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Effectiveness of All-Red Clearance Interval on Intersection Crashes

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Crashes at signalized intersections account for approximately 20% of all crashes both nationally and within the State of Minnesota. Past research suggests that the use of all-red clearance interval at signalized intersections may reduce intersection crashes, particularly those related to signal violations. Other research suggests that this reduction may only be temporary. This research evaluates the safety effect of all-red clearance intervals at low speed urban 4 way intersections in the City of Minneapolis. The study includes a review of literature and assessment of Midwestern state and local practice related to the use of all-red phasing. A cross-section analysis using four years of data is presented, which does not substantiate any safety benefit of all-red phasing at study area intersections. Several regression models (generalized linear mixed models with Poisson error distribution and log link function and linear mixed models with transformed data) are also presented. The models also point to no safety benefit. A before and after analysis using 11 years of data was conducted to evaluate both short and long term effects. While results indicate short-term reductions in crash rates (approximately one year after the implementation), long-term reductions are not observed.

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Final Report

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List of Acronyms

AADT	Average Annual Daily Traffic
ADT	Average Daily Traffic
DEV	Daily Entering Vehicles
DOT	Department of Transportation
FHWA	Federal Highway Administration
INDOT	Indiana Department of Transportation
ITE	Institute of Transportation Engineers
LRRB	Local Road Research Board
MUTCD	Manual on Uniform Traffic Control Devices
NDOR	Nebraska Department of Roads
SAS	Statistical Analysis Software
VMT	Vehicle Miles of Travel
VPD	Vehicles per Day

EXECUTIVE SUMMARY

This document reports the results of a research project that investigated the effectiveness of all-red clearance intervals in enhancing the safety of urban, low speed signalized intersections.

Intersections account for twenty percent of all crashes that occur at intersections. The economic loss associated with red light running crashes at intersections is estimated at $14 billion per year, and is on the rise. There are no specific categories of drivers who run red lights, but it is estimated that 30 percent of red lights are run because of disobeying signals while about 50 percent are run because of driver inattention. Driver familiarity with signal timing plays a role, and the fraction of red light running crashes are lower during peak periods.

The purpose of an all-red interval is to provide clearance for vehicles which have entered an intersection prior to opposing movements receiving a green indication. The interval time usually ranges from 0.5 to 3.0 seconds, and most modern traffic controllers can implement the interval. All-red intervals are perceived by many to have a safety benefit.

Research suggests all-red intervals may reduce intersection crashes, but most studies are for short time periods and are limited to intersections where other improvements were made at the same time, making it difficult or impossible to isolate the benefit of adding the clearance interval. Other, longer term research shows mixed results or no safety benefit at all. Recommendations of these latter studies have sometimes been ignored in favor of the "intuitive" benefits of all-red clearance intervals. Most studies show that longer clearance phases (yellow plus all-red), are helpful in reducing crashes, and recommend that Institute of Traffic Engineers (ITE) guidelines be used in setting the lengths of these phases. In the Midwest, most cities and states use these guidelines and use all-red intervals where signal controllers are capable.

This report was scoped to low speed, urban intersections where capacity benefits may be realized if all-red intervals are not used, thereby reducing lost time each cycle. The research was conducted using data from Minneapolis, Minnesota where engineers are considering the implementation of all-red intervals on some 104 signals that currently do not have the intervals. Two studies were performed, a cross-sectional analysis and a before-and-after study. Intersection types were limited to two-way, non skewed, 4-legged configurations. All study area signals meeting these criteria (and currently without all-red intervals) were at low speed locations, with approach speed limits of 30 miles per hour.

In the cross-sectional analysis, 38 intersections without all-red were compared to 38 similar intersections with all-red. Variables that were considered to potentially have an effect of safety performance were collected and included traffic volume, signal mounting type and presence of intersection lighting. Four years of crash data were obtained and to control for the correlated effects of other variables, a linear mixed model was fit to the data. Traffic volume (daily entering vehicles) was collected from the City or estimated using several techniques developed in the research and described in the report. Results indicate no safety benefit of all-red intervals for the study intersections. While it is possible that all-red clearance intervals had been implemented at the most "dangerous" Minneapolis intersections (biasing study results), data were not available to substantiate that possibility.

A before-and-after study was also conducted using five years of before and five years of after data. Data was also collected for the year during implementation. A sample of 22 intersections where all-red was implemented was compared to a sample of 47 without all-red during the eleven-year study period. Results indicate that while relevant crashes (head on, rear end, right angle, left turn, right turn, and side swipe) were reduced in the year immediately following implementation, there was no long term reduction when compared to the control group.

The report concludes that all-red intervals should not, in general, be implemented for intersections that are similar to the intersections of this study (low speed, urban intersections). The report also recommends that if all-red intervals are being considered for removal at a set of intersections, those with the lowest rates of relevant crashes be considered first (a ranked list of Minneapolis intersections is provided). Alternatively, the report also presents a list of intersections ranked by highest rate of relevant crashes if engineers wish to implement all-red intervals despite study recommendations.

Finally, the report presents a set of policies and procedures adopted by Midwest states and cities and recommends the development of a written policy, use of ITE timing procedures, and suggests cities investigate the use of alternatives to all-red to increase signal compliance.

1. INTRODUCTION

Each year there are more than 1.8 million intersection crashes in the United States. It is estimated that in 2001, 218,000 crashes, 181,000 injuries, and 880 fatalities nationally were associated with signal violations. The economic loss associated with red light running crashes at intersections is estimated at $14 billion per year and is increasing (1). All-red clearance intervals, in which all movements receive a red indication, were implemented to reduce crashes by providing additional time for vehicles to clear the intersection. Without an all-red clearance interval, the yellow interval is followed immediately by a green interval for the opposing movements. This allows conflicting movements to start directly after the yellow interval. Currently, it is almost standard practice in the United States to incorporate the all-red clearance interval. Although commonly used, consensus on the effectiveness of the all-red interval has not been reached. A number of research efforts have suggested that the use of all-red intervals at signalized intersections reduces intersection crashes, particularly those related to signal violations and those involving pedestrians and bicyclists. However, other research has shown that an all-red interval does not result in a reduction in crash rates. Further, including an all-red clearance interval may decrease capacity and level of service at intersections, especially during peak traffic periods.

Because of increasing demands to enhance mobility through more efficient signal timing, and as no complete agreement exists on the effectiveness of an all-red clearance interval as a safety measure, the Local Road Research Board (LRRB) commissioned this research to evaluate the benefits and costs of implementing the all-red clearance interval. The outcome of this research could then be used to develop a policy on whether to universally adopt the all-red interval. This research study assessed the short and long term safety impacts of the all-red clearance interval in the City of Minneapolis, Minnesota through the use of a cross-section analysis, before-and-after analysis, and statistical models comparing Minneapolis sites with and without the all-red clearance interval.

Red light running is the most frequent cause of urban intersection crashes (2). Some literature on this topic has acknowledged that the use of the all-red clearance interval at signalized intersections may reduce intersection crashes. Several short-term (up to one year before-and-after implementation of all-red clearance interval) studies show that the all-red clearance interval is particularly beneficial in reducing intersection crashes related to signal violations. On the other hand, long-term (more than two years before-and-after implementation of the all-red clearance interval) research findings do not concur that these benefits are sustained. Seven studies show that the all-red clearance interval is effective in reducing intersection crashes, three show mixed results, and one found it to be ineffective in reducing intersection crashes.

1.1. Research Objectives and Scope of Work

Three categories of intersections were studied: intersections with an all-red interval for at least four years, intersections without an all-red interval, and intersections where all-red clearance intervals were recently implemented. First, in a cross-section study, intersections historically operating with an all-red clearance interval are compared to intersections operating without an all-red clearance interval. A before-and-after analysis is next presented to assess the effectiveness of adding an all-red clearance interval. Treated intersections are compared to a control group operating without the all-red clearance interval. Finally, to account for contributing factors, statistical models are developed to analyze the impact of volume, lighting, signal mounting, and all-red phasing on study intersections.

The scope of research included the following activities:

- A review of literature regarding the effectiveness of the all-red clearance interval and recommended all-red clearance interval timing practices.
- A review of Midwest signal phasing practices at the state and local level.
- Collection, compilation and presentation of signalized intersection data for the City of Minneapolis, Minnesota.
- A comparison of intersections with and without an all-red clearance interval using a cross-section analysis.
- A before-and-after analysis to compare crash data for a group of intersections 5 years before, during and 5 years after the implementation of the all-red clearance interval.
- Statistical models to assess the impact of the all-red clearance interval and contributing factors

Minneapolis intersection plans were studied to limit the analysis to intersections of two-way roads with four approaches. Skewed, offset, or intersections with horizontal curves on approaches were not used. An intersection database was created for the analysis, and includes the following attributes: intersection number (defined by the City of Minneapolis), intersection name, treatment (all-red, no all-red), date of addition of the all-red clearance interval, all-red implementation date, speed (Because all intersections in Minneapolis without all-red phasing are found on streets with 30 mph posted speeds, all study intersections were 30 mph. Consequently, it was not possible to test the effect of speed on safety performance of all-red phasing in this study.), signal mount (overhead or pedestal), presence of street lighting at the intersection, daily entering vehicles (DEV), crashes, and relevant crashes (head on, rear end, right angle, left turn, right turn, and side swipe).

Based on crash experience and the analysis and models developed in this research, conclusions do not support the system wide implementation of additional all-red phasing at all Minneapolis intersections

2. BACKGROUND AND RESULTS OF PREVIOUS RESEARCH

It appears to be fairly standard practice of most transportation agencies the United States to incorporate an all-red clearance interval into intersection signal design. Research efforts have suggested that the use of all-red clearance intervals at signalized intersections may reduce intersection crashes, particularly those related to signal violations, and crashes involving pedestrians and bicyclists and especially in the short term. However, research has also shown that an all-red clearance interval may not reduce crash rates, especially in the long term.

2.1. Use of the All-Red Clearance Interval

The purpose of an all-red clearance interval is to allow additional time for motorists already in the intersection to clear the intersection on the red indication before conflicting traffic movements are released (2). All-red may also be useful in mitigating amber dilemma zone problems, particularly at high speed intersections. Generally, the duration of the all-red clearance interval is from 0.5 to 3.0 seconds.

2.2. Red Light Violations

In Minnesota and many other states, a red light violation is defined as any vehicle entering an intersection after the onset of the red light. A red light violation can be either deliberate or unintentional and is related to individual driver behavior but may also be affected by intersection characteristics as discussed in the following sections. Although this study does not specifically analyze violations, intersections with frequent violations are likely to experience more crashes (originally within the scope of work for the project, an assessment of violations was dropped due to lack of available data).

2.2.1. Human Factors Affecting Decisions at Signalized Intersections

Red light violations are primarily a function of driver behavior. One of the major problems with determining the most effective way to stop red light violators is that there is not a specific category of individuals who habitually run red lights. Red light runners are drivers of all ages, economic classes, and gender (2). An estimated 48 percent of American drivers run red lights because they are in a hurry, not because they are under the influence of chemicals, unable to stop, or unable to see the red light (2). The fact that almost half of red light violations are deliberate reduces the benefit of an all-red clearance interval, and suggests alternative approaches, such as photo enforcement. (See section 2.5.3)

Although the Federal Highway Administration (FHWA) (2) states there is not a specific category of red light violators, Retting, et al, makes some generalizations about characteristics of drivers who are more likely to run red lights. Red light runners are more likely to be younger, less likely to use seatbelts, have poorer driving records, drive smaller vehicles, and have multiple speed convictions (3).

It is also believed that drivers who are familiar with a particular intersection are also familiar with the length of the yellow interval. They know to stop if the yellow phase is particularly short, or push the limits on a longer yellow phase (4).

Many studies have examined the effects of the all-red clearance interval for several months to a year before-and-after the implementation. Over time, if drivers become familiar with the presence and length of the all-red interval, they might push the limits trying to make it through the signal. If this is the case, over a longer time period intersection crashes might return to pre implementation rates.

According to Moon, et al, approximately 30% of red light running crashes are caused by deliberate disobeying of red lights, and over 50% of red light running crashes can be attributed to driver unawareness of the signal status. If 80% of red light running crashes can be attributed to deliberate disobeying of signals and unawareness of signal status, providing an all-red clearance interval can potentially only affect 20% of intersection crashes (5).

The number of red light violations is typically low during peak hour volumes because urban intersections are operating at or near capacity, limiting the ability of drivers to run red lights. Conversely, the study found the majority of red light violations to occur during off-peak hours when volumes are low, approach speeds are high, and traffic arrival is random (4).

2.2.2. Operational and Geometric Factors Affecting Decisions at Signalized Intersections

Factors that affect the decision of a driver to either stop or proceed through an intersection include: the vehicle approach speed, color or intensity of the traffic signal, location of the vehicle with respect to the traffic signal when the yellow light is observed, weather conditions, pavement conditions, and vehicle type (4). Clearly, the presence of another vehicle directly ahead also affects the decision.

The use of fully actuated, semi-actuated, and pre-timed signals was analyzed by the Highway Safety Information System to determine the effect of traffic control on red light running (6). The number of red light running crashes for fully actuated signals was approximately 35 – 39 percent higher than those for pre-timed signals. This is possibly due to drivers anticipating the green at actuated signals, and expecting it to turn green for them.

The effect of the number of cross-street lanes on red light running crashes was evaluated by FHWA's Highway Safety Information System (6). The researchers created a Negative-Binomial (N-B) model with controls for signal operation type, opposite street Average Daily Traffic (ADT), and left turn channelization. For each one-lane increase on the mainline (major road), there was a 7% increase in cross-street (minor road) red light running crashes. Interestingly, the increase in cross-street lanes did not have a significant effect on mainline red light running crashes. The number of mainline (major road) red light running crashes increased with higher mainline ADT and higher cross-street ADT. In addition, red light running crashes for the cross-street also increased with increasing cross-street ADT and mainline ADT. The authors suggest two possible explanations. The first is that when there is higher ADT, there are fewer and shorter gaps in the cross street which causes more possibilities for vehicle interaction. Because there are fewer and shorter gaps, the possibility for vehicle conflict increases for those running red lights. The other is that when there is an increase in vehicles approaching the signalized intersection, there are more opportunities for red light running crashes (6). Clearly, there is a discrepancy between these findings and those of the previous study by Datta, Schlatter, and Datta (4).

It would seem that the length of cycle would also have an effect on the propensity of drivers to push the limits of the clearance interval. Of course, longer cycle lengths also imply fewer change periods during a given time, which reduces the exposure of traffic to red light violators. The authors are not aware of any study that has addressed the optimal cycle length in relation to intersection crashes.

2.3. Effectiveness of the All-Red Clearance Interval

In order to reduce red violations, many jurisdictions have implemented an all-red clearance interval. Most studies have reported safety benefits from addition of the all-red clearance interval, but a handful of studies have produced mixed results. These findings are discussed in the following sections. Studies have focused on both the use and length of the all-red clearance interval.

2.3.1. Benefits of All-Red Clearance Interval

A study conducted in Detroit, Michigan compared red light violations at intersections where properly designed yellow and all-red intervals were added at intersections without all-red intervals (4). Fewer crashes were observed at signals with the all-red clearance interval. In addition, there was a reduction in right angle injury crashes at the treated intersections. It is important to note that all intersections studied in this before-and-after analysis were improved at the same time the all-red clearance interval was implemented; therefore results probably cannot be wholly attributed to implementation of the interval. These improvements included:

- Increasing signal head size to 12-inches
- Yellow calculated on the basis of observed approach speed
- All-red clearance time based on the roadway geometry
- Exclusive painted left turn lanes at all approaches
- Exclusive left turn phases
- 4.0-seconds of yellow and 1.5 to 2 seconds of all-red
- Intersection approaches were repaved with asphalt
- On-street parking was removed for 200-feet on all approaches
- All missing and deteriorated signs were replaced

2.3.2. Mixed Benefits of All-Red Clearance Interval

A before-and-after analysis was conducted in Oakland County, Michigan to determine the before-and-after impacts of red light violations and late exits when clearance intervals were calculated according to the Institute of Transportation Engineers (ITE) guidelines. In this study, a late exit is defined as exiting the intersection after the signal has changed to red. Three sites were chosen for analysis. Two of the intersections contained heavy traffic volumes and divided approaches, while the other intersection was a suburban, low volume intersection (7).

Red light cameras were used to collect red light violations and late exit data for the through movement before-and-after implementation of the all-red clearance interval. The before period took place from October 2000 to February 2001 (4 months). The after period ranged from March 2001 to January 2002 (9 months). There were mixed results for reducing red light violations at the intersections, but the adequate clearance length was effective in reducing late exits. This indicates that use of the ITE recommended clearance interval timing might increase the safety for late exiting vehicles that are exposed to traffic before clearing the intersection.

In addition to the red light violations and late-exit study, a before-and-after crash analysis was completed at the three intersections for two years before and two years after the signal retiming. All crashes within 150 feet of the intersections were included, although crashes directly related to driveways within this radius were omitted from the analysis. At the time of publication of the study, intersection crashes were reduced at the three study intersections, but no follow-up research is published on the final results (7).

2.3.3. Disadvantages of All-Red Clearance Interval

A study conducted in Indiana took a different approach to evaluate the effectiveness of the all-red clearance interval. Rather than looking at only the short term before-and-after effects of implementation of the all-red clearance interval, this study examined 2 years before and 2 to 4 years after implementation of the all-red clearance interval. In addition to conducting a long-term analysis, this study also used a comparison group, something that is generally not included in other studies. Also, three previous studies of the all-red clearance interval were reproduced in the Indiana data (8).

Intersections used in the study were chosen based on the availability of intersection crash data, date of implementation of all-red clearance, traffic volumes, and geometry (4-leg approach intersections with 2-way traffic). Twenty-eight intersections were chosen for the before-and-after analysis, and an additional 28 intersections were chosen for the comparison group. The authors acknowledge that the following items may impact the effectiveness of the all-red clearance interval, but were not considered due to lack of sufficient sample size or to lack of data:

- Length and adequacy of the all-red interval
- Need for the all-red interval
- Existence or location of vehicle detectors
- Type of signal (fixed, semi, or fully actuated)
- Minor changes in signal phasing throughout the time period of the study
- Number of lanes on the approach, including left turn lanes
- New development and/or driveways near the intersections
- Discrepancies between travel speed and posted speed limit
- Changes in the traffic composition over the course of the study
- Level of service

The first part of the Indiana study involved examining intersection crash data for one and two years before and up to four years after the implementation of the all-red clearance interval. The before-and-after periods were isolated by a one-year period during which the all-red clearance interval was implemented. During the one-year treatment period, the total crash rates, left turn crash rates, rear end crash rates, right turn crash rates, and right angle crash rates decreased. This immediate decrease in crash rates was attributed to the implementation of the all-red clearance interval. Although crash rates decreased initially, for the two years following the treatment year, crash rates increased to rates similar to or higher than the initial rates during the before period.

