test yellow change intervals were reduced by 0.1 and 0.4 seconds, the mean red light violation rates were reduced after the modified intervals were installed. However, at the other two study locations, no significant differences were found in the RLV rates in the 'before' and 'after' periods. The test yellow change intervals implemented at these locations were reduced by 0.4 to 0.6 seconds on the main arterial streets and by 0.4 to 1.3 seconds on the minor cross streets.

The rates of late exits significantly decreased after the installation of the test change and clearance intervals at all three study intersections. Therefore, the effects of implemented all-red clearance intervals, which ranged from 2.0 to 3.0 seconds, were effective in reducing the opportunity and risk of late exiting vehicles being exposed to oncoming traffic at the three study intersections.

The main focus of this study was to examine the effects on RLV and LE. However traffic crash experience at all three intersections were also studied. Since the signal change and clearance intervals were implemented, (March 2001) the traffic crashes appear to be reducing at all three of the study intersections.

The traffic crash analysis did indicate that some of the crashes occurring in the 'after' period may have been caused due to other signal timing factors. These factors were related to progression parameters and/or the offset between the two sets of traffic signals (near and far) required at large divided highways. Thus, when modifying the signal change and clearance interval, special attention should be given to ensure that the progression and signal timing parameters are optimal in order to achieve maximum safety benefits.

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3. Michigan Department of Transportation. Michigan Manual of Uniform Traffic Control Devices, Michigan Department of State Police, Lansing, Michigan, 1994.
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TABLE 1 Traffic Volume Data

Intersection	Peak Hour	Approach	Approach Volumes (VPH)[a]	Total Intersection Volume (VPH)	ADT (VPD)[b]	
					N-S Street	E-W Street
Telegraph Road and Maple Road	AM	Northbound	2,761	9,278	75,500	31,800
		Southbound	3,490			
		Eastbound	1,711			
		Westbound	1,316			
	PM	Northbound	4,922	10,171		
		Southbound	3,186			
		Eastbound	840			
		Westbound	1,223			
North Oakland Boulevard and M-59/Highland Road	AM	Northbound	172	2,726	*	51,800
		Southbound	38			
		Eastbound	1,833			
		Westbound	683			
	Midday	Northbound	179	3,055		
		Southbound	133			
		Eastbound	1,429			
		Westbound	1,313			
Josephine Street and M-59/Huron Road	AM	Northbound	108	1,965	*	29,500
		Southbound	95			
		Eastbound	1,147			
		Westbound	615			

[a] vehicles per hour
[b] vehicles per day
*not applicable N/A

TABLE 2 Change and Clearance Intervals

Intersection	Approach	Existing Change and Clearance Intervals (Seconds)		Test Change and Clearance Intervals (Seconds)	
		Yellow	All Red	Yellow	All Red
Telegraph Road and Maple Road	North and Southbound	4.8	1.1	4.7	2.0
	East and Westbound	4.7	$AR_{1(pseudo)}$[a] = 2.0 AR_2[b] = 0.1	4.3	AR_1 = 4.0 AR_2 = 2.0
North Oakland Boulevard and M-59/Highland Road	North and Southbound	4.9	0.1	3.6	2.5
	East and Westbound	4.9	0.1	4.3	2.0
Josephine Street and M-59/Huron Road	North and Southbound	4.4	0.1	4.0	3.0
	East and Westbound	4.4	0.1	4.0	2.88

[a] pseudo all-red clearance interval at the near signal for two of the three directions of traffic
[b] all-red clearance interval at the far signal

TABLE 3 Hourly Rates of RLV and LE Converted from the Observations for the 'Before' and 'After' Periods