The second portion of the study compared the intersection crash rates of 28 intersections with the all-red clearance interval versus 28 intersections without the all-red clearance interval. In this portion of the study, each intersection was paired with an intersection based on entering Average Annual Daily Traffic (AADT), approach speed, and angle of intersection. This comparison showed no significant difference in intersection crash rates between intersections with and without the all-red clearance interval.

Finally, three different studies were reproduced using the Indiana data. Just as they did in the before-and-after analysis, there was a treatment year separating the before-and-after periods to account for the sharp decline in crash rates immediately following the implementation of the all-red clearance interval.

The Indiana study concluded that the all-red clearance interval did not reduce crash rates after implementation. In addition, intersection crash rates for intersections with the all-red interval were not significantly lower than those without the all-red interval. Moreover, after reproducing three previous studies with the Indiana data and including the treatment year concept, several interesting conclusions were drawn. It was determined that the all-red clearance interval did not reduce injury crashes at intersections. In cases where the all-red clearance interval reduced intersection crashes, it did so for only one year after (regression to the mean?), but not in the longer term. With regard to the ability of the all-red interval to improve safety, these findings seem to conflict with the FHWA's statement on all-red clearance intervals: "The red clearance interval is not intended to reduce the incidence of red light running; rather it is a safety measure" (9).

2.3.4. Clearance Interval Length

Results from several studies indicate that clearance intervals (amber and or all-red clearance intervals) consistent with the ITE recommended values can reduce red light violations. This reduction in red light violations can consequentially decrease right angle conflicts, thus increasing safety at intersections without the use of the all-red interval. The safety benefits can affect vehicles as well as pedestrians and bicycles.

2.3.4.1. Clearance Interval Length for Vehicles

A 1985 study conducted by Zador, Stein, Shapiro, and Tarnoff (10, 11) concluded that intersections with more adequate (longer) clearance intervals (amber and all-red clearance intervals) had fewer right angle and rear end crashes than intersections with inadequate clearance intervals.

Data was acquired from ninety-one intersections in eight different metropolitan areas: Chicago, Illinois; Denver, Colorado; Miami, Florida; Montgomery County, Maryland; Richmond, Virginia; San Diego, California; and White Plains, New York. These intersections were monitored for signal changes, vehicle speeds, and times through the use of a traffic data logging system developed by PRC Voorhees. The following six variables were chosen to analyze data:

- Cross-street Width
- Estimated Average Crossing Time
- Indirect Measures of Yellow Signal Timing
- Indirect Measures of Yellow and All-red
- ADT for Monitored Street
- Ratio of Mainline ADT to the Cross-street ADT

Initially, the standard statistical procedure of cluster analysis was used to divide the ninety-one intersections into eight relatively uniform clusters. The average number of vehicles per second entering the intersection during the last four seconds of the green interval was defined as the base flow rate. An adjusted crash rate was computed for each approach. These eight clusters were then merged into five overlapping intersection cluster groups. The range in clearance interval times for the five cluster groups was 10% greater than recommended clearance interval timing to 10% less than recommended clearance interval timing. The clusters with shorter than recommended clearance interval timing experienced much higher crash rates than intersections with longer than recommended clearance intervals (10, 11).
A 2000 study conducted by Retting, et al, (12) explored whether the length of the all-red clearance interval had an effect on red light running. One hundred and twenty-two four legged intersections in Long Island, New York were chosen for analysis. Half of these intersections were chosen as control sites, while the other half were retimed using the ITE Clearance Interval Equations (13). These intersections were monitored for 36 months after the retiming of the signals. At the intersections with signals timed to ITE standards, there were 8% fewer reportable crashes (reportable crashes are crashes over $1000), 37% fewer pedestrian and bicycle crashes, and 12% fewer injury crashes. (12) This study shows the strong safety impact of the longer clearance interval for pedestrians and bicyclists, in addition to the safety effect for motorists.

2.3.4.2. Clearance Interval Length for Pedestrians and Bicycles

When timing signals, it is important to consider all intersection users, including pedestrians and bicycles. However, there is little research into all-red clearance intervals as related to pedestrian and bicycle safety. It has been suggested that short amber phases should not be used at intersections where there is the potential for use by pedestrians and bicycles (14, 15). In addition, some literature states that in some cases the all-red clearance interval may be necessary to accommodate pedestrians and bicycles at intersections (14, 15).

2.4. Guidelines for Calculating the Duration of All-Red Clearance Interval

When agencies utilize the all-red clearance interval, there are different ways to select interval duration. Most Midwest agencies use the recommended ITE Guidelines, or a variation of the guidelines, and a few apply the equations presented in the "additional signal timing methods" section of this report.

2.4.1. ITE Yellow Change Interval Guidelines

There are a variety of methods used to determine the length of the clearance interval. In this case the clearance interval is defined as the yellow change interval and possible all-red clearance interval. Equations 2-1a and 2-1b from ITE are used to determine the yellow change interval. Currently, this is the most common method used in the Midwest. These equations are based on assumed driver perception-reaction time (1 second), deceleration rate (10 feet per second^2), and vehicle length (20 feet). The approach speed, percent grade, and intersection width are specific to the particular intersection.

2.4.2. ITE All-Red Clearance Interval Timing

ITE specifies 3 methods for all-red clearance interval timing. They are the rule-of-thumb method, the use of the formula for a left-turn lane, and uniform value for the change interval. These methods of all-red clearance interval calculations are depicted in Equations 2.2.a, 2.2.b, and 2.2.c.

The all-red clearance interval is a function of the width of the intersection, length of clearing vehicle, and approach speed. Following are equations used to calculate yellow change and all-red intervals (16).

Equation 2-1 ITE Method for Calculating Yellow Change Interval

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

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

Where:

t = driver perception-reaction time for stopping, taken as 1s

v = approach speed, feet per second (meters per second), taken as the 85^{th} percentile speed

a = deceleration rate for stopping, taken as 10 feet per $second^2$ (3.0 $meters/second^2$)

g = percent grade, divided by 100

G = acceleration due to gravity 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)

(ITE, 1994)

Equation 2-2 ITE Methods for Calculating the All-Red Clearance Interval

$$r = \frac{(w + L)}{V} \qquad \text{(a)}$$

$$r = \frac{P}{V} \qquad \text{(b)}$$

$$r = \frac{(P + L)}{V} \qquad \text{(c)}$$

where:

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

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

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

L = length of vehicle, in feet (meters) assumed to be 20 feet (6 meters)

V = speed of the vehicle through the intersection, in feet /second (meters/second) (13)

2.5. Alternative Solutions to the All-Red Clearance Interval

Retting et. al.(3) conducted a study of two intersections in Arlington, VA. After conducting this study, some alternative red light running countermeasures were suggested. They included: removal of unwarranted traffic signals, changing traffic signal timing, enforcement, and the use of red light running cameras.

2.5.1. Extension of Yellow Interval

Two studies have evaluated extending the yellow phase and/or retiming the yellow phase to match driver behavior at particular intersections. A study conducted in a medium sized city in New York explored the relationships between yellow phase length and red light violations, and all-red length and red light violations. Twenty sites were chosen for analysis. Three sets of data were manually collected. The first set of data was collected in October 1992. Red light violations were recorded for the existing signal phasing. Beginning in January, 1993, the following changes were applied to selected signalized intersections;

- The yellow interval was increased to meet ITE standards at four sites.
- The all-red interval was increased at five sites to meet ITE standards.
- Both the yellow and all-red intervals were increased to ITE standards at four intersections.

- The remaining intersections did not experience any phase changes besides minor timing changes in conjunction with signal maintenance.

The second set of data was collected in April 1993. The signal timing was then changed back to the original October 1992 timing, and the third set of data was collected in September and October 1993. The study concluded, "increasing the length of the yellow signal toward the ITE recommendations significantly decreased the chance of red light running and the length of the all-red interval did not seem to affect red light running" (17). This means that if signals were retimed to include the longer, more adequate yellow time, red light violations would significantly decrease. In addition, since the all-red clearance interval did not seem to affect red-light violations, an all-red clearance interval may not be necessary and the time saved by omitting it can increase the capacity of the intersection. If signals were retimed to include longer yellow time, this would have very important policy implications in the United States.

A study conducted in the Tucson Metropolitan Area examined traffic characteristics during signal change intervals. Five intersections were chosen for analysis of the duration of the yellow change interval, effect of enforcement, and intersection approach grades. In order to obtain data, time-lapse photography was used. The cameras were able to detect vehicles within approximately 350 to 400 feet of the intersection. The study focused on the last vehicle to enter the intersection and the first vehicle to stop.

In part of this study, the yellow interval was extended from 2 to 4 seconds at two of the intersections, and was compared with two control intersections. For each of these intersections, descriptive statistics were computed for: approach speeds, distance from the intersection at the beginning of the yellow interval, response time, deceleration rate, and percent of vehicles entering on the red.

Results were mixed, however. At one of the intersections with extended yellow, the average speed of the vehicles entering the intersection increased. At the other intersection, approach speeds, response time, and deceleration rate were lower after the extension of the yellow interval. It is important to note that at both intersections the number of vehicles entering the intersection after the onset of the red was reduced after the increase of the yellow interval. These findings were similar to those found by Stimpson, Zador, and Tarnoff (18).

2.5.2. Officer Enforcement

Officer enforcement of red light running laws is particularly difficult for a variety of reasons. The primary reason is that in most cases the officer will have to follow the vehicle through the intersection with sometimes fatal results. Although two officers may team up to work an intersection, enforcement is expensive and limited in coverage (3). In 1998, Minneapolis had 923 sworn police officers. Today, the number is 852. (19) Clearly additional enforcement for red light running laws competes for increasingly limited resources.

2.5.3. Red-Light Running Cameras

To supplement officer enforcement of intersections, red light running cameras are being considered and used in some locations. One of the issues with red light running cameras is that the owner of the vehicle might not be driving when the red light is run. However, according to Retting, Williams, and Greene, several studies have shown almost all vehicles caught running red lights are driven by the vehicle owner or by someone in the same residence as the registered vehicle owner (3).

According to the Insurance Institute for Highway Safety the installation of red light running cameras has greatly reduced red light running and intersection crashes. In a study in Oxnard, California, nine red light running cameras were installed across the city. After the installation of these cameras, there was a 42 percent drop in red light violations across the entire city. As a result, there was a 29 percent reduction in injury crashes in the city. International studies have concluded that red light running cameras reduce red light violations by 40-50 percent and injury crashes by 25-30 percent (20).

For additional information on approaches to limit red light running, see FHWA's Stop Red Light Running web page at http://safety.fhwa.dot.gov/programs/srlr.htm and the National Campaign to Stop Red Light Running at http://www.stopredlightrunning.com/

2.6. Summary of Findings

Several points can be made regarding the research on the effectiveness of the all-red clearance interval

- Most studies examined the short term effects of the all-red clearance interval
- Some studies showing significant safety improvements were performed on intersections that were treated with other intersection safety improvements at the time of implementation of the all-red
- Other studies have shown mixed results after the addition of the all-red clearance interval
- A study by Purdue showed that the delay caused by the all-red clearance interval negated the safety benefits of implementing the all-red clearance interval
- Extending the yellow appears to have positive safety benefits

To address the fact that no consensus exists on the effectiveness of the all-red clearance interval on intersection crashes and violations, this study is conducted to assist jurisdictions in making informed decisions about the use of the all-red clearance interval.

3. MIDWEST STATE AND LOCAL PRACTICES

In order to assess Midwest state and local practices, a sample of state and local traffic engineering departments were contacted. Most states and cities in the Midwest follow or use a variation of the ITE guidelines to determine clearance intervals. A few have written policies. (Policies and practices were collected and summarized as part of this study. See appendix E). All states and cities contacted use all-red clearance intervals at most intersections. The only major exception to this rule is intersections containing older timing equipment that do not accommodate the all-red interval. The following sections outline the state and local practices for the use of the all-red clearance interval.

3.1. Use of All-Red Clearance Intervals at State Levels in the Midwest

All states contacted used some form of an all-red interval, but their methods for determining the duration of the red vary. The different methods are described in the following sections.

3.1.1. Illinois Department of Transportation (DOT)

The Illinois DOT's policy on the use of the all-red clearance interval is outlined in the Bureau of Operations Traffic Policies and Procedures Manual (21). The difference between the Illinois equation and the ITE equations is that there is no consideration of grades on stopping distance. Grade adjustments are allowed if field observations deem them necessary. The length of the yellow interval should be the sum of the first two terms in equation 3-1 rounded up to a half second. The remainder of the time is allocated to the all-red interval. The range of acceptable yellow intervals is 3 to 5 seconds. When a yellow interval longer than 5 seconds is calculated for the yellow interval, the remaining time is assigned to the all-red interval.

Equation 3-1 Illinois DOT's Method for Calculating the All-Red Clearance Interval

$$Y + AR = t + \frac{v}{2a} + \frac{w + l}{v}$$

Where:

Y = length of yellow in seconds

AR = length of all-red in seconds

t = perception - reaction time of driver in seconds; the standard value is 1 second

v = approach speed in feet per second

a = deceleration rate in feet per second per second; 10 feet per second per second should be used

w = width of intersection in feet

l = length of vehicle in feet; the standard value is 20 feet

3.1.2. Indiana DOT

The Indiana Department of Transportation (INDOT) is divided into six districts. Although each district has its own discretion in dealing with signal timing, all six districts have agreed on a common method. The all-red period is used on all roads controlled by the INDOT, except intersections with older equipment not capable of handling the all-red interval. In these instances, the yellow time is lengthened up to the Manual on Uniform Traffic Control Devices (MUTCD) maximum of 6 seconds (22, 23).

In the state of Indiana, there are several purposes for the all-red clearance interval. The first is to warn drivers the green interval is over and allow drivers who are far enough away from the intersection to stop. Another purpose of the clearance interval is to allow drivers who are unable to stop to clear the intersection. Finally, the clearance interval allows vehicles that illegally enter the intersection time to clear prior to the movement of traffic in conflicting lanes.

The clearance interval for through traffic is determined from tables provided by INDOT. The clearance intervals provided are based on equation 3-2. This equation is a modified "nondilemma zone" determination of clearance interval as denoted in the ITE Transportation and Traffic Engineering Handbook (16). The major difference is that the yellow time is determined by the initial velocity of vehicles on the roadway. This is either the posted speed limit, established speed from radar studies, or observed approach speed. The length of the all-red is determined by the speed of the vehicles entering the intersection. This is usually the same as the initial velocity, but sometimes differs based on a case-by-case basis (24).

Equation 3-2 Indiana DOT's Method for Calculating the All-Red Clearance Interval

$$\text{Clearance Interval} = t_p + \frac{v_i}{(2a + 2Gg)} + \frac{(w + l)}{v_c}$$

Where:

Clearance Interval = yellow + all-red

t_p = perception time, taken as 1 second

v_i = initial velocity, feet/second

a = deceleration rate for stopping, taken as 10 feet per second^2 (3.0 meters/second^2)

G = grade, percent

g = acceleration due to gravity 32.2 feet per second^2 (9.8 meters/second^2)

w = width of intersection, feet (meters), measured from the

upstream stop bar to the downstream far edge of pavement

l = length of clearing vehicle, taken as 20 feet (6.1 meters)

v_c = velocity of the vehicle going through the intersection, feet/second

The yellow interval on Indiana state highways is restricted to 3 to 5 seconds when an all-red clearance interval is present. The remainder of the clearance interval is included in the all-red interval. Indiana also has a special provision for heavy truck volumes. When there are heavy truck volumes, the vehicle length in equation 3-2 is changed from 20 to 55 feet. The Indiana DOT is aware of the study conducted by Purdue University, which concludes that intersection delay outweighs the safety impacts of the all-red clearance interval. However, they have decided to continue using the all-red interval "in order to provide the safest roadway system possible" (22).

3.1.3. Minnesota DOT

The Minnesota DOT views the yellow interval as an indication for vehicles to come to a safe stop before entering the intersection or allows vehicles that cannot safely stop to clear the intersection prior to the onset of conflicting movements. The internal timing guidelines for the Minnesota DOT recommend using the ITE Guidelines for calculating the yellow and all-red clearance interval.

The Internal Timing Guidelines for the Minnesota DOT make it clear that the ITE equations are only to be used as a guide for determining vehicle clearance times. Discretion is given to the traffic engineer to lengthen or shorten the clearance interval based on grade, truck traffic, intersection visibility, and intersection size. The maximum allowable all-red interval is 5.0 seconds (25).

3.1.4. Missouri DOT

The Missouri DOT Phasing and Timing the Signal guidelines views the change and clearance interval as a necessary practice to clear intersections before reassigning right-of-way to conflicting movements (26). The change period (yellow phase and all-red) allows vehicles that are unable to stop to clear the intersection. In order to develop uniformity throughout the state, the Missouri DOT suggests that yellow change intervals range from 4 to 5 seconds. The MUTCD suggests 3 to 6 seconds (23).

The Missouri DOT states, "The addition of an all-red clearance interval should not be automatically provided after every movement" (26). The use of an all-red clearance interval is reserved for situations when the needed change period is longer than yellow interval or where traffic engineers deem it is needed. There is generally a need at exceptionally wide intersections. By limiting the use of the all-red clearance interval, the Missouri DOT hopes to reduce the driver expectancy of the all-red clearance interval. The following equation is used to determine the length of the change interval. This equation is the same as the ITE equation for the Length of the Yellow Change Interval (when all-red clearance intervals are not used) except for the recommended deceleration values vary. Also, the MUTCD suggests using the 85th percentile speed or prevailing speed limit to determine the change period, but the Missouri DOT also suggests using the 15th percentile speeds. This lower speed will help accommodate wide intersections or left turns. Computing the equation with the 85th and 15th percentile speeds and using the more conservative value will provide safer intersections (26).

Equation 3-3 Missouri DOT's Method for Calculating the All-Red Clearance Interval

$$CP = t + \frac{V}{(2a \pm 64.4g)} + \frac{(W+L)}{V}$$

Where:

CP = nondilemma change period (yellow plus all-red), seconds

t = perception-reaction time, recommended as 1.0 s

V = approach speed, feet/second

g = percent grade (positive for upgrade, negative for downgrade)

a = deceleration rate, recommended values as follows:

- 10 ft/s2 - low speed approaches, i.e. CBD
- 12.5 ft/s2 - typical arterial approaches
- 15 ft/s2 - high speed approaches

W = width of intersection, ft

L = length of vehicle, recommended as 20 ft

NOTE: CP greater than 7 seconds not recommended.

Occasionally there are cases involving extremely steep grades or very high-speed approaches, causing the change period calculation to yield values larger than 7 seconds. When this occurs, the Missouri DOT suggests the use of advanced warning signs instead of lengthening the change period. This will increase the capacity of the intersection while maintaining signal-timing consistency throughout the state (26, 27).

3.1.5. Nebraska Department of Roads

Unlike the other Midwest DOTs, the Nebraska Department of Roads (NDOR) does not follow the ITE recommended practice for clearance intervals. This is because the state requires vehicles to stop at yellow lights. The NDOR has a policy calling for 4.5 to 5.0 seconds of yellow and 0.5 to 1.0 seconds of all-red. The only city in the state using more than the recommended all-red time is the city of Lincoln. Lincoln uses three seconds of all-red in the central business district (28).

3.1.6. Ohio DOT

The Ohio Department of Transportation Manual of Uniform Control Devices, and Traffic Engineering Manual describes the use of the all-red clearance interval and the recommended length of yellow and all-red time. In the state of Ohio: "The exclusive function of the steady yellow interval shall be to warn traffic of an impending change in the right-of-way assignment." During this time vehicles should stop or proceed through the intersection if they are unable to stop. Most yellow vehicle change intervals range from three to six seconds depending on the speed of the approach traffic. In some instances, the yellow change interval may be followed by an all-red interval. This all-red interval allows vehicle to clear the intersection prior to conflicting traffic movements entering the intersection. The typical maximum all-red interval is two seconds (29).

The Ohio Department of Transportation Traffic Engineering Manual contains the following equation for determining the length of the clearance interval. It is important to note that all local agencies are required to follow the OMUTCD. The difference between this equation and that of the ITE recommended equations is that ITE has two equations: one when there is an all-red clearance interval and one when there is not an all-red clearance interval. The ODOT Traffic Engineering Manual also allows the engineer to account for start-up time lost for conflicting movements in order to shorten the all-red interval for more efficient operations at busy intersections.

Equation 3-4 Ohio DOT's Method for Calculating the All-Red Clearance Interval

$$Y + AR = t + \frac{V}{(2a + 64.4g)} + \frac{W + L}{V} \qquad \text{English Units}$$

$$Y + AR = t + \frac{V}{(2a + 19.6g)} + \frac{W + L}{V} \qquad \text{Metric Units}$$

Where:

Y = yellow time

AR = all-red time

t = driver perception-reaction time for stopping, taken as 1s

V = approach speed, feet per second (meters per second)

a = deceleration rate for stopping, taken as 10 feet per second2 (3.0 meters/second2)

g = percent grade, divided by 100 (positive for upgrade, minus for downgrade)

W = width of intersection, in feet (meters), measured from the near
Stop Line to the far edge of the conflicting traffic lane, along the
actual vehicular path)

L = length of clearing vehicle, taken as 20 feet (6.0 meters)

(29, 30, 31)

3.2. Use of All-Red Clearance Intervals at Local Levels in the Midwest

Local policies for the all-red clearance interval were investigated. Traffic engineers from cities similar in size to Minneapolis were contacted and questioned about signal phasing practices on the local level. Table 3-1 presents a summary of the responses from traffic engineers in cities similar in size to Minneapolis.

Table 3-1 Midwest Cities Comparable in Size to Minneapolis

Midwest Cities Comparable in Size to Minneapolis

City	State	City Population	Metro Area Population
Bloomington *	Minnesota	85,182	2,968,806
Cincinnati	Ohio	311,258	1,646,395
Cleveland	Ohio	478,403	2,945,831
Columbus	Ohio	711,470	1,540,157
Lincoln	Nebraska	232,362	274,178
Milwaukee	Wisconsin	596,974	1,500,741
Minneapolis	Minnesota	382,618	2,968,806

* Bloomington, Minnesota was chosen because of its close proximity to Minneapolis (32)

3.2.1. Bloomington, Minnesota

According to the traffic engineer for the City of Bloomington, Minnesota has all-red clearance intervals at almost all signalized intersections. The only exceptions are a handful of mid-block pedestrian crossings with old controllers that do not have the capability of containing an all-red interval. The city is currently in the process of updating these controllers and when complete, all signalized intersections in Bloomington will contain an all-red interval. Bloomington, Minnesota follows the Minnesota DOT guidelines for determining the length of all-red clearance intervals. This equation is the same as the ITE recommended length for an all-red interval (33)

Equation 3-5 Bloomington, Minnesota's Method of Calculating the All-Red Clearance Interval

$$R = \frac{W + L}{1.467\ v}$$

Where:

R = All-red clearance interval in seconds

W = Width of intersection, stop line to center of farthest conflicting lane

L = Vehicle length, assumed to be 20 feet

v = 85th Percentile speed in miles per hour

1.467 = Unit conversion factor

3.2.2. Cincinnati, Cleveland, and Columbus, Ohio

All local agencies in Ohio are required to follow the previously outlined guidelines for determining the all-red clearance interval contained in the OMUTCD (29).

3.2.3. Lincoln, Nebraska

According to the Nebraska DOR, the City of Lincoln applies 3.0 seconds of all-red to all signals in the central business district regardless intersection design (28).

3.2.4. Milwaukee, Wisconsin

The City of Milwaukee generally follows the ITE recommended signal-phasing equations as a guideline for the clearance interval at intersections. All intersections controllers with the capability for an all-red interval contain one. As a rule of thumb, most intersections within the city have 3.0 to 3.5 seconds of yellow (approximately one tenth of the speed limit), plus a minimum of 0.5 seconds of all-red. If an intersection had a speed limit of 30 mph, the yellow would be 3.0 seconds and there would be a minimum of 0.5 seconds of all-red. More complicated intersections (skewed, five-way, or extremely large) are sometimes allotted more yellow or all-red time. The maximum all-red used is 2.5 seconds (34).

3.3. Summary of All-Red Phasing in the Midwest

Most states and cities in the Midwest follow the ITE Guidelines or a variation of the ITE Guidelines for determining clearance interval. Tables 3-2 and 3-3 summarize the methods for calculating clearance intervals used by several Midwest states and cities. In addition, Tables 3-2 and 3-3 depict the length of the amber interval, all-red clearance interval, and total clearance interval for an intersection with an approach speed of 30 miles per hour, 0% grade, and a 50-foot effective intersection width, rounded to the nearest 0.5ft.

Table 3-2 Method of Calculating All-Red Clearance Intervals at State Levels

State	ITE Guidelines	Variation of ITE Guidelines	Other	Length of Amber Interval	Length of All-Red Interval	Total Length of Clearance Interval
Illinois		X		3	1.5	4.5
Indiana		X		3	1.5	4.5
Minnesota	X			3	1.5	4.5
Missouri		X		3	1.5	4.5
Nebraska			X	4.5 to 5	0.5 to 1.0	5 to 6
Ohio		X		3	1.5	4.5

Table 3-3 Method of Calculating All-Red Clearance Intervals at Local Levels

City	ITE Guidelines	Variation of ITE Guidelines	Other	Length of Amber Interval	Length of All-Red Interval	Total Length of Clearance Interval
Bloomington	X			3	1.5	4.5
Cincinnati		X		3	1.5	4.5
Cleveland		X		3	1.5	4.5
Columbus		X		3	1.5	4.5
Lincoln			X	Varies	3.0	Varies
Milwaukee			X	3.0 to 3.5	0.5	3.5 to 4.0

4. DATA COLLECTION AND SITE SELECTION

Because intersection information was not readily available in electronic formats, a digital intersection database was created for this project. Data were obtained from several sources at the City of Minneapolis. The completed intersection database for the cross-sectional and before-and-after analysis includes the following attributes:

- Intersection number (defined by the City of Minneapolis)
- Intersection name
- Treatment (all-red, no all-red)
- Date of addition of all-red (not available at all intersections)
- Speed
- Signal mount (overhead or pedestal)
- Presence of lighting at the intersection
- Daily Entering Vehicles (DEV)
- All intersection crashes per year
- Relevant intersection crashes per year (head on, rear end, right angle, left turn, right turn, and side swipe)
- Other intersection characteristics that were not investigated due to time constraints or data availability include:
    - Intersection grade
    - Presence of on-street parking
    - Signal timing including length of the all-red clearance interval
    - Number of approach lanes
    - Type of signal (fixed versus fully- or semi-actuated)
    - Intersection width
    - Observed approach speeds versus posted speeds

In addition, whether or not an individual signal was warranted was not investigated although this might play a role in the number of drivers running red lights. The MUTCD cautions this is a consequence of signals that are perceived as unnecessary by the public.

4.1. Description of Study Area

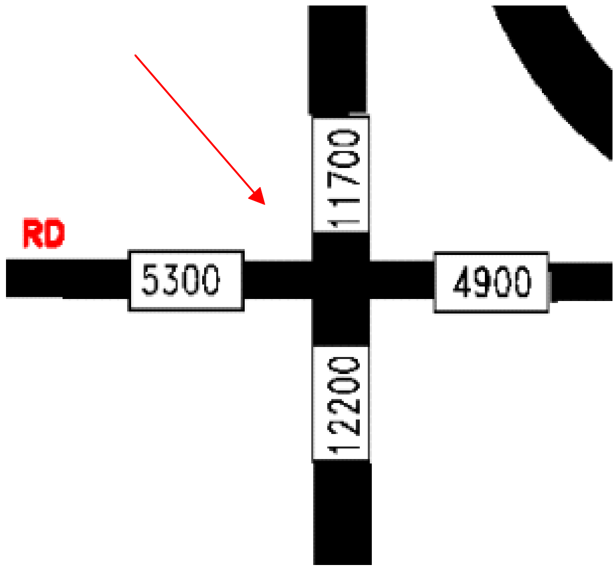
The study area is Minneapolis, Minnesota. At the time of this study, there were 803 signalized intersections. Six hundred and ninety-nine of the signalized intersections had an all-red clearance interval while 104 did not.

4.2. Usable Intersections

Only intersections of two-way roads with four approaches were analyzed. Skewed, offset, or intersections with horizontal curves on approaches were not used to eliminate the influence of geometry on study intersections. In order to identify acceptable locations, plans for all Minneapolis signalized intersections were examined resulting in 228 usable intersections for analysis. A usable intersection is an intersection with two-way roads with four approaches, and no skew, offset or horizontal curves. Thirty-eight of these intersections did not have an all-red clearance interval. Appendix A.1 contains a list of usable intersections.

4.3. Intersection DEV

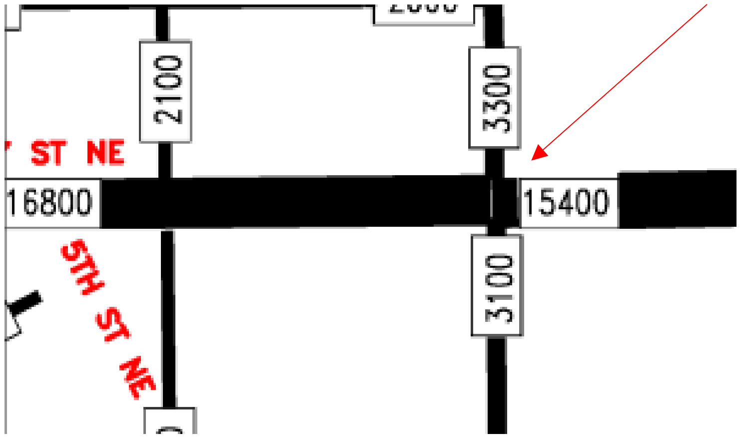
Because traffic counts were not directly available for each intersection approach, AADTs were estimated through a variety of methods. The first method used a vehicular traffic flow map obtained from the City of Minneapolis Transportation Division. If the street was not shown on this map, traffic was obtained from an AADT station history database obtained from the City of Minneapolis Transportation Division. All of the AADTs were not obtained from this database because it was more cumbersome to use and was not obtained until after the first method was complete. Finally, if neither source provided the counts of interest, AADT was estimated as an average of AADT on all municipal streets in Hennepin County. The first method of determining AADT for all usable intersection approaches involved utilizing the vehicular traffic flow map. Information was available for all 228 intersections' phase 2 (major) approaches using this method. In addition, information was available from the vehicular traffic flow map for 139 of the minor approaches. Several rules were followed to obtain AADT for approaches as depicted in Figures 4-1, 4-2, and 4-3.



Situation 1: AADT Information for Each Approach

DEV = (5300 + 11700 + 4900 +12200)/2

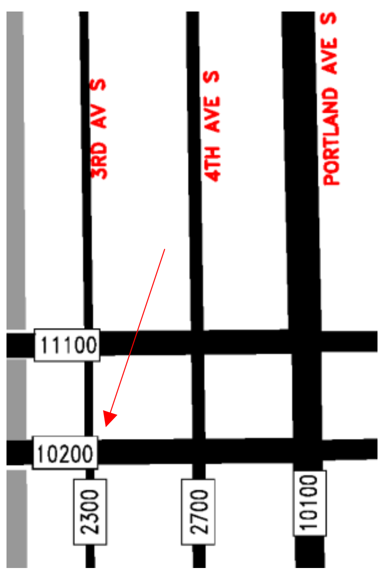
Figure 4-1 AADT Information Available for Each Approach



Situation 2: AADT Available for 3 Approaches,
And Information for 4th Approach Within Several Blocks

DEV = (3300 + 15400 + 3100 + 16800)/2

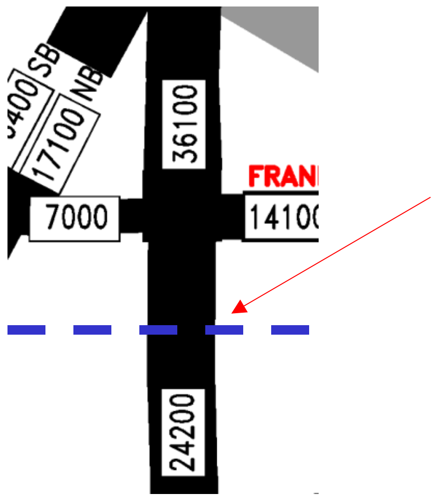
Figure 4-2 AADT Available for 3 Approaches, and Information for 4th Approach within Several Blocks



Situation 3: AADT Information Available for Only 2 Approaches

DEV = (10200 x 2 + 2300 x 2)/2

Figure 4-3 AADT Information Available for Only 2 Approaches



Situation 4: Minor Approach is not on AADT Map

DEV = (24200 + 36100 + Either Database Values for Each Approach or Default of 600 for Each Approach)/2

Figure 4-4 Minor Approach is not on AADT Map

In some instances there was no AADT information for a phase 4 (or minor approach) intersection approach. Figure 4-4 depicts this scenario. In these cases, an AADT station history database was used to estimate the AADT on the minor approach. Just as in the previous diagrams, the locations of the count stations were determined, and the AADT was based on the same spatial parameters previously depicted in the figures. This occurred at 59 intersections.

If AADT information was not available from the map or database, vehicle miles of travel (VMT) and miles of roadway for municipal streets in Minneapolis was used to estimate AADT. This occurred at 30 intersections. Using Equation 4-1 AADT was determined to be 607 vehicles per day (VPD). The implication of using this estimate is that if actual volumes are higher than the estimate, the intersection might appear to have a higher crash rate than it is actually experiencing (the opposite is true if the estimate is too high). The three lowest AADT in the dataset are 300, 459, and 600; therefore, the estimate of 607 VPD seems reasonable.

Equation 4-1 Determining Average Minneapolis AADT

$$AADT = \frac{DailyVMT}{\text{Miles of Roadway}}$$

Where:

$DailyVMT = 464{,}023$ for Minneapolis

Miles of Roadway $= 764.9$ for Minneapolis

Once AADT information was estimated for each intersection approach, intersection DEV was determined by taking the sum of all approaches and dividing by 2. This method was chosen because turning movements and other information such as AADT directional split was not available. Equation 4-2 depicts how DEV was determined for each intersection.

Equation 4-2 Determining DEV for Each Intersection

$$DEV = \frac{\left(AADT_1 + AADT_2 + AADT_3 + AADT_4\right)}{2}$$

Where:

$AADT_1$ = AADT on North Approach

$AADT_2$ = AADT on South Approach

$AADT_3$ = AADT on East Approach

$AADT_4$ = AADT on West Approach

After the DEV was determined at each intersection, a growth factor was applied to forecast DEV for each year in the study time frame. The Minnesota DOT State Aid Manual has a growth factor for each county, which can be used to prepare a 20-year forecast for growth. For Hennepin County, where Minneapolis is located, the growth factor is 1.4. Equation 4-3 can be used to annualize the growth factor.

Equation 4-3 Annualizing the Minneapolis Traffic Growth Factor

Growth Factor for y years $= (1 + i)^y$

Where:

i = Annual Growth Factor for Minneapolis

y = Number of Years

If one annualizes this growth factor of 1.4 over 20 years, a 1.69% growth in traffic is expected each year. Initially, this 1.69% growth factor may sound low, but Minneapolis has been fully developed for many years, and one would not expect to see a significant increase in traffic on local streets. The growth factor was used to factor up or down DEV values at each study intersection over the course of the study period. For example, at most intersections DEV was calculated from the 2002 vehicular traffic flow maps and needed to be factored down for other years in the study such as 2001, 2000, 1999, etc.

4.4. Approach Speed

Initially, it was assumed that approach speed would affect the number of crashes at an intersection. However, all posted speed limits for the study area were 30 miles per hour. Although a number of approaches did not have posted speed limits, according to the Minnesota statutory speed laws, urban streets in the state of Minnesota have a speed limit of 30 miles per hour (35). Collection of actual speeds was beyond the scope of the project. Consequently, the impact of speed was not investigated.

4.5. Visibility of Signal Heads

In order to account for signal visibility, intersection plans were examined to determine whether there were overhead or pedestal signals on the Phase 2 and Phase 4 (major and minor) approaches. In order to accomplish this, two dummy variables were created: D1 and D2. Values were then assigned to D1 and D2 based on whether there were overhead signal or pedestal signals on the major and minor approaches. Table 4-1 depicts the method for coding the location of signals at study intersections.