Hourly Rates (Converted from Observations)	Intersection of Telegraph Road and Maple Road				Intersection of North Oakland Boulevard and M-59/Highland Road				Intersection of Josephine Street and M-59/Huron Road			
	Red Light Violation Rates (RLV/Hour) Total of All Intersection Approaches		Late Exit Rates (LE/Hour) Total of All Intersection Approaches		Red Light Violation Rates (RLV/Hour) Total of All Intersection Approaches		Late Exit Rates (LE/Hour) Total of All Intersection Approaches		Red Light Violation Rates (RLV/Hour) Total of All Intersection Approaches		Late Exit Rates (LE/Hour) Total of All Intersection Approaches	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
1	26.0	5.0	16.0	1.0	0.0	0.0	6.4	0.0	6.0	0.0	3.0	2.0
2	2.5	1.0	19.0	2.0	0.0	0.9	7.0	1.0	7.0	6.0	3.8	0.0
3	3.8	4.8	26.8	2.0	0.0	0.0	2.0	0.0	0.0	0.0	7.5	0.0
4	2.0	1.7	6.0	6.0	1.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0
5	1.6	0.0	7.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	1.0	0.0
6	0.5	0.0	2.0	0.0	0.0	1.3	0.0	0.0	0.0	2.0	0.0	0.0
7	2.0	3.0	5.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
8	20.0	0.0	16.4	0.0	0.0	0.0	2.0	0.0	0.0	0.0	1.0	0.0
9	0.0	2.2	4.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0
10	2.5	0.0	20.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	7.5	0.0
11	0.0	3.8	6.9	1.0	0.0	0.0	1.5	0.0	-	0.0	-	0.0
12	7.0	8.0	7.8	0.0	1.5	0.0	0.0	0.0	-	0.0	-	0.0
13	3.0	4.0	5.0	1.8	0.0	0.0	3.0	0.0	-	0.0	-	0.0
14	8.0	6.0	24.0	0.0	0.0	0.0	3.0	0.0	-	0.0	-	0.0
15	1.2	4.0	13.2	0.0	-	0.0	2.1	0.0	-	0.0	-	0.0
16	0.0	6.0	7.0	3.4	-	1.8	2.0	0.0	-	4.0	-	0.0
17	10.0	7.0	7.5	0.0	-	0.0	5.0	0.0	-	2.0	-	0.0
18	12.4	2.7	7.1	0.0	-	2.0	6.0	0.0	-	3.0	-	1.0
19	5.0	1.0	15.0	0.0	-	0.0	3.0	0.0	-	4.0	-	0.0
20	2.0	4.6	2.0	0.0	-	1.5	-	0.0	-	2.0	-	0.0
21	20.4	2.9	4.8	0.0	-	0.0	-	-	-	2.7	-	0.0
22	12.0	1.5	16.0	0.0	-	2.0	-	-	-	2.0	-	0.0
23	10.0	0.0	23.0	0.0	-	-	-	-	-	2.0	-	-
24	-	1.0	-	1.8	-	-	-	-	-	0.0	-	-
25	-	0.0	-	3.0	-	-	-	-	-	1.7	-	-
26	-	0.0	-	3.4	-	-	-	-	-	-	-	-
27	-	3.6	-	0.0	-	-	-	-	-	-	-	-
28	-	2.0	-	2.0	-	-	-	-	-	-	-	-
29	-	3.4	-	1.1	-	-	-	-	-	-	-	-
30	-	0.0	-	1.5	-	-	-	-	-	-	-	-
31	-	2.0	-	0.0	-	-	-	-	-	-	-	-
32	-	0.0	-	0.0	-	-	-	-	-	-	-	-
33	-	0.0	-	0.0	-	-	-	-	-	-	-	-
34	-	0.0	-	0.0	-	-	-	-	-	-	-	-
35	-	0.0	-	0.0	-	-	-	-	-	-	-	-
36	-	-	-	0.0	-	-	-	-	-	-	-	-
37	-	-	-	3.0	-	-	-	-	-	-	-	-
38	-	-	-	0.0	-	-	-	-	-	-	-	-
39	-	-	-	0.0	-	-	-	-	-	-	-	-
40	-	-	-	0.0	-	-	-	-	-	-	-	-
41	-	-	-	0.0	-	-	-	-	-	-	-	-
42	-	-	-	0.0	-	-	-	-	-	-	-	-
43	-	-	-	0.0	-	-	-	-	-	-	-	-

TABLE 4 Distribution Characteristics for the 'Before' and 'After' Periods of Observations for (a) Red Light Violations per Hour and (b) Late Exits per Hour

(a) Red Light Violations per Hour

Characteristics of Red Light Violation Rates (RLV/hr)	STUDY INTERSECTIONS					
	Telegraph Road and Maple Road		North Oakland Boulevard and M-59/Highland Road		Josephine Street and M-59/Huron Road	
	Before	After	Before	After	Before	After
Mean ($\bar{X}$)	6.61	2.32	0.18	0.43	1.30	1.26
Standard Deviation	7.31	2.32	0.46	0.75	2.75	1.68
Variance (σ^2)	53.45	5.36	0.22	0.57	7.57	2.82
Unbiased Estimates of σ^2 ($\hat{\sigma}^2$)	55.88	5.52	0.24	0.60	8.41	2.94
Sample Size (Number of Observations)	23	35	14	22	10	25