Table 4-1 Method for Coding the Location of Signals at Study Intersections

$D1 = 1$ If there are overhead signals for both approaches
$D1 = 0$ Otherwise

$D2 = 1$ If there are overhead signals for one direction
$D2 = 0$ Otherwise

4.6. Presence of Intersection Lighting

Research is available on whether or not the presence of intersection lighting plays a role in decreasing crashes (36, 37). Many studies conclude that lighting decreases crashes at night in rural and urban settings. Since the presence of lighting might have an impact on intersection crashes, intersection plans were inspected to see if intersections had street lighting. Only the presence of intersection lighting was noted, as intensity data was not available for every intersection.

4.7.Crashes

Crash reports at each intersection were obtained from the City of Minneapolis Office of Transportation and Parking Services. Crashes were classified into 15 different categories. Of these fifteen categories, 6 groups were presumed to be related to red light violations and/or the absence or presence of the red light clearance interval (Roper, et al). These 6 categories (termed relevant, hereafter) are denoted with an asterisk (*).

HO*	Head On	PKG	Parking
RE*	Rear End	BKG	Backing
RA*	Right Angle	TRN	Train
LT*	Left Turn	PED	Pedestrian
SS*	Side Swipe	BIC	Bicycle
RT*	Right Turn	OTH	Other
FO	Fixed Object	UNK	Unknown
PV	Parked Vehicle		

Relevant crashes and total crashes were determined for each year at each intersection under investigation.

4.8. Site Selection

Two different studies were performed to determine the effectiveness of the all-red clearance interval. The first study (termed cross-sectional study) compared the safety performance of intersections operating with and without all-red for the most recent four year period. To study the short and long term effects of implementation, a second study (before-and-after) analyzed the safety performance of intersections where all-red clearance intervals were added during an eleven year study period. Sites were selected to support these two studies.

4.8.1. Cross-Section Study

In Minneapolis, there are 228 intersections with two-way approaches, four-legs, no skew, offset, and no horizontal curves. Thirty-eight of these have never had an all-red clearance interval. These intersections were used in the cross-section study as control.
The remaining 190 intersections were considered for selection of a treatment group. In order to avoid any possible immediate or short-term effects of the addition of the all-red clearance interval, only intersections with an all-red addition prior to 1996 were deemed eligible for use. Using a spreadsheet random number generator, 38 of the remaining intersections were chosen to represent locations with all-red clearance intervals. Figure 4-5 shows the relatively even spatial distribution of treatment and control intersections used in the cross-section study. Table 4-2 lists the same intersections. A complete intersection database for the cross-section study is located in Appendix A.2.

Cross-Section Study Intersections

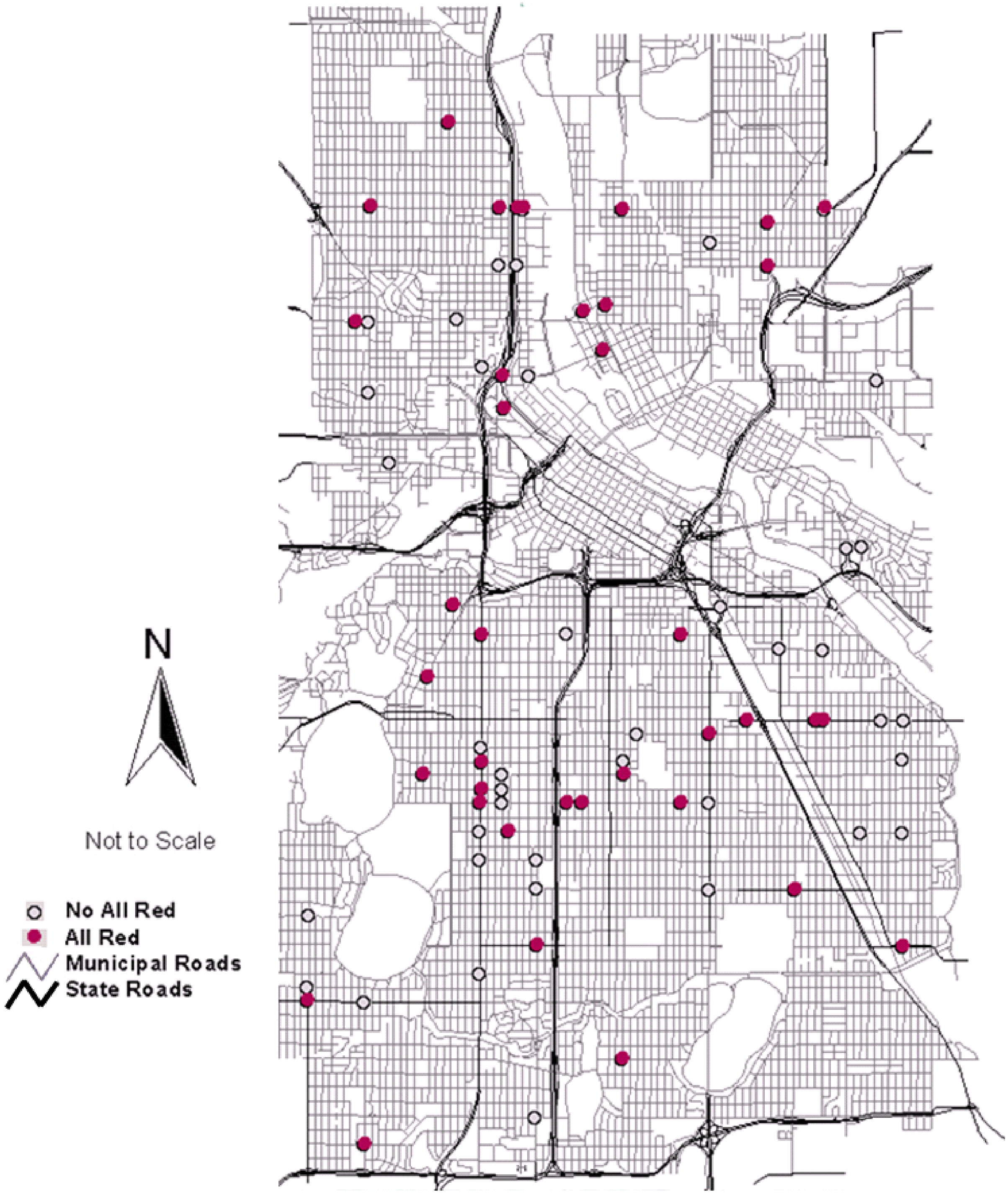


Figure 4-5 Map of Intersections used in the Cross-Section Study

Table 4-2 Intersections Used in the Cross-Section Study

#	Location	All-red interval?	Implementation Date
26	E Lake St & 42 Ave S	N	N/A
28	E 31 St & 10 Ave S	N	N/A
34	Lyndale Ave S & W 40 St	N	N/A
52	Cedar Ave & E 36 St	N	N/A
74	W 50 St & Penn Ave S	N	N/A
112	E 25 St & 31 Ave S	N	N/A
116	E Lake St & 39 Ave S	N	N/A
150	Chicago Ave & E 33 St	N	N/A
176	Washington Ave N & 26 Ave N	N	N/A
177	E Hennepin Ave & Hoover St	N	N/A
203	E Franklin Ave & Cedar Ave	N	N/A
227	26 Ave S & E 25 St	N	N/A
231	Central Ave NE & 20 Ave NE	N	N/A
267	Nicollet Ave & 58 St	N	N/A
268	Huron Blvd & Fulton St	N	N/A
299	Grand Ave & W 34 St	N	N/A
339	Plymouth Ave & 2 St N	N	N/A
345	Lyndale Ave N & 14 Ave N	N	N/A
361	3 Ave S & E 24 St	N	N/A
368	Lyndale Ave S & W 48 St	N	N/A
389	27 Ave SE & Essex St	N	N/A
463	Lyndale Ave S & W 38 St	N	N/A
468	Nicollet Ave & 42 St	N	N/A
469	Nicollet Ave & 40 St	N	N/A
490	W 35 St & Grand Ave	N	N/A
497	W 36 St & Grand Ave	N	N/A
499	W Broadway & Dupont Ave N	N	N/A
577	Penn Ave N & 12 Ave N	N	N/A
791	Xerxes Ave S & W 44 St	N	N/A
797	Penn Ave N & Golden Valley Rd	N	N/A
837	Lyndale Ave S & W 32 St	N	N/A
841	Cedar Ave & E 42 St	N	N/A
870	42 Ave S & E 38 St	N	N/A
919	E 38 St & 36 Ave S	N	N/A
942	26 Ave N & 4 St N	N	N/A
970	42 Ave S & E 33 St	N	N/A
975	Xerxes Ave S & W 49 St	N	N/A
981	Glenwood Ave & Morgan Ave N	N	N/A
43	W 50 St & Chowen Ave S	Y	4/14/80
51	Lyndale Ave S & W 24 St	Y	2/13/84
75	Lowry Ave N & Penn Ave N	Y	12/5/86

109	E Lake St & 31 Ave S	Y	11/9/62
121	W 50 St & Xerxes Ave S	Y	4/14/80
125	Chicago Ave & E 34 St	Y	6/16/72
233	Lyndale Ave N & Plymouth Ave	Y	10/21/80
237	10 Ave N & 5 St N	Y	6/9/80
265	Lowry Ave N & 4 St N	Y	12/12/75
272	Washington Ave N & Lowry Ave N	Y	3/12/81
298	W Franklin Ave & Dupont Ave S	Y	2/11/87
349	Lyndale Ave S & W 36 St	Y	7/14/81
355	Lyndale Ave S & W 33 St	Y	11/4/76
412	Hennepin Ave & W 34 St	Y	9/6/79
439	E Lake St & 22 Ave S	Y	12/3/86
441	Dowling Ave & Emerson Ave N	Y	1/13/82
459	Cedar Ave & E 31 St	Y	8/26/87
467	Hennepin Ave & W 27 St	Y	5/21/84
478	Stinson Pkwy & Lowry Ave NE	Y	9/21/79
486	Bloomington Ave & E 36 St	Y	6/2/70
572	W 38 St & Pleasant Ave	Y	3/27/85
582	E 36 St & 4 Ave S	Y	9/23/81
783	E 46 St & 42 Ave S	Y	9/20/72
809	Johnson St & 18 Ave NE	Y	11/18/87
851	Johnson St & 23 Ave NE	Y	7/30/74
855	Marshall St & 13 Ave NE	Y	3/5/81
860	Lowry Ave & University Ave NE	Y	3/8/51
861	Nicollet Ave & 46 St	Y	3/27/81
864	2 St NE & 13 Ave NE	Y	11/20/70
865	E 36 St & 3 Ave S	Y	8/12/83
873	E Lake St & 30 Ave S	Y	10/22/86
886	Bloomington Ave & E 24 St	Y	11/16/81
897	Lowry Ave N & 2 St N	Y	6/2/86
898	8 Ave NE & Marshall St	Y	9/26/85
914	Lyndale Ave S & W 35 St	Y	1/9/67
943	Penn Ave S & W 60 St	Y	6/10/69
969	Golden Valley Rd & Russell Ave	Y	7/18/72
980	28 Ave S & E 42 St	Y	4/18/75

4.8.2. Before-and-after Study

To study immediate as well as longer term impacts of the implementation of all-red phasing, 11 years of data were desired for the before-and-after study (5 years before, the year of implementation, and 5 years after.) As data were available between 1987 and 2002, intersections where all-red was implemented between 1991 and 1997 were eligible for study as the treatment group. Twenty-two intersections met this criterion.

A group of control intersections were selected from those that operated without an all-red clearance interval during the study period from 1985 through 2002. Forty-seven intersections met this criterion and all were used to comprise the control group (it is statistically permissible to select a control group which is larger than the treatment group). The locations of the intersections used in the before-and-after study are illustrated in Figure 4-6. Table 4-3 lists the intersections used in the before-and-after study. A complete intersection database for the before-and-after study can be found in Appendix Table A.3.

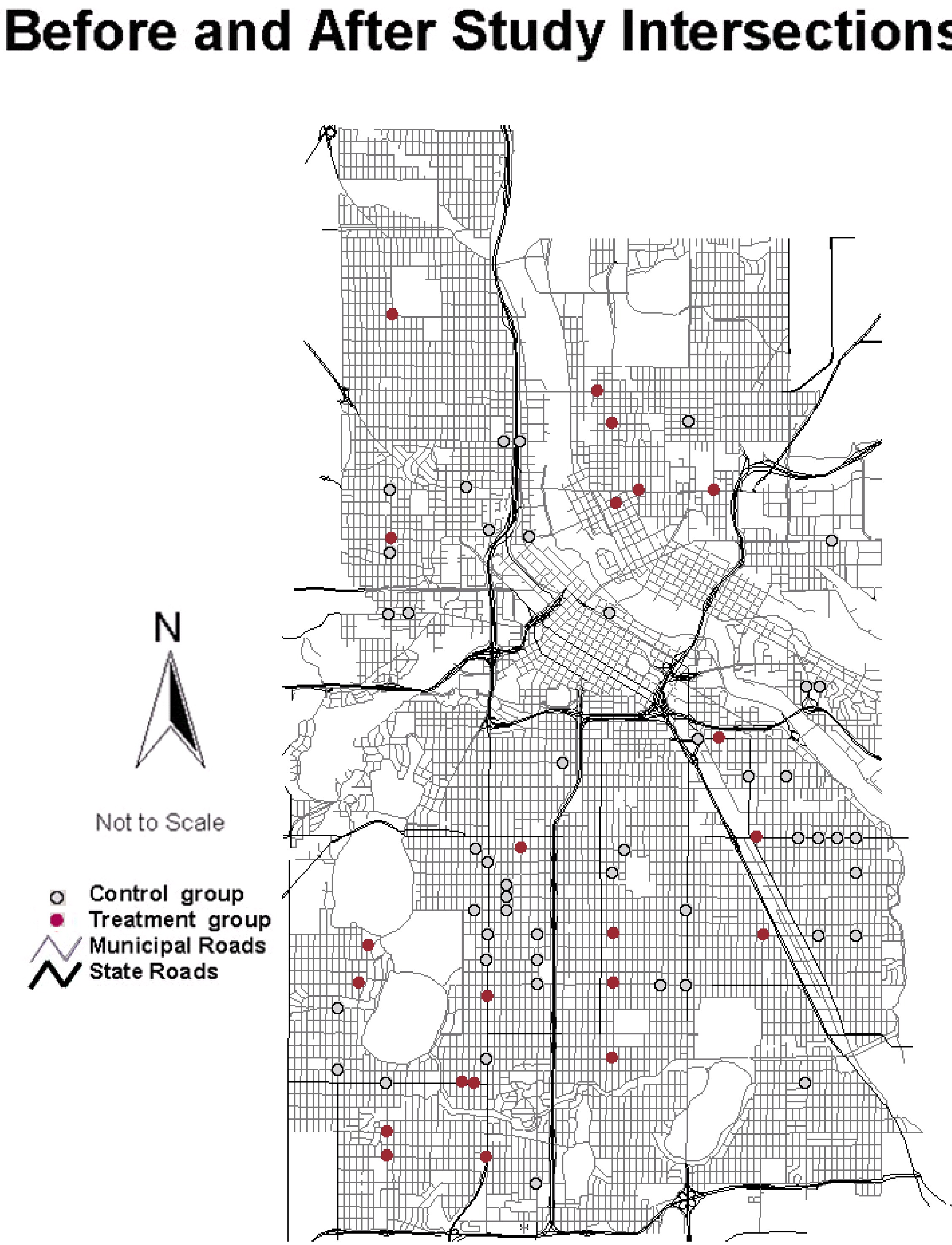


Figure 4-6 Map of Intersections Used in the Before-and-after Study

Table 4-3 Intersections in the Before-and-after study

NUM	INTERSECTION NAME	A-	A-	Group
981	Glenwood Ave & Morgan Ave N	N	N/A	Ctrl
975	Xerxes Ave S & W 49 St	N	N/A	Ctrl
970	42 Ave S & E 33 St	N	N/A	Ctrl
942	26 Ave N & 4 St N	N	N/A	Ctrl
919	E 38 St & 36 Ave S	N	N/A	Ctrl
870	42 Ave S & E 38 St	N	N/A	Ctrl
841	Cedar Ave & E 42 St	N	N/A	Ctrl
837	Lyndale Ave S & W 32 St	N	N/A	Ctrl
797	Penn Ave N & Golden Valley Rd	N	N/A	Ctrl
791	Xerxes Ave S & W 44 St	N	N/A	Ctrl
577	Penn Ave N & 12 Ave N	N	N/A	Ctrl
499	W Broadway & Dupont Ave N	N	N/A	Ctrl
497	W 36 St & Grand Ave	N	N/A	Ctrl
490	W 35 St & Grand Ave	N	N/A	Ctrl
469	Nicollet Ave & 40 St	N	N/A	Ctrl
468	Nicollet Ave & 42 St	N	N/A	Ctrl
463	Lyndale Ave S & W 38 St	N	N/A	Ctrl
389	27 Ave SE & Essex St	N	N/A	Ctrl
368	Lyndale Ave S & W 48 St	N	N/A	Ctrl
361	3 Ave S & E 24 St	N	N/A	Ctrl
345	Lyndale Ave N & 14 Ave N	N	N/A	Ctrl
339	Plymouth Ave & 2 St N	N	N/A	Ctrl
299	Grand Ave & W 34 St	N	N/A	Ctrl
268	Huron Blvd & Fulton St	N	N/A	Ctrl
267	Nicollet Ave & 58 St	N	N/A	Ctrl
231	Central Ave NE & 20 Ave NE	N	N/A	Ctrl
227	26 Ave S & E 25 St	N	N/A	Ctrl
203	E Franklin Ave & Cedar Ave	N	N/A	Ctrl
177	E Hennepin Ave & Hoover St	N	N/A	Ctrl
176	Washington Ave N & 26 Ave N	N	N/A	Ctrl
150	Chicago Ave & E 33 St	N	N/A	Ctrl
116	E Lake St & 39 Ave S	N	N/A	Ctrl
112	E 25 St & 31 Ave S	N	N/A	Ctrl
74	W 50 St & Penn Ave S	N	N/A	Ctrl
52	Cedar Ave & E 36 St	N	N/A	Ctrl
34	Lyndale Ave S & W 40 St	N	N/A	Ctrl
28	E 31 St & 10 Ave S	N	N/A	Ctrl
26	E Lake St & 42 Ave S	N	N/A	Ctrl
356	W 36 St & Bryant Ave S	Y	4/8/03	Ctrl
736	3 Ave S & 2 St S	Y	5/5/03	Ctrl
17	Penn Ave N & Glenwood Ave	Y	5/5/03	Ctrl

598	Bloomington Ave & E 42 St	Y	5/8/03	Ctrl
892	34 Ave S & E 50 St	Y	5/14/03	Ctrl
9	W 31 St & Bryant Ave S	Y	5/19/03	Ctrl
872	E Lake St & 33 Ave S	Y	5/28/03	Ctrl
261	Nicollet Ave & 38 St	Y	5/29/03	Ctrl
115	E Lake St & 36 Ave S	Y	6/27/03	Ctrl
97	Lowry Ave NE & 2 St NE	Y	7/10/91	Trt
938	E Franklin Ave & 22 Ave S	Y	7/11/91	Trt
600	Broadway St NE & Washington St	Y	7/26/91	Trt
2	W 50 St & Bryant Ave S	Y	8/27/91	Trt
388	Upton Ave S & W 43 St	Y	7/30/93	Trt
983	W 39 St & Sheridan Ave S	Y	8/13/93	Trt
751	Chicago Ave & E 48 St	Y	9/2/93	Trt
82	University Ave NE & 20 Ave NE	Y	9/20/93	Trt
882	Penn Ave S & W 54 St	Y	5/27/94	Trt
482	Plymouth Ave & Penn Ave N	Y	7/14/94	Trt
966	Penn Ave N & Dowling Ave	Y	7/27/94	Trt
832	Chicago Ave & E 42 St	Y	11/12/94	Trt
895	Broadway St NE & Fillmore St	Y	12/29/94	Trt
342	E Lake St & 27 Ave S	Y	1/3/95	Trt
162	Chicago Ave & E 38 St	Y	3/16/95	Trt
920	E 38 St & 28 Ave S	Y	3/23/95	Trt
68	Lyndale Ave S & W 56 St	Y	10/3/95	Trt
5	W 50 St & Dupont Ave S	Y	10/5/95	Trt
902	Penn Ave S & W 56 St	Y	12/22/95	Trt
900	University Ave NE & 8 Ave NE	Y	7/13/96	Trt
810	Lyndale Ave S & W 43 St	Y	5/1/97	Trt
989	W 31 St & Pillsbury Ave	Y	6/4/97	Trt

5. ANALYSIS AND RESULTS

5.1. Cross-Section Analysis

The purpose of the cross-section study was to determine if there is a difference in the number of crashes or crash rates between intersections operating with and without all-red clearance phasing. Intersections were selected randomly and crash data was obtained for 1999-2002. Descriptive statistics were computed and graphed for:

- Relevant crashes
- Relevant crash rate
- Total crashes
- Total crash rate

Crashes and crash rate are presented below. Figures and tables are presented for relevant crashes (relevant crashes include: head on, rear end, right angle, left turn, right turn, and side swipe crashes) and crash rates. Additional figures and tables for total crashes and crash rates are available in Appendix B. Although intersection characteristics were not intentionally controlled for in the cross section analysis (controlling for these factors would have limited the number of comparable intersections to an unusable low number), both groups are relatively similar with regard to DEV, signal mounting type, and intersection lighting (see table 5-1).

Figure 5-1 displays average total and relevant crashes for the cross-section study intersections. Table 5-2 presents descriptive statistics for relevant crashes at cross-section study intersections for each of the four study years. Figure 5-2 and Table 5-3 provide similar results for relevant crash rates.

Relevant and total crashes and crash rates are observed to be higher at intersections with the all-red clearance interval. For additional investigation into this finding see section 5.3, Statistical Models and Chapter 6, Conclusions and Recommendations.

Table 5-1 Descriptive Statistics for Cross-Section Study Intersections

	No All-Red	All-Red	Percent Difference
Avg. **Total** Crashes, annual	3.3	5.8	73%
Avg. **Relevant** Crashes, annual	2.1	4.0	92%
Avg. Daily Entering Volume (DEV)	13,278	16,105	21%
Overhead on both approaches (1 yes, 0 no)	0.11	0.21	
Overhead on one approach only (1 yes, 0 no)	0.37	0.34	
Intersection lighting (1 yes, 0 no)	0.89	0.92	

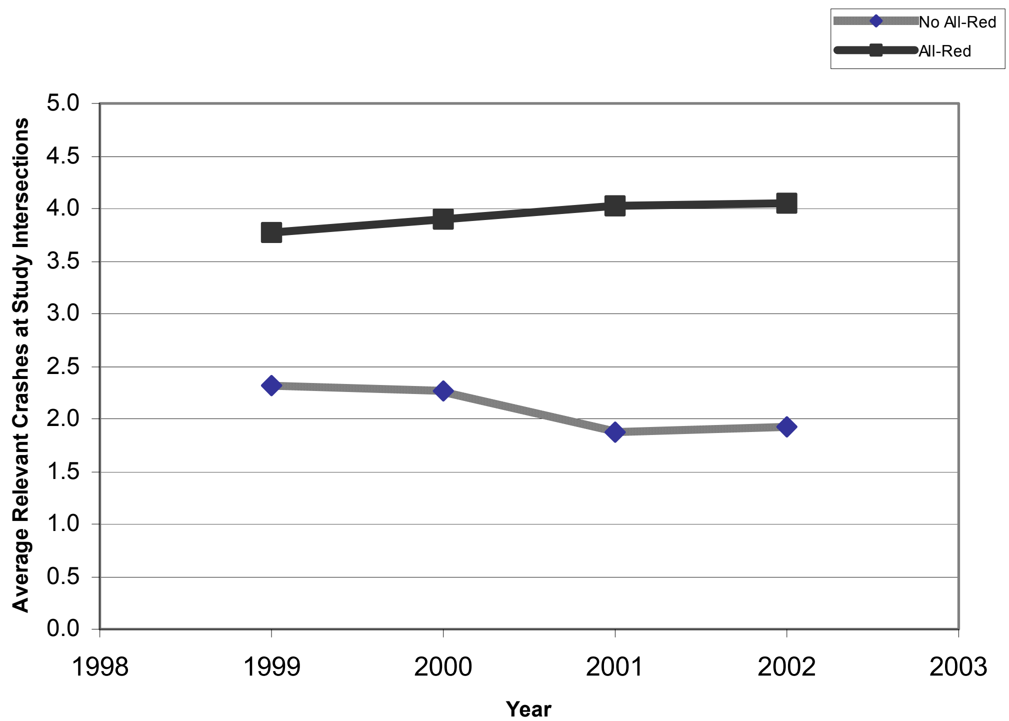


Figure 5-1 Average Relevant Crashes for Cross-Section Study Intersections

Relevant Crashes: head on, rear end, right angle, left turn, right turn, and side swipe

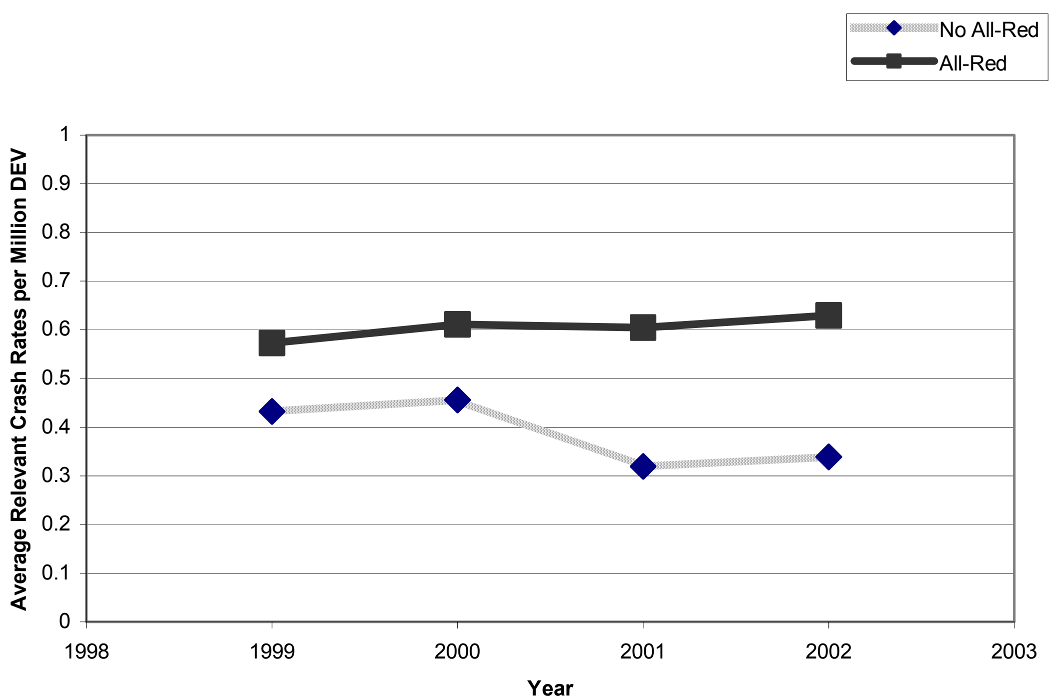
Table 5-2 Descriptive Statistics for Relevant Crashes at Cross-Section Study Intersections

	1999		2000		2001		2002		1999-2002	
	No A-R	A-R	No A-R	A-R	No A-R	A-R	No A-R	A-R	No A-R	A-R
Average	**2.3**	**3.9**	**2.3**	**4.0**	**1.9**	**4.1**	**1.9**	**4.1**	**2.1**	**4.0**
Minimum	0	0	0	0	0	0	0	0	0	0
Maximum	21	18	17	16	12	21	14	14	21	21
Median	1	3	2	3	1	2	1	3	1	3
Standard Deviation	3.7	4.3	2.8	3.8	2.4	4.6	2.7	3.6	2.9	4.0
Variance	13.6	18.4	8.0	14.1	5.6	21.0	7.2	12.7	8.5	16.2

No A-R: Intersections without the all-red clearance interval

A-R: Intersections with the all-red clearance interval

Relevant Crashes: head on, rear end, right angle, left turn, right turn, and side swipe



Relevant Crashes: head on, rear end, right angle, left turn, right turn, and side swipe

Figure 5-2 Average Relevant Crash Rates for Cross-Section Study

Table 5-3 Descriptive Statistics for Relevant Crash Rates at Cross-Section Study Intersections

	1999		2000		2001		2002		1999-2002	
	No A-R	A-R	No A-R	A-R	No A-R	A-R	No A-R	A-R	No A-R	A-R
Average	**0.43**	**0.59**	**0.46**	**0.62**	**0.32**	**0.61**	**0.34**	**0.64**	**0.39**	**0.61**
Minimum	0	0	0	0	0	0	0	0	0	0
Maximum	1.921	2.208	1.529	1.93	1.061	1.835	1.223	1.633	1.921	2.208
Median	0.308	0.412	0.424	0.594	0.259	0.411	0.263	0.669	0.336	0.508
Standard Deviation	0.452	0.556	0.376	0.484	0.301	0.54	0.335	0.426	0.371	0.499
Variance	0.204	0.309	0.141	0.234	0.091	0.292	0.112	0.182	0.138	0.249

No A-R: Intersections without the all-red clearance interval

A-R: Intersections with the all-red clearance interval

Relevant Crashes: head on, rear end, right angle, left turn, right turn, and side swipe

Crash Rate: Per million Daily Entering Vehicle

5.2. Before-and-after Study

The goal of the before-and-after study was to evaluate a treatment group of intersections for five years before-and-after implementation of all-red clearance interval, with a one-year treatment year in-between. The treatment group was compared to a control group of intersections that does not have the all-red clearance interval. Descriptive statistics were computed and graphed for:

- Relevant crashes
- Relevant crash rate
- Total crashes
- Total crash rate

Crashes and crash rate are presented below. Figures and tables are presented for relevant crashes (relevant crashes include: head on, rear end, right angle, left turn, right turn, and side swipe crashes) and crash rates. Additional figures and tables for total crashes and crash rates are available in Appendix B. Although intersection characteristics were not intentionally controlled in the cross section analysis (controlling for these factors would have limited the number of comparable intersections to an unusable low number), both groups are relatively similar with regard to DEV, signal mounting type, and intersection lighting (see table 5-4). Figure 5-3 displays average relevant crashes for the before-and-after study intersections. Table 5-5 presents descriptive statistics for relevant crashes for each of the eleven study years. Table 5-6 summarizes this information into before, during and after periods. Figure 5-4 and Tables 5-7 and 5-8 provide similar results for relevant crash rates.

Total and relevant crashes are higher, before-and-after implementation of all-red at treated intersections. In the first year after the addition of the all-red clearance interval, the data reveal a decline in the total crashes, relevant crashes, total crash rate, and relevant crash rate. This observation agrees with other short-term before-and-after studies (less than a year) for installation of an all-red clearance interval which also report short-term safety benefits. However, after the first year, the number of relevant crashes and relevant crash rates return to the same levels or higher levels than before the addition of the all-red clearance interval. This observation agrees with other long-term studies (more than a year) that did not report safety benefits of the all-red clearance interval (8).

Table 5-4 Descriptive Statistics for Characteristics of Before-and-after Study Intersections

	Control Group	Treatment	Percent Difference
Avg. Total Crashes, annual	**3.3**	**4.1**	**25%**
Avg. Relevant Crashes, annual	**2.1**	**2.9**	**40%**
Avg. Daily Entering Volume (DEV)	**12,150**	**13,130**	**8%**
Overhead on both approaches (1 yes, 0 no)	**0.09**	**0.05**	**na**
Overhead on one approach only (1 yes, 0 no)	**0.38**	**0.41**	**na**
Intersection lighting (1 yes, 0 no)	**0.89**	**0.95**	**na**

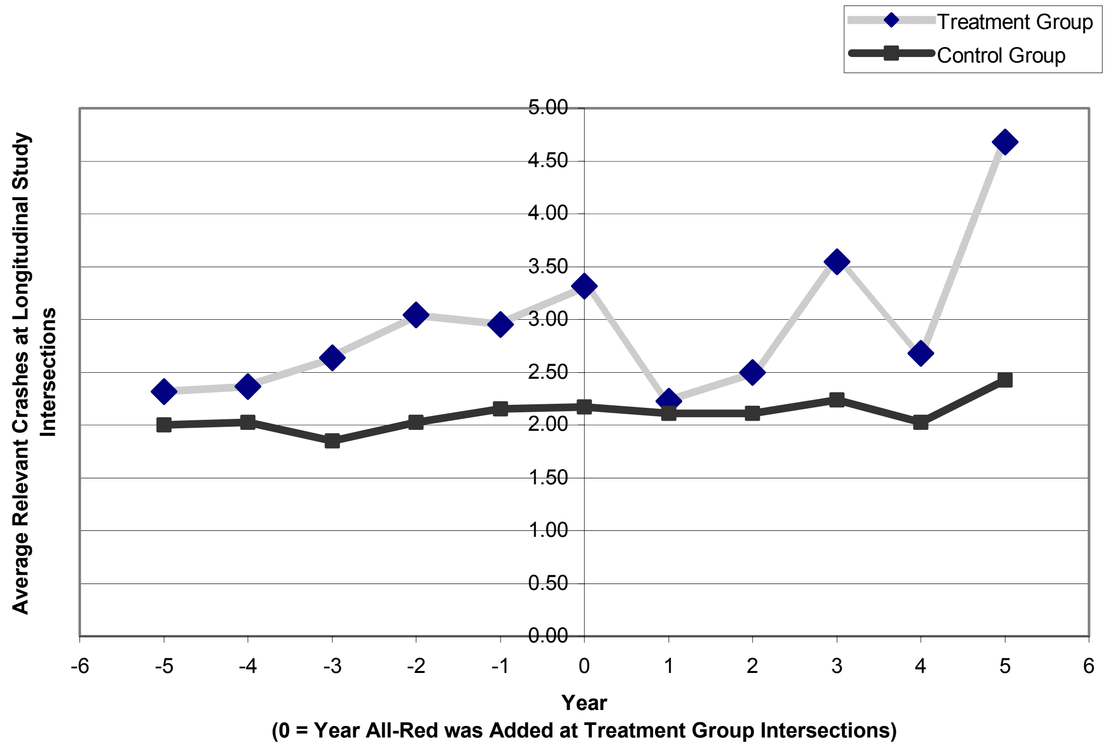


Figure 5-3 Average Relevant Crashes for Treatment and Control Group Intersections

Relevant Crashes: head on, rear end, right angle, left turn, right turn, and side swipe

Table 5-5 Descriptive Statistics for Relevant Crashes at Treatment and Control Group Intersections

	-5		-4		-3		-2	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	2.32	2.00	2.36	2.02	2.64	1.85	3.05	2.02
Minimum	0	0	0	0	0	0	0	0
Maximum	8	7	11	9	12	9	12	9
Median	2	2	2	1	2	1	2	2
Standard Deviation	1.99	1.85	2.44	2.08	3.05	2.14	2.84	2.10
Variance	3.94	3.43	5.96	4.33	9.29	4.56	8.05	4.41

	-1		0		1	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	2.95	2.15	3.32	2.17	2.23	2.11
Minimum	0	0	0	0	0	0
Maximum	9	12	9	13	9	11
Median	2.5	2	2	2	1	2
Standard Deviation	2.84	2.42	2.90	2.36	2.45	2.12
Variance	8.05	5.87	8.42	5.58	5.99	4.49

	2		3		4		5	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	2.50	2.11	3.55	2.23	2.68	2.02	4.68	2.43
Minimum	0	0	0	0	0	0	0	0
Maximum	8	13	12	13	8	9	17	21
Median	2	2	2	1	2	2	3.5	1
Standard Deviation	2.09	2.54	3.96	2.61	2.01	1.96	4.30	3.39
Variance	4.36	6.44	15.69	6.84	4.04	3.85	18.51	11.51