(b) Late Exits per Hour

Characteristics of Late Exit Rates s (LE/Hour)	STUDY INTERSECTIONS					
	Telegraph Road and Maple Road		North Oakland Boulevard and M-59/Highland Road		Josephine Street and M-59/Huron Road	
	Before	After	Before	After	Before	After
Mean ($\bar{X}$)	11.37	0.77	3.16	0.05	2.38	0.14
Standard Deviation	7.50	1.35	2.03	0.22	3.01	0.47
Variance (σ^2)	56.27	1.81	4.12	0.05	9.04	0.22
Unbiased Estimates of σ^2 ($\hat{\sigma}^2$)	58.83	1.85	4.35	0.05	10.04	0.23
Sample Size (Number of Observations)	23	43	19	20	10	22

TABLE 5 Results of the Students t-Test for RLV Rate and LE Rate for the 'Before' and 'After' Periods

(a) RLV per Hour

	Telegraph Road and Maple Road	North Oakland Boulevard and M-59/Highland Road	Josephine Street and M-59/Huron Road
$t_{calculated}$	2.66	-1.19	0.40
Degrees of Freedom k'	26	35	13
t Critical (one-tail test) at $\alpha = 0.05$ and k'	1.706	1.6905	1.771
Significant Reduction?	Yes; since $t_{calculated} > t_{critical}$	No; non-significant increase	No; since $t_{calculated} < t_{critical}$

(b) LE per Hour

	Telegraph Road and Maple Road	North Oakland Boulevard and M-59/Highland Road	Josephine Street and M-59/Huron Road
$t_{calculated}$	6.57	6.45	2.411
Degrees of Freedom k^1	25	19	10
t Critical (one-tail test) at $\alpha = 0.05$ and k'	1.711	1.729	1.812
Significant Reduction?	Yes; since $t_{calculated} > t_{critical}$	Yes; since $t_{calculated} > t_{critical}$	Yes; since $t_{calculated} > t_{critical}$

TABLE 6 Traffic Crash Comparison

Crash Types	Telegraph Road and Maple Road		North Oakland Boulevard and M-59/Highland Road		Josephine Street and M-59/Huron Road	
	Before Annual Average of 2 years of data	**After** Annual Average of 13 months of data	**Before** Annual Average of 2 years of data	**After** Annual Average of 15 months of data	**Before** Annual Average of 1 year of data	**After** Annual Average of 15 months of data
Rear End	25	14	8	5	9	10
Sideswipe	7	6	3	0	0	0
Angle	5	5	5	3	7	1
Left Turn Head On	0	0	5	6	0	0
Other	1	3	3	2	0	1
Total	**38**	**28**	**24**	**16**	**16**	**12**