Trt: Treatment group intersections that received the all-red at year 0

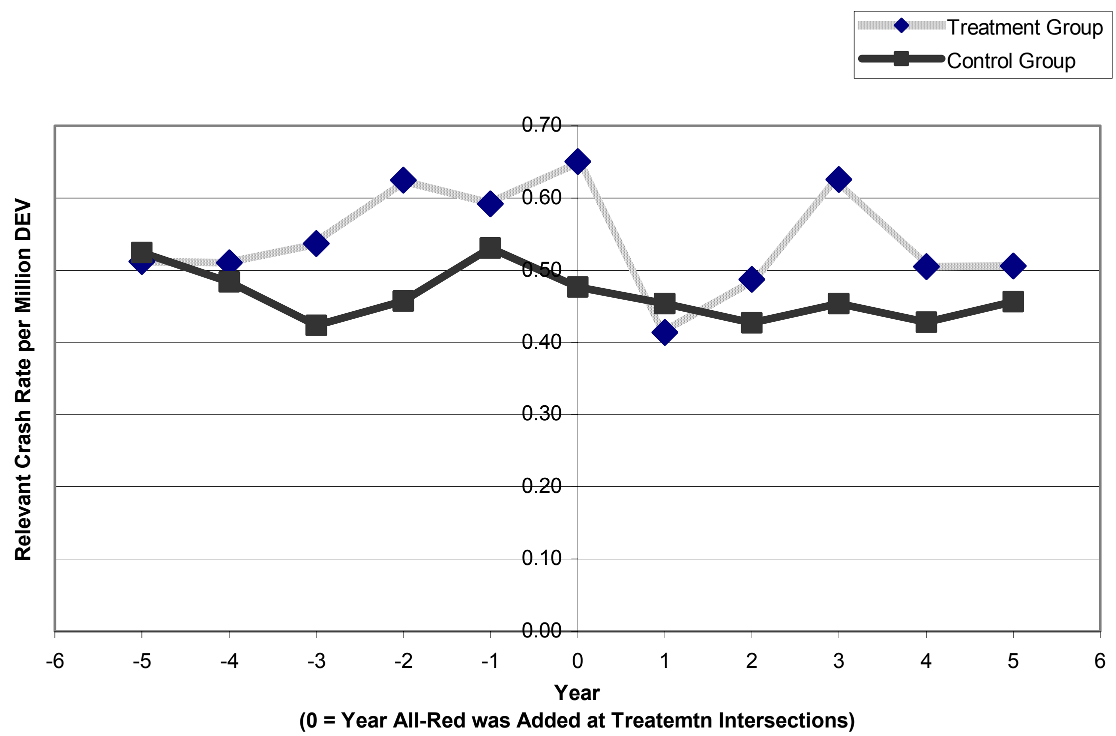
Ctrl: Control group intersections that do not have the all-red

Relevant Crashes: head on, rear end, right angle, left turn, right turn, and side swipe

Table 5-6 Average Relevant Crashes for Treatment and Control Group Intersections

Relevant Crashes: head on, rear end, right angle, left turn, right turn, and side swipe

Time Period	Treatment Group	Control Group
-5 to -1	2.66	2.01
0	3.32	2.17
1 to 5	3.13	2.18



Relevant Crashes: head on, rear end, right angle, left turn, right turn, and side swipe

Figure 5-4 Average Relevant Crash Rates for Treatment and Control Group Intersections

Table 5-7 Descriptive Statistics for Relevant Crash Rates at Treatment and Control Group Intersections

	-5		-4		-3		-2	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	0.512	0.524	0.511	0.484	0.537	0.424	0.624	0.458
Minimum	0	0	0	0	0	0	0	0
Maximum	1.747	1.705	1.601	1.486	1.718	1.518	2.257	1.683
Median	0.474	0.465	0.441	0.361	0.363	0.322	0.485	0.403
Standard Deviation	0.414	0.469	0.443	0.416	0.543	0.431	0.538	0.402
Variance	0.171	0.220	0.196	0.173	0.295	0.185	0.290	0.162

	-1		0		1	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	0.592	0.531	0.650	0.477	0.413	0.454
Minimum	0	0	0	0	0	0
Maximum	1.617	2.055	1.691	2.612	1.726	1.955
Median	0.461	0.324	0.571	0.392	0.327	0.383
Standard Deviation	0.529	0.530	0.536	0.465	0.403	0.394
Variance	0.279	0.281	0.287	0.216	0.162	0.155

	2		3		4		5	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	0.487	0.427	0.625	0.454	0.505	0.428	0.506	0.456
Minimum	0	0	0	0	0	0	0	0
Maximum	1.509	1.927	2.020	2.235	1.459	1.290	1.501	1.921
Median	0.399	0.322	0.394	0.312	0.458	0.353	0.408	0.379
Standard Deviation	0.370	0.426	0.633	0.469	0.346	0.350	0.457	0.428
Variance	0.137	0.181	0.400	0.220	0.120	0.123	0.209	0.183

Trt: Treatment group intersections that received the all-red at year 0

Ctrl: Control group intersections that do not have the all-red

Relevant Crashes: head on, rear end, right angle, left turn, right turn, and side swipe

Crash Rate: Per million Daily Entering Vehicles

Table 5-8 Average Relevant Crash Rates for Treatment and Control Group Intersections

Time Period	Treatment Group	Control Group
-5 to -1	0.56	0.48
0	0.65	0.48
1 to 5	0.51	0.44

5.3. Statistical Models

The cross-section study results are counter-intuitive as they imply that all-red phasing increases crashes. However, it is more likely that all-red phasing has simply been implemented at locations which are inherently more dangerous than locations without. To attempt to explain this counterintuitive result, a statistical modeling approach was taken. Regression models are often developed to explain the effects of additional variables. Variables which may affect the safety performance of intersections include volume, geometry and control characteristics. Due to the nature of the data available for this study of all-red effectiveness, simple linear regressions (such as those which can be developed using spreadsheet techniques) are not appropriate. In the cross-section study, crashes and rates at intersections were measured repeatedly over time 1999-2002. Count data (crash counts) should not be modeled with a simple linear regression model. Also, simple linear regression requires errors to be normally distributed. In addition, a simple linear regression model also assumes that all observations are independent. In this case, the observations were not independent because there were four measurements at each intersection. Therefore, alternative modeling forms were required.

To address these limitations, four linear mixed models were developed using Statistical Analysis Software (SAS) version 9.0 (see Appendix C for model development). Variables chosen for each of the models were:

- presence of all-red phasing
- daily entering volume
- presence of intersection illumination
- signal mount type (an indication of visibility)
- interactions between these variables

It is important to note that consideration was given to studying additional causal variables that might affect crash frequency, such as number of through lanes, presence of right or left turn lanes, signal phasing etc. However, data were not available for most of these variables, and disaggregating to the level required to analyze additional variables would have resulted in sample sizes too small to be statistically significant.

All four models had relatively similar solutions. Model 4 (a linear mixed model with structured covariance structure) produced the most statistically reliable results. Table 5-9 shows the predicted number of intersection crashes with and without all-red using the different models for a typical study intersection and "average of intersections" (results of the model averaged over all study intersections). The "typical" study intersection was defined to have 14,700 daily entering vehicles, pedestal mounted signals, and intersection illumination. Please refer to Appendix C for model development and analysis.

Results from the statistical models indicate that all-red intersections experience higher crash rates even when available variables are controlled for. Model 4 results for two "typical" intersections that differ only in their use of an all-red interval, are 3.3 crashes per year with an all-red interval versus 2.4 for the same intersection without all-red. See Chapter 6, Conclusions and Recommendations, for implications of this finding.

Table 5-9 Predicted Number of Relevant Intersection Crashes

	Typical Intersection			Average of Intersections		
	All-red	No all-red	Diff.	All-red	No all-red	Diff.
Linear Mixed Models						
Model 1 (GLMM-UN)	3.4	2.1	1.7	4.0	2.0	2.0
Model 2 (GLMM-CS)	3.4	2.2	1.7	4.0	2.1	1.9
Model 3 (LMM-UN)	3.4	2.4	1.7	3.8	1.9	1.9
Model 4 (LMM-CS)	3.3	2.4	1.6	3.8	1.9	1.9
Ordinary Regression	4.0	3.1	1.9	4.0	2.1	1.9
Observed data	n.a.	n.a.	n.a.	4.0	2.1	1.9

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary of Findings

The results of this study do not support the commonly held hypothesis that an all-red clearance interval inherently improves traffic safety at signalized intersections. Tables 6-1 and 6-2 present summary findings for the cross section study and statistical models. In all cases, signals without all-red, even when accounting for volume, lighting and signal visibility, had lower expected crashes and crash rates than intersections with the all-red clearance interval. However, a direct comparison of crashes and crash rates at intersections with and without all-red clearance intervals might be misleading since high crash locations are more likely to be considered for clearance interval modification and an all-red period is most likely to be implemented where safety is a perceived concern. Conversely, intersections with high crash histories tend to feature higher traffic volumes, and increasing clearance intervals will adversely impact delay and congestion, especially during peak periods.

This study found agreement with other research, in that short-term (one year) safety improvements do result from implementation of a red clearance interval, but these benefits are not sustainable and may in fact be mitigated by reduced capacity (Tables 6-3 and 6-4). Familiarity with an established clearance interval after a period of use may contribute to increasing crash rates as some drivers continue to enter the intersection after onset of a yellow signal.

Table 6-1 Cross section results, all crashes

All Crashes	Annual Frequency (Average) Crashes per Year		Rate per million entering vehicles	
	All-red (treatment)	Without (control)	All-red (treatment)	Without (control)
Cross Section	5.8	3.3	0.90	0.69

Table 6-2 Cross section and model results, relevant crashes

Relevant Crashes	Annual Frequency (Average)	Rate per million entering vehicles

	Crashes per Year			
	All-red	Without	All-red	Without
Cross Section	4.0	2.1	0.61	0.39
Best Model (4), typical intersection	3.3	2.4	0.62	0.45

Table 6-3 Before-and-after results, all crashes

All Crashes	Annual Frequency (Average) Crashes per Year		Rate per million entering vehicles	
	All-red (treatment)	Without (control)	All-red (treatment)	Without (control)
Before (average of 5 years before)	4.0	3.2	0.85	0.80
Before (year before)	4.5	3.4	0.93	0.86
After (year after)	3.3	3.3	0.64	0.76
After (average of 5 years after)	4.3	3.5	0.82	0.75
Short term reduction	1.2 (27%)	0.1 (3%)	0.29 (31%)	0.10 (12%)
Long term reduction	-0.3 (-8%)	-0.3 (-9%)	0.03 (4%)	0.05 (6%)

Table 6-4 Before-and-after results, relevant crashes

Relevant Crashes	Annual Frequency (Average) Crashes per Year		Rate per million entering vehicles	
	All-red (treatment)	Without (control)	All-red (treatment)	Without (control)
Before (average of 5 years before)	2.7	2.0	0.56	0.48
Before (year before)	3.0	2.2	0.59	0.53
After (year after)	2.2	2.1	0.41	0.45

After (average of 5 years after)	3.1	2.2	0.51	0.44
Short term reduction	0.8 (27%)	0.1 (5%)	0.08 (14%)	0.08 (15%)
Long term reduction	-0.4 (-15%)	-0.2 (-10%)	0.05 (9%)	0.04 (8%)

6.2. Conclusions

The data developed through this research do not imply that an all-red clearance interval is effective in reducing intersection crashes over time. In considering the descriptive statistics for either a cross section study or a before-and-after comparison, the all-red interval does not appear to be effective in reducing crashes at intersections in Minneapolis.

In the before-and-after study, comparing intersections with and without a red clearance interval, a reduction of approximately 1 crash per intersection in the first year following implementation was noted. However after a year of service, crash numbers returned to pre-implementation levels. In all four statistical models employed with this research, intersections without a red clearance interval exhibited lower numbers of relevant crashes than comparable intersections with this feature. However, these results may be misleading since it is likely that higher crash history intersections were selected for an all-red clearance implementation. Of added importance, it would also seem logical that longer clearance intervals should benefit safety and convenience for pedestrians and bicyclists.

Extending clearance time at signalized intersections increases user costs through delay and resultant congestion. Capacity reductions, especially during peak use periods due to reduced green time are accumulative and may mitigate any temporary safety benefits for drivers.

6.3. Recommendations

Based on the results of this research, several recommendations for implementation of a red clearance interval at specific signalized intersections can be drawn.

- Clearance intervals should only be established using criteria developed by the Institute of Transportation Engineers, ITE. This includes existing signals with all-red intervals as well as any contemplated for implementation in the future. Extension of the yellow change interval and minimal use of an all-red interval may accomplish desired safety improvements while avoiding capacity losses.
- Warrants should be developed and adopted prior to implementation of a red clearance interval at specific intersections. Criteria could include crash history, traffic volume, approach speeds, and pedestrian and bicyclist needs.

Consider other options for improving signal compliance such as:

- More visible signal heads; larger sizes, LED lamps, over lane mounting, etc.
- Improved timing, coordination, and synchronization
- Removal of unwarranted signals
- Use of automated enforcement (red light cameras)
- Public information and education regarding intersection safety

Past research and experience has indicated several alternatives such as these can benefit both signal compliance and capacity while also improving safety for all road users. Approximately 104 signalized intersections remain in the City of Minneapolis without a red clearance interval. Prior to establishing an all-red interval at these additional locations, the recommendations listed above should be considered. In addition, yellow change and red clearance intervals should be reviewed for compliance with ITE guidelines at intersections where an all-red clearance interval has been previously established.

It is important to consider the development of a sound written policy regarding the use of all-red to provide protection from liability under Minnesota law.

6.4. Future Research

Although research data do not conclude a long-term reduction of intersection crashes through use of an all-red clearance interval, investigation of the effects of additional variables may prove worthwhile. In addition, examining the impacts of longer clearance intervals, use of automated enforcement, development of all-red clearance interval warrants, and variable phasing for peak periods may also prove worthwhile as study subjects.

6.4.1. Investigating the Effects of Additional Variables

Although the statistical models used in this research did not indicate a long-term crash reduction from an all-red clearance interval at intersections, only a limited number of factors were considered. If additional variables were investigated, long-term advantages may be identified. Other parameters to consider might include:

- Intersection grade
- Presence of on-street parking
- Proper signal timing at the intersections
- Warrants for signals
- Signal design; number of heads, size, LEDs, etc.
- Number of approaches, including turning lanes
- Type of signal operation (fixed versus fully or semi actuated)
- Intersection width
- Various posted approach speeds
- Observed actual versus posted speeds
- Weather conditions
- Cycle length

Inclusion of additional variables in future research efforts may define long-term safety or other benefits from the use of an all-red clearance interval.

6.4.2. Exploring the Effects of Different Lengths of Clearance Intervals

The Institute of Transportation Engineers has developed guidelines for clearance intervals based primarily on approach speeds, vehicle lengths, and intersection widths. However study of signal compliance impacts from various yellow change and red clearance intervals may prove beneficial.

6.4.3. Automated Enforcement (Red Light Running Cameras)

According to the Insurance Institute for Highway Safety, installation of automated enforcement cameras can reduce signal violations by 40-50 percent and injury crashes by 25-30 percent (20). In addition to reducing intersection crashes, red light running cameras do not result in adverse affects on delay and congestion. A study of the effectiveness of automated enforcement in reducing intersection crashes and improving signal compliance could be conducted in the City of Minneapolis, perhaps as an option to extended clearance intervals.

6.4.4. Other Topics for Research

In addition to these suggested research topics, other issues of potential benefit for study include;

- Development of quantifiable warrants for the implementation of a red clearance interval, primarily considering factors such as crash history, pedestrian and bicyclist needs, approach speeds, traffic volumes, and physical characteristics of the intersection.
- Benefits of utilization of an all-red interval only during off-peak periods. This study could support a hypothesis that, since signal violations and resultant crashes can be higher during non-peak hours, implementation of an extended clearance interval only during those times might prove beneficial for safety while not adversely affecting peak hour capacity.

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Appendix A
Intersections

A.1. Usable Intersections

NUM	INTERSECTION NAME	All_Red	AR_Added	Confident
26	E Lake St & 42 Ave S	N	N/A	Y
28	E 31 St & 10 Ave S	N	N/A	Y
34	Lyndale Ave S & W 40 St	N	N/A	Y
52	Cedar Ave & E 36 St	N	N/A	Y
74	W 50 St & Penn Ave S	N	N/A	Y
112	E 25 St & 31 Ave S	N	N/A	Y
116	E Lake St & 39 Ave S	N	N/A	Y
150	Chicago Ave & E 33 St	N	N/A	Y
176	Washington Ave N & 26 Ave N	N	N/A	Y
177	E Hennepin Ave & Hoover St	N	N/A	Y
203	E Franklin Ave & Cedar Ave	N	N/A	Y
227	26 Ave S & E 25 St	N	N/A	Y
231	Central Ave NE & 20 Ave NE	N	N/A	Y
267	Nicollet Ave & 58 St	N	N/A	Y
268	Huron Blvd & Fulton St	N	N/A	Y
299	Grand Ave & W 34 St	N	N/A	Y
339	Plymouth Ave & 2 St N	N	N/A	Y
345	Lyndale Ave N & 14 Ave N	N	N/A	Y
361	3 Ave S & E 24 St	N	N/A	Y
368	Lyndale Ave S & W 48 St	N	N/A	Y
389	27 Ave SE & Essex St	N	N/A	Y
463	Lyndale Ave S & W 38 St	N	N/A	Y
468	Nicollet Ave & 42 St	N	N/A	Y
469	Nicollet Ave & 40 St	N	N/A	Y
490	W 35 St & Grand Ave	N	N/A	Y
497	W 36 St & Grand Ave	N	N/A	Y
499	W Broadway & Dupont Ave N	N	N/A	Y
577	Penn Ave N & 12 Ave N	N	N/A	Y
791	Xerxes Ave S & W 44 St	N	N/A	Y
797	Penn Ave N & Golden Valley Rd	N	N/A	Y
837	Lyndale Ave S & W 32 St	N	N/A	Y
841	Cedar Ave & E 42 St	N	N/A	Y
870	42 Ave S & E 38 St	N	N/A	Y
919	E 38 St & 36 Ave S	N	N/A	Y
942	26 Ave N & 4 St N	N	N/A	Y
970	42 Ave S & E 33 St	N	N/A	Y
975	Xerxes Ave S & W 49 St	N	N/A	Y
981	Glenwood Ave & Morgan Ave N	N	N/A	Y
2	W 50 St & Bryant Ave S	Y	8/27/1991	Y
5	W 50 St & Dupont Ave S	Y	10/5/1995	Y
9	W 31 St & Bryant Ave S	Y	5/19/2003	Y
11	W 50 St & France Ave S	Y	11/6/1970	N
17	Penn Ave N & Glenwood Ave	Y	5/5/2003	Y
19	W Lake St & Drew Ave S	Y	2/3/1993	N