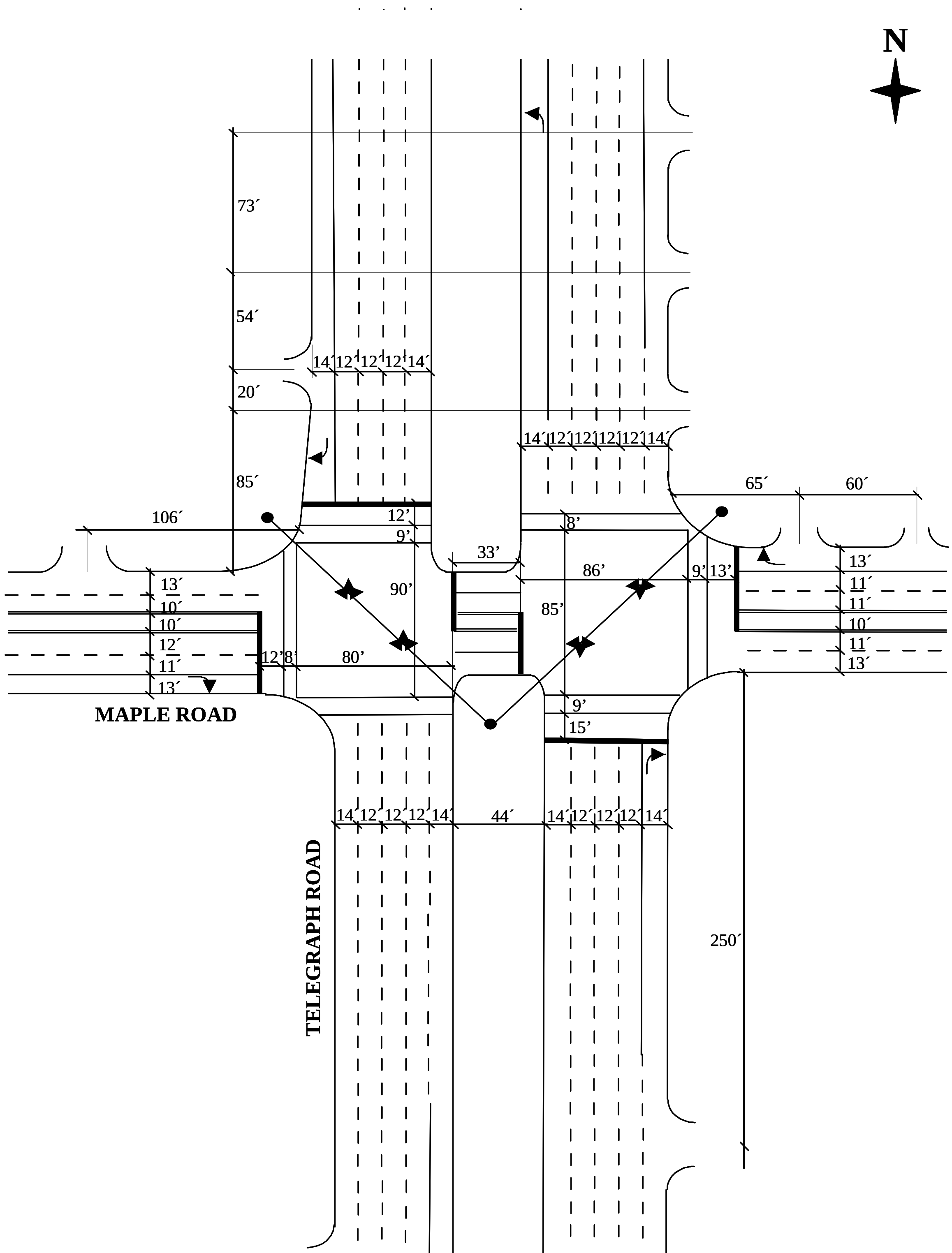

FIGURE 1 Condition diagram of the Telegraph Road and Maple Road intersection.