21	Chicago Ave & E 25 St	Y	7/29/1993	N
37	Emerson Ave N & 16 Ave N	Y	3/11/1994	N
42	Lowry Ave N & James Ave N	Y	4/3/1987	N
43	W 50 St & Chowen Ave S	Y	4/14/1980	Y
50	Lyndale Ave S & W 50 St	Y	1/28/1988	Y
51	Lyndale Ave S & W 24 St	Y	2/13/1984	Y
58	Lyndale Ave N & Dowling Ave	Y	12/20/1995	N
61	E 54 St & 12 Ave S	Y	10/3/1998	Y
64	Bloomington Ave & E 31 St	Y	12/15/1992	N
68	Lyndale Ave S & W 56 St	Y	10/3/1995	Y
75	Lowry Ave N & Penn Ave N	Y	12/5/1986	Y
82	University Ave NE & 20 Ave NE	Y	9/20/1993	Y
83	Cedar Ave & E 32 St	Y	5/7/1992	N
89	E 38 St & 3 Ave S	Y	7/10/1995	N
94	Lyndale Ave N & 24 Ave N	Y	11/10/1994	N
95	W Broadway & Emerson Ave N	Y	1/9/1997	N
97	Lowry Ave NE & 2 St NE	Y	7/10/1991	Y
98	Nicollet Ave & Franklin Ave	Y	8/23/1997	N
102	University Ave NE & 3 Ave NE	Y	7/16/1994	N
104	E Hennepin Ave & 15 Ave	Y	10/7/1999	N
109	E Lake St & 31 Ave S	Y	11/9/1962	N
111	Washington Ave S & 10 Ave S	Y	9/30/1999	N
115	E Lake St & 36 Ave S	Y	6/27/2003	Y
121	W 50 St & Xerxes Ave S	Y	4/14/1980	Y
122	W 50 St & Zenith Ave S	Y	9/4/1985	N
125	Chicago Ave & E 34 St	Y	6/16/1972	N
143	Bloomington Ave & E 38 St	Y	1/26/1993	N
144	4 Ave S & E 38 St	Y	11/18/1992	N
146	Lyndale Ave N & 42 Ave N	Y	5/1/1984	N
156	University Ave SE & 27 Ave SE	Y	5/17/1994	N
159	Chicago Ave & E 39 St	Y	11/3/1995	N
161	E Franklin Ave & 4 Ave S	Y	10/8/1994	N
162	Chicago Ave & E 38 St	Y	3/16/1995	Y
178	Hennepin Ave & W 31 St	Y	4/10/1995	N
183	Washington Ave SE & Ontario St	Y	9/3/1993	N
188	Penn Ave N & 42 Ave N	Y	1/8/1990	Y
189	Lyndale Ave N & 36 Ave N	Y	11/22/1995	N
211	W Broadway & Lyndale Ave N	Y	7/13/1995	N
215	Washington Ave SE & Oak St	Y	2/12/1992	N
216	Cedar Ave & E 38 St	Y	5/5/1988	Y
217	Cedar Ave & E Lake St	Y	6/12/1997	N
218	W 36 St & Hennepin Ave	Y	4/13/1992	N
219	Bloomington Ave & E 35 St	Y	1/21/1993	N
226	Fremont Ave N & 42 Ave N	Y	10/22/1998	N
233	Lyndale Ave N & Plymouth Ave	Y	10/21/1980	Y
234	Washington Ave S & 11 Ave S	Y	11/4/1998	N
236	E Franklin Ave & 3 Ave S	Y	1/28/1988	Y

237	10 Ave N & 5 St N	Y	6/9/1980	Y
243	E 46 St & 4 Ave S	Y	11/30/1990	Y
248	Penn Ave N & 26 Ave N	Y	12/19/1988	Y
254	E Franklin & Clinton Ave	Y	11/1/2002	Y
255	Fremont Ave N & 36 Ave N	Y	10/22/1998	N
259	Como Ave & 18 Ave SE	Y	8/7/1992	N
261	Nicollet Ave & 38 St	Y	5/29/2003	Y
262	Emerson Ave N & 24 Ave N	Y	10/15/1996	N
265	Lowry Ave N & 4 St N	Y	12/12/1975	N
270	Huron Blvd & Washington Ave SE	Y	7/2/1992	N
272	Washington Ave N & Lowry Ave N	Y	3/12/1981	Y
281	Nicollet Ave & 34 St	Y	5/31/2002	Y
296	Lyndale Ave N & 18 Ave N	Y	9/26/1991	N
298	W Franklin Ave & Dupont Ave S	Y	2/11/1987	N
308	Lowry Ave NE & Monroe St	Y	2/29/1988	Y
310	Lowry Ave NE & Washington St	Y	12/29/1995	N
313	W 50 St & Upton Ave S	Y	1/8/1993	N
315	Lyndale Ave N & 29 Ave N	Y	11/10/1994	N
333	Lyndale Ave S & W 46 St	Y	8/6/1981	Y
335	Central Ave NE & 14 Ave NE	Y	3/15/1994	N
342	E Lake St & 27 Ave S	Y	1/3/1995	Y
349	Lyndale Ave S & W 36 St	Y	7/14/1981	Y
354	Lyndale Ave N & 26 Ave N	Y	11/21/1994	N
355	Lyndale Ave S & W 33 St	Y	11/4/1976	N
356	W 36 St & Bryant Ave S	Y	4/8/2003	Y
369	26 Ave S & E 26 St	Y	8/17/1983	Y
373	Lyndale Ave S & W 31 St	Y	1/11/1989	Y
378	Nicollet Ave & 31 St	Y	2/25/1998	N
381	Lyndale Ave S & W Franklin Ave	Y	1/25/1995	N
382	Broadway St NE & Buchanan St	Y	6/27/1994	N
388	Upton Ave S & W 43 St	Y	7/30/1993	Y
412	Hennepin Ave & W 34 St	Y	9/6/1979	N
414	Nicollet Ave & 15 St	Y	3/11/1998	N
439	E Lake St & 22 Ave S	Y	12/3/1986	N
441	Dowling Ave & Emerson Ave N	Y	1/13/1982	N
443	Washington Ave N & 2 Ave N	Y	5/11/1998	N
446	Central Ave NE & 18 Ave NE	Y	8/22/1995	N
457	E Lake St & Stevens Ave	Y	2/4/1997	N
458	E Lake St & 3 Ave S	Y	3/10/1997	N
459	Cedar Ave & E 31 St	Y	8/26/1987	Y
467	Hennepin Ave & W 27 St	Y	5/21/1984	N
476	Lowry Ave N & Emerson Ave N	Y	12/5/1996	N
478	Stinson Pkwy & Lowry Ave NE	Y	9/21/1979	N
482	Plymouth Ave & Penn Ave N	Y	7/14/1994	Y
485	E Lake St & Bloomington Ave	Y	7/9/1997	N
486	Bloomington Ave & E 36 St	Y	6/2/1970	N
487	W 35 St & Bryant Ave S	Y	10/15/1981	Y

489	E Franklin Ave & Chicago Ave	Y	11/27/1978	Y
491	E Franklin Ave & 11 Ave S	Y	1/18/1989	Y
493	W Broadway & Washington Ave N	Y	10/19/1999	N
495	Hennepin Ave & Lagoon Ave	Y	2/20/1992	N
498	Broadway St & Central Ave NE	Y	7/1/1998	N
572	W 38 St & Pleasant Ave	Y	3/27/1985	N
573	E 38 St & 13 Ave S	Y	4/5/1988	N
576	Penn Ave N & Oak Park Ave	Y	8/27/1994	N
582	E 36 St & 4 Ave S	Y	9/23/1981	Y
588	University Ave NE & 17 Ave NE	Y	4/13/1989	N
590	W Lake St & W Dean Pkwy	Y	1/22/1992	N
592	W 50 St & Vincent Ave S	Y	2/1/1993	N
595	University Ave SE & 25 Ave SE	Y	7/1/1992	N
598	Bloomington Ave & E 42 St	Y	5/8/2003	Y
600	Broadway St NE & Washington St	Y	7/26/1991	Y
611	Oak St & Fulton St	Y	12/5/1989	N
623	E Lake St & 21 Ave S	Y	7/14/1997	N
634	Cedar Ave & E 34 St	Y	2/10/1989	N
639	Johnson St & 27 Ave NE	Y	2/20/1991	N
645	Hennepin Ave & 13 St	Y	6/8/1998	N
659	Lyndale Ave S & W 22 St	Y	7/22/1991	N
670	W Lake St & Bryant Ave S	Y	8/19/1996	N
674	E Lake St & 13 Ave S	Y	7/10/1997	N
735	3 Ave S & Washington Ave S	Y	3/29/1990	Y
736	3 Ave S & 2 St S	Y	5/5/2003	Y
738	Johnson St & 29 Ave NE	Y	2/6/1991	N
751	Chicago Ave & E 48 St	Y	9/2/1993	Y
783	E 46 St & 42 Ave S	Y	9/20/1972	N
803	E Lake St & 10 Ave S	Y	3/31/1997	N
806	E Lake St & 4 Ave S	Y	8/23/1996	N
807	Lyndale Ave N & 41 Ave N	Y	8/10/1999	N
808	E Lake St & 17 Ave S	Y	7/8/1997	N
809	Johnson St & 18 Ave NE	Y	11/18/1987	N
810	Lyndale Ave S & W 43 St	Y	5/1/1997	Y
812	Chicago Ave & E Lake St	Y	7/22/1996	N
813	W 50 St & James Ave S	Y	7/22/1996	N
820	Olson Mem Hwy & Penn Ave N	Y	9/20/1999	N
827	Chicago Ave & E 24 St	Y	5/28/1981	Y
831	Chicago Ave & E 36 St	Y	4/5/1990	Y
832	Chicago Ave & E 42 St	Y	11/12/1994	Y
838	Cedar Ave & Minnehaha Pkwy	Y	4/25/1988	N
840	Cedar Ave & E 26 St	Y	5/24/1989	Y
842	University Ave NE & 13 Ave NE	Y	5/24/1989	Y
846	Cedar Ave & E 35 St	Y	3/11/1988	Y
848	Lowry Ave NE & Johnson St	Y	12/18/1991	N
850	2 St NE & 8 Ave NE	Y	7/11/1995	N
851	Johnson St & 23 Ave NE	Y	7/30/1974	N

855	Marshall St & 13 Ave NE	Y	3/5/1981	Y
857	Cedar Ave & E 46 St	Y	7/16/1994	N
860	Lowry Ave & University Ave NE	Y	3/8/1951	N
861	Nicollet Ave & 46 St	Y	3/27/1981	Y
864	2 St NE & 13 Ave NE	Y	11/20/1970	N
865	E 36 St & 3 Ave S	Y	8/12/1983	Y
871	E Lake St & 44 Ave S	Y	10/8/1994	N
872	E Lake St & 33 Ave S	Y	5/28/2003	Y
873	E Lake St & 30 Ave S	Y	10/22/1986	N
875	Penn Ave S & W 58 St	Y	8/28/1996	N
877	University Ave NE & 5 Ave NE	Y	7/16/1994	N
882	Penn Ave S & W 54 St	Y	5/27/1994	Y
884	Central Ave NE & 28 Ave NE	Y	12/12/1994	N
885	Franklin Ave SE & Seymour Ave	Y	9/7/1950	N
886	Bloomington Ave & E 24 St	Y	11/16/1981	Y
890	Nicollet Ave & Diamond Lake Rd	Y	2/19/1993	N
892	34 Ave S & E 50 St	Y	5/14/2003	Y
895	Broadway St NE & Fillmore St	Y	12/29/1994	Y
896	W Broadway & 2 St N	Y	3/14/1990	Y
897	Lowry Ave N & 2 St N	Y	6/2/1986	Y
898	8 Ave NE & Marshall St	Y	9/26/1985	Y
900	University Ave NE & 8 Ave NE	Y	7/13/1996	Y
902	Penn Ave S & W 56 St	Y	12/22/1995	Y
905	Portland Ave & E 47 St	Y	12/21/1995	N
914	Lyndale Ave S & W 35 St	Y	1/9/1967	N
917	France Ave S & W 44 St	Y	4/9/1990	N
920	E 38 St & 28 Ave S	Y	3/23/1995	Y
923	E Lake St & Elliot Ave	Y	3/17/1997	N
931	Lowry Ave N & Russell Ave N	Y	3/17/1994	N
936	42 Ave S & E 42 St	Y	9/18/1971	N
938	E Franklin Ave & 22 Ave S	Y	7/11/1991	Y
940	Johnson St & 33 Ave NE	Y	12/21/1991	N
941	37 Ave NE & Johnson St	Y	9/2/1994	N
943	Penn Ave S & W 60 St	Y	6/10/1969	N
945	Fremont Ave N & Dowling Ave	Y	2/19/1999	N
951	Washington Ave N & 6 Ave N	Y	11/17/1994	N
966	Penn Ave N & Dowling Ave	Y	7/27/1994	Y
967	Lyndale Ave S & W 61 St	Y	10/6/1999	N
969	Golden Valley Rd & Russell Ave	Y	7/18/1972	N
980	28 Ave S & E 42 St	Y	4/18/1975	N
983	W 39 St & Sheridan Ave S	Y	8/13/1993	Y
987	Chicago Ave & E 54 St	Y	4/7/1987	Y
989	W 31 St & Pillsbury Ave	Y	6/4/1997	Y

A.2. Cross-Section Study Data

NUM	Year	Rel_A	TOT_A	DEV	Rel_ARt	TOT_ARt	TRT	D1	D2	LIGHTS
26	1999	2	4	15783	0.347	0.694	0	0	1	1
28	1999	0	1	10729	0.000	0.255	0	0	0	1
34	1999	2	2	14452	0.379	0.379	0	0	1	1
52	1999	5	7	17637	0.777	1.087	0	0	0	1
74	1999	0	1	19348	0.000	0.142	0	0	0	1
112	1999	0	1	5610	0.000	0.488	0	0	0	1
116	1999	1	2	12455	0.220	0.440	0	0	1	1
150	1999	3	6	9745	0.843	1.687	0	0	0	1
176	1999	4	5	8847	1.239	1.548	0	0	1	1
177	1999	1	1	15284	0.179	0.179	0	0	1	1
203	1999	21	24	29949	1.921	2.195	0	1	0	1
227	1999	0	3	7606	0.000	1.081	0	0	0	1
231	1999	1	1	15767	0.174	0.174	0	0	1	1
267	1999	5	6	15545	0.881	1.057	0	0	0	1
268	1999	4	4	24559	0.446	0.446	0	1	0	1
299	1999	0	0	2108	0.000	0.000	0	0	0	0
339	1999	4	4	27267	0.402	0.402	0	1	0	1
345	1999	1	2	10933	0.251	0.501	0	0	1	1
361	1999	2	2	9127	0.600	0.600	0	0	0	1
368	1999	0	1	14945	0.000	0.183	0	0	1	1
389	1999	0	3	4840	0.000	1.698	0	0	0	1
463	1999	5	7	15925	0.860	1.204	0	0	1	1
468	1999	0	1	11837	0.000	0.231	0	0	1	1
469	1999	1	2	10173	0.269	0.539	0	0	1	1
490	1999	1	1	7654	0.358	0.358	0	0	0	1
497	1999	3	3	10649	0.772	0.772	0	0	0	1
499	1999	1	2	19442	0.141	0.282	0	0	1	1
577	1999	1	1	12963	0.211	0.211	0	0	1	1
791	1999	0	0	15593	0.000	0.000	0	0	0	1
797	1999	5	13	16486	0.831	2.160	0	1	0	1
837	1999	0	1	16290	0.000	0.168	0	0	0	1
841	1999	8	10	21868	1.002	1.253	0	0	0	1
870	1999	1	1	4564	0.600	0.600	0	0	1	1
919	1999	2	3	5990	0.915	1.372	0	0	0	1
942	1999	1	2	3681	0.744	1.489	0	0	0	0
970	1999	0	0	9660	0.000	0.000	0	0	0	0
975	1999	0	0	8938	0.000	0.000	0	0	0	0
981	1999	3	4	7670	1.072	1.429	0	0	0	1
26	2000	3	4	16051	0.512	0.683	0	0	1	1
28	2000	2	3	10911	0.502	0.753	0	0	0	1
34	2000	0	1	14697	0.000	0.186	0	0	1	1
52	2000	6	9	17936	0.916	1.375	0	0	0	1
74	2000	2	3	19677	0.278	0.418	0	0	0	1
112	2000	1	1	5705	0.480	0.480	0	0	0	1

116	2000	2	3	12666	0.433	0.649	0	0	1	1
150	2000	4	5	9911	1.106	1.382	0	0	0	1
176	2000	2	5	8997	0.609	1.523	0	0	1	1
177	2000	2	5	15543	0.353	0.881	0	0	1	1
203	2000	17	21	30458	1.529	1.889	0	1	0	1
227	2000	2	4	7735	0.708	1.417	0	0	0	1
231	2000	1	1	16035	0.171	0.171	0	0	1	1
267	2000	3	3	15809	0.520	0.520	0	0	0	1
268	2000	1	2	24976	0.110	0.219	0	1	0	1
299	2000	0	1	2144	0.000	1.278	0	0	0	0
339	2000	2	2	27729	0.198	0.198	0	1	0	1
345	2000	1	1	11118	0.246	0.246	0	0	1	1
361	2000	1	3	9282	0.295	0.885	0	0	0	1
368	2000	2	2	15199	0.361	0.361	0	0	1	1
389	2000	1	2	4922	0.557	1.113	0	0	0	1
463	2000	1	4	16196	0.169	0.677	0	0	1	1
468	2000	1	4	12038	0.228	0.910	0	0	1	1
469	2000	2	2	10346	0.530	0.530	0	0	1	1
490	2000	0	0	7784	0.000	0.000	0	0	0	1
497	2000	4	4	10829	1.012	1.012	0	0	0	1
499	2000	3	5	19771	0.416	0.693	0	0	1	1
577	2000	1	3	13183	0.208	0.623	0	0	1	1
791	2000	3	4	15857	0.518	0.691	0	0	0	1
797	2000	4	8	16765	0.654	1.307	0	1	0	1
837	2000	2	5	16566	0.331	0.827	0	0	0	1
841	2000	5	7	22239	0.616	0.862	0	0	0	1
870	2000	1	1	4641	0.590	0.590	0	0	1	1
919	2000	0	2	6092	0.000	0.900	0	0	0	1
942	2000	2	2	3743	1.464	1.464	0	0	0	0
970	2000	0	0	9824	0.000	0.000	0	0	0	0
975	2000	0	0	9090	0.000	0.000	0	0	0	0
981	2000	2	4	7800	0.702	1.405	0	0	0	1
26	2001	1	2	16323	0.168	0.336	0	0	1	1
28	2001	1	1	11096	0.247	0.247	0	0	0	1
34	2001	2	3	14946	0.367	0.550	0	0	1	1
52	2001	3	9	18240	0.451	1.352	0	0	0	1
74	2001	1	6	20010	0.137	0.821	0	0	0	1
112	2001	1	3	5802	0.472	1.417	0	0	0	1
116	2001	1	4	12881	0.213	0.851	0	0	1	1
150	2001	1	2	10079	0.272	0.544	0	0	0	1
176	2001	0	0	9150	0.000	0.000	0	0	1	1
177	2001	2	4	15807	0.347	0.693	0	0	1	1
203	2001	12	18	30974	1.061	1.592	0	1	0	1
227	2001	1	2	7867	0.348	0.697	0	0	0	1
231	2001	0	0	16307	0.000	0.000	0	0	1	1
267	2001	5	5	16077	0.852	0.852	0	0	0	1
268	2001	1	1	25400	0.108	0.108	0	1	0	1