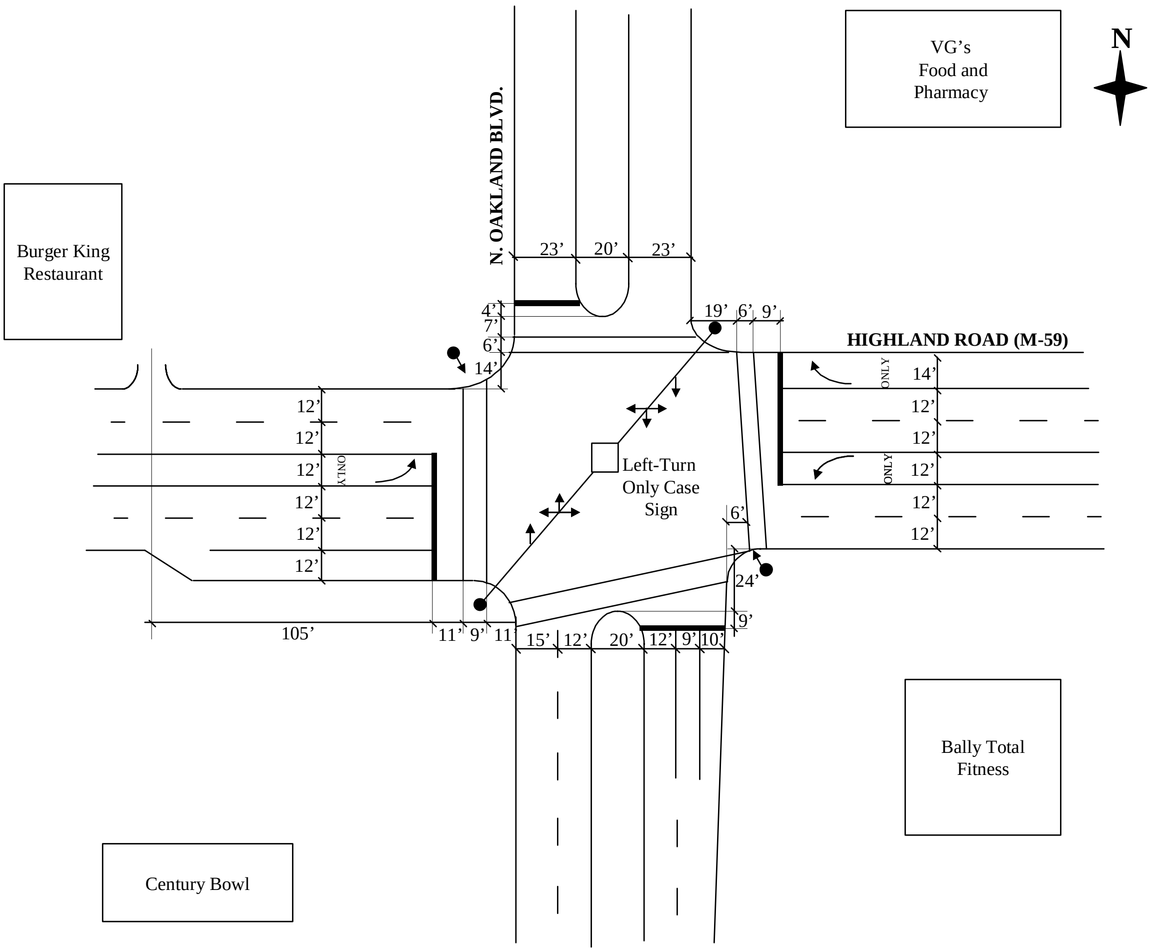

FIGURE 2 Condition Diagram of the North Oakland Boulevard and M-59/Highland Road intersection.

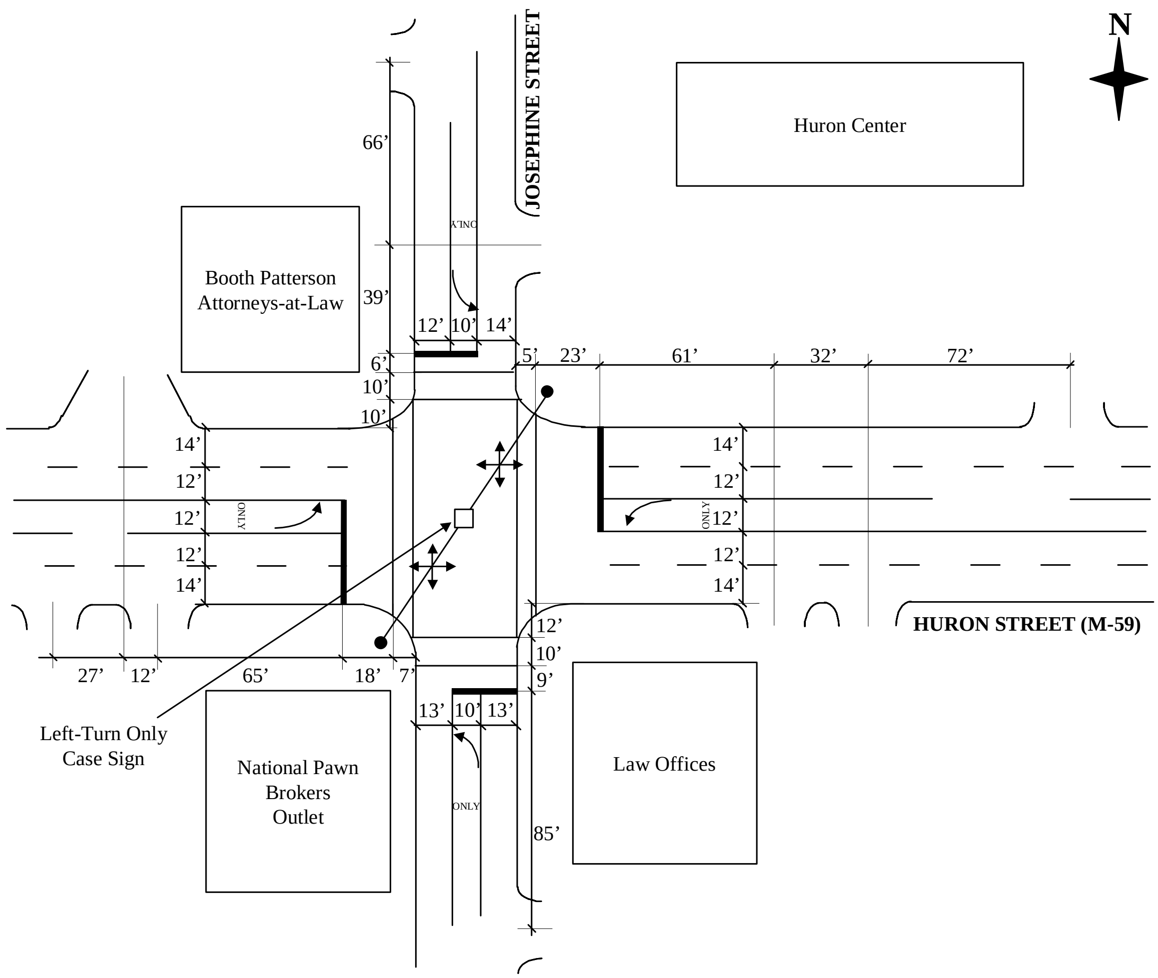

FIGURE 3 Condition diagram of the Josephine Street and M-59/Huron Street intersection.