299	2001	0	1	2180	0.000	1.257	0	0	0	0
339	2001	5	6	28200	0.486	0.583	0	1	0	1
345	2001	0	0	11307	0.000	0.000	0	0	1	1
361	2001	2	4	9440	0.580	1.161	0	0	0	1
368	2001	1	3	15457	0.177	0.532	0	0	1	1
389	2001	0	3	5006	0.000	1.642	0	0	0	1
463	2001	6	7	16470	0.998	1.164	0	0	1	1
468	2001	3	5	12242	0.671	1.119	0	0	1	1
469	2001	0	0	10521	0.000	0.000	0	0	1	1
490	2001	1	3	7916	0.346	1.038	0	0	0	1
497	2001	3	4	11013	0.746	0.995	0	0	0	1
499	2001	4	4	20107	0.545	0.545	0	0	1	1
577	2001	2	2	13407	0.409	0.409	0	0	1	1
791	2001	1	1	16126	0.170	0.170	0	0	0	1
797	2001	3	4	17050	0.482	0.643	0	1	0	1
837	2001	1	2	16847	0.163	0.325	0	0	0	1
841	2001	5	8	22616	0.606	0.969	0	0	0	1
870	2001	0	1	4720	0.000	0.580	0	0	1	1
919	2001	0	0	6195	0.000	0.000	0	0	0	1
942	2001	0	3	3807	0.000	2.159	0	0	0	0
970	2001	0	0	9990	0.000	0.000	0	0	0	0
975	2001	0	1	9244	0.000	0.296	0	0	0	0
981	2001	2	3	7933	0.691	1.036	0	0	0	1
26	2002	0	2	16600	0.000	0.330	0	0	1	1
28	2002	1	2	11284	0.243	0.486	0	0	0	1
34	2002	2	4	15200	0.360	0.721	0	0	1	1
52	2002	3	6	18550	0.443	0.886	0	0	0	1
74	2002	6	8	20350	0.808	1.077	0	0	0	1
112	2002	1	1	5900	0.464	0.464	0	0	0	1
116	2002	1	1	13100	0.209	0.209	0	0	1	1
150	2002	0	5	10250	0.000	1.336	0	0	0	1
176	2002	2	3	9305	0.589	0.883	0	0	1	1
177	2002	0	0	16075	0.000	0.000	0	0	1	1
203	2002	14	17	31500	1.218	1.479	0	1	0	1
227	2002	0	0	8000	0.000	0.000	0	0	0	1
231	2002	2	2	16584	0.330	0.330	0	0	1	1
267	2002	3	3	16350	0.503	0.503	0	0	0	1
268	2002	2	2	25831	0.212	0.212	0	1	0	1
299	2002	0	1	2217	0.000	1.236	0	0	0	0
339	2002	2	2	28679	0.191	0.191	0	1	0	1
345	2002	0	0	11499	0.000	0.000	0	0	1	1
361	2002	2	6	9600	0.571	1.712	0	0	0	1
368	2002	0	0	15719	0.000	0.000	0	0	1	1
389	2002	0	0	5090	0.000	0.000	0	0	0	1
463	2002	1	2	16750	0.164	0.327	0	0	1	1
468	2002	2	2	12450	0.440	0.440	0	0	1	1
469	2002	1	2	10700	0.256	0.512	0	0	1	1

490	2002	1	3	8050	0.340	1.021	0	0	0	1
497	2002	5	5	11200	1.223	1.223	0	0	0	1
499	2002	7	8	20448	0.938	1.072	0	0	1	1
577	2002	1	1	13635	0.201	0.201	0	0	1	1
791	2002	0	1	16400	0.000	0.167	0	0	0	1
797	2002	4	7	17339	0.632	1.106	0	1	0	1
837	2002	0	0	17133	0.000	0.000	0	0	0	1
841	2002	5	10	23000	0.596	1.191	0	0	0	1
870	2002	1	1	4800	0.571	0.571	0	0	1	1
919	2002	1	1	6300	0.435	0.435	0	0	0	1
942	2002	0	0	3872	0.000	0.000	0	0	0	0
970	2002	1	1	10160	0.270	0.270	0	0	0	0
975	2002	0	0	9401	0.000	0.000	0	0	0	0
981	2002	2	4	8067	0.679	1.358	0	0	0	1
43	1999	2	2	14514	0.378	0.378	1	0	0	1
51	1999	11	17	26812	1.124	1.737	1	0	1	1
75	1999	18	22	22336	2.208	2.699	1	1	0	1
109	1999	3	5	18160	0.453	0.754	1	0	1	1
121	1999	3	5	21535	0.382	0.636	1	0	0	0
125	1999	0	2	9072	0.000	0.604	1	0	0	1
233	1999	7	7	18758	1.022	1.022	1	1	0	1
237	1999	0	0	10449	0.000	0.000	1	0	0	0
265	1999	1	4	12577	0.218	0.871	1	0	1	1
272	1999	6	8	16147	1.018	1.357	1	1	0	1
298	1999	1	4	9057	0.302	1.210	1	0	0	1
349	1999	3	8	21107	0.389	1.038	1	0	1	1
355	1999	0	2	16156	0.000	0.339	1	0	1	1
412	1999	0	0	8652	0.000	0.000	1	0	1	1
439	1999	1	1	18081	0.152	0.152	1	0	1	1
441	1999	0	1	16834	0.000	0.163	1	0	1	1
459	1999	11	12	18350	1.642	1.792	1	0	0	0
467	1999	7	12	28042	0.684	1.172	1	0	1	1
478	1999	1	1	14939	0.183	0.183	1	1	0	1
486	1999	1	1	8082	0.339	0.339	1	0	1	1
572	1999	0	0	6859	0.000	0.000	1	0	0	1
582	1999	4	5	10268	1.067	1.334	1	0	0	1
783	1999	3	3	16543	0.497	0.497	1	0	0	1
809	1999	3	6	18903	0.435	0.870	1	1	0	1
851	1999	2	2	14462	0.379	0.379	1	0	0	1
855	1999	6	6	9344	1.759	1.759	1	0	0	1
860	1999	16	21	30312	1.446	1.898	1	1	0	1
861	1999	7	11	22058	0.869	1.366	1	1	0	1
864	1999	0	1	5366	0.000	0.511	1	0	0	1
865	1999	4	4	11885	0.922	0.922	1	0	0	1
873	1999	4	5	15134	0.724	0.905	1	0	1	1
886	1999	7	9	14452	1.327	1.706	1	0	0	1
897	1999	5	6	20933	0.654	0.785	1	1	0	1

898	1999	3	4	16534	0.497	0.663	1	0	0	1
914	1999	2	5	16686	0.328	0.821	1	0	1	1
943	1999	1	4	18112	0.151	0.605	1	0	0	1
969	1999	0	0	5712	0.000	0.000	1	0	1	1
980	1999	4	6	13406	0.817	1.226	1	0	0	1
43	2000	1	2	14761	0.186	0.371	1	0	0	1
51	2000	10	21	27267	1.005	2.110	1	0	1	1
75	2000	16	20	22715	1.930	2.412	1	1	0	1
109	2000	1	2	18468	0.148	0.297	1	0	1	1
121	2000	8	12	21900	1.001	1.501	1	0	0	0
125	2000	2	3	9226	0.594	0.891	1	0	0	1
233	2000	6	7	19076	0.862	1.005	1	1	0	1
237	2000	1	2	10627	0.258	0.516	1	0	0	0
265	2000	4	4	12790	0.857	0.857	1	0	1	1
272	2000	5	6	16421	0.834	1.001	1	1	0	1
298	2000	2	5	9211	0.595	1.487	1	0	0	1
349	2000	4	6	21465	0.511	0.766	1	0	1	1
355	2000	1	2	16431	0.167	0.333	1	0	1	1
412	2000	0	0	8799	0.000	0.000	1	0	1	1
439	2000	6	8	18388	0.894	1.192	1	0	1	1
441	2000	1	1	17119	0.160	0.160	1	0	1	1
459	2000	7	9	18661	1.028	1.321	1	0	0	0
467	2000	3	5	28518	0.288	0.480	1	0	1	1
478	2000	3	3	15192	0.541	0.541	1	1	0	1
486	2000	1	2	8219	0.333	0.667	1	0	1	1
572	2000	0	0	6976	0.000	0.000	1	0	0	1
582	2000	3	6	10443	0.787	1.574	1	0	0	1
783	2000	2	3	16824	0.326	0.489	1	0	0	1
809	2000	2	5	19224	0.285	0.713	1	1	0	1
851	2000	3	3	14707	0.559	0.559	1	0	0	1
855	2000	4	4	9503	1.153	1.153	1	0	0	1
860	2000	13	17	30827	1.155	1.511	1	1	0	1
861	2000	9	11	22432	1.099	1.343	1	1	0	1
864	2000	0	1	5457	0.000	0.502	1	0	0	1
865	2000	7	7	12086	1.587	1.587	1	0	0	1
873	2000	0	3	15391	0.000	0.534	1	0	1	1
886	2000	8	12	14697	1.491	2.237	1	0	0	1
897	2000	6	8	21289	0.772	1.030	1	1	0	1
898	2000	4	5	16815	0.652	0.815	1	0	0	1
914	2000	5	6	16969	0.807	0.969	1	0	1	1
943	2000	0	0	18420	0.000	0.000	1	0	0	1
969	2000	0	3	5808	0.000	1.415	1	0	1	1
980	2000	3	7	13633	0.603	1.407	1	0	0	1
43	2001	4	4	15011	0.730	0.730	1	0	0	1
51	2001	11	17	27729	1.087	1.680	1	0	1	1
75	2001	13	16	23100	1.542	1.898	1	1	0	1
109	2001	2	4	18781	0.292	0.584	1	0	1	1

121	2001	1	3	22272	0.123	0.369	1	0	0	0
125	2001	2	3	9383	0.584	0.876	1	0	0	1
233	2001	9	10	19400	1.271	1.412	1	1	0	1
237	2001	0	1	10807	0.000	0.254	1	0	0	0
265	2001	1	3	13007	0.211	0.632	1	0	1	1
272	2001	7	7	16700	1.148	1.148	1	1	0	1
298	2001	1	2	9367	0.292	0.585	1	0	0	1
349	2001	1	1	21830	0.126	0.126	1	0	1	1
355	2001	0	5	16709	0.000	0.820	1	0	1	1
412	2001	1	3	8948	0.306	0.919	1	0	1	1
439	2001	10	12	18700	1.465	1.758	1	0	1	1
441	2001	1	3	17410	0.157	0.472	1	0	1	1
459	2001	11	13	18978	1.588	1.877	1	0	0	0
467	2001	6	12	29002	0.567	1.134	1	0	1	1
478	2001	1	1	15450	0.177	0.177	1	1	0	1
486	2001	1	2	8358	0.328	0.656	1	0	1	1
572	2001	0	0	7094	0.000	0.000	1	0	0	1
582	2001	6	7	10620	1.548	1.806	1	0	0	1
783	2001	2	3	17110	0.320	0.480	1	0	0	1
809	2001	2	4	19550	0.280	0.561	1	1	0	1
851	2001	1	1	14957	0.183	0.183	1	0	0	1
855	2001	0	1	9664	0.000	0.283	1	0	0	1
860	2001	21	23	31350	1.835	2.010	1	1	0	1
861	2001	9	13	22813	1.081	1.561	1	1	0	1
864	2001	1	3	5550	0.494	1.481	1	0	0	1
865	2001	6	9	12291	1.337	2.006	1	0	0	1
873	2001	4	5	15652	0.700	0.875	1	0	1	1
886	2001	4	6	14946	0.733	1.100	1	0	0	1
897	2001	4	8	21650	0.506	1.012	1	1	0	1
898	2001	1	2	17100	0.160	0.320	1	0	0	1
914	2001	6	6	17257	0.953	0.953	1	0	1	1
943	2001	2	3	18732	0.293	0.439	1	0	0	1
969	2001	0	1	5907	0.000	0.464	1	0	1	1
980	2001	4	7	13865	0.790	1.383	1	0	0	1
43	2002	1	3	15266	0.179	0.538	1	0	0	1
51	2002	10	19	28200	0.972	1.846	1	0	1	1
75	2002	14	16	23492	1.633	1.866	1	1	0	1
109	2002	6	8	19100	0.861	1.148	1	0	1	1
121	2002	1	4	22650	0.121	0.484	1	0	0	0
125	2002	3	4	9542	0.861	1.148	1	0	0	1
233	2002	7	10	19729	0.972	1.389	1	1	0	1
237	2002	0	0	10990	0.000	0.000	1	0	0	0
265	2002	1	1	13228	0.207	0.207	1	0	1	1
272	2002	7	10	16983	1.129	1.613	1	1	0	1
298	2002	0	0	9526	0.000	0.000	1	0	0	1
349	2002	8	8	22200	0.987	0.987	1	0	1	1
355	2002	2	4	16993	0.322	0.645	1	0	1	1

412	**2002**	**3**	**4**	**9100**	**0.903**	**1.204**	**1**	**0**	**1**	**1**
439	**2002**	**6**	**7**	**19017**	**0.864**	**1.008**	**1**	**0**	**1**	**1**
441	**2002**	**2**	**4**	**17705**	**0.309**	**0.619**	**1**	**0**	**1**	**1**
459	**2002**	**8**	**12**	**19300**	**1.136**	**1.703**	**1**	**0**	**0**	**0**
467	**2002**	**4**	**5**	**29494**	**0.372**	**0.464**	**1**	**0**	**1**	**1**
478	**2002**	**2**	**2**	**15712**	**0.349**	**0.349**	**1**	**1**	**0**	**1**
486	**2002**	**1**	**4**	**8500**	**0.322**	**1.289**	**1**	**0**	**1**	**1**
572	**2002**	**1**	**1**	**7214**	**0.380**	**0.380**	**1**	**0**	**0**	**1**
582	**2002**	**4**	**5**	**10800**	**1.015**	**1.268**	**1**	**0**	**0**	**1**
783	**2002**	**2**	**2**	**17400**	**0.315**	**0.315**	**1**	**0**	**0**	**1**
809	**2002**	**6**	**6**	**19882**	**0.827**	**0.827**	**1**	**1**	**0**	**1**
851	**2002**	**8**	**8**	**15211**	**1.441**	**1.441**	**1**	**0**	**0**	**1**
855	**2002**	**3**	**4**	**9828**	**0.836**	**1.115**	**1**	**0**	**0**	**1**
860	**2002**	**14**	**20**	**31882**	**1.203**	**1.719**	**1**	**1**	**0**	**1**
861	**2002**	**6**	**9**	**23200**	**0.709**	**1.063**	**1**	**1**	**0**	**1**
864	**2002**	**2**	**2**	**5644**	**0.971**	**0.971**	**1**	**0**	**0**	**1**
865	**2002**	**1**	**3**	**12500**	**0.219**	**0.658**	**1**	**0**	**0**	**1**
873	**2002**	**1**	**2**	**15917**	**0.172**	**0.344**	**1**	**0**	**1**	**1**
886	**2002**	**5**	**7**	**15200**	**0.901**	**1.262**	**1**	**0**	**0**	**1**
897	**2002**	**5**	**7**	**22017**	**0.622**	**0.871**	**1**	**1**	**0**	**1**
898	**2002**	**4**	**5**	**17390**	**0.630**	**0.788**	**1**	**0**	**0**	**1**
914	**2002**	**6**	**8**	**17550**	**0.937**	**1.249**	**1**	**0**	**1**	**1**
943	**2002**	**1**	**2**	**19050**	**0.144**	**0.288**	**1**	**0**	**0**	**1**
969	**2002**	**0**	**0**	**6007**	**0.000**	**0.000**	**1**	**0**	**1**	**1**
980	**2002**	**2**	**2**	**14100**	**0.389**	**0.389**	**1**	**0**	**0**	**1**

A.3. Before-and-after Study Data

NUM	B&A	DEV	Rel_A	Rel_ARt	TOT_A	TOT_ARt	TRT	D1	D2	LIGHTS
989	-5	11735	0	0.000	2	0.000	0	0	0	1
810	-5	11569	0	0.000	0	0.000	0	0	0	1
900	-5	13408	3	0.613	5	0.613	0	0	0	1
902	-5	7845	0	0.000	0	0.000	0	0	0	1
5	-5	11685	1	0.235	2	0.234	0	0	0	1
68	-5	14954	3	0.550	3	0.550	0	0	1	1
920	-5	11930	4	0.919	6	0.919	0	0	0	1
162	-5	13851	4	0.791	7	0.791	0	0	0	1
342	-5	16833	2	0.326	4	0.326	0	1	0	1
895	-5	14224	1	0.193	2	0.193	0	0	1	1
832	-5	10647	2	0.515	3	0.515	0	0	0	0
966	-5	12911	5	1.061	10	1.061	0	0	1	1
482	-5	18508	5	0.740	6	0.740	0	0	1	1
882	-5	10847	1	0.253	1	0.253	0	0	0	1
82	-5	11898	3	0.691	4	0.691	0	0	0	1
751	-5	6335	1	0.433	2	0.432	0	0	1	1
983	-5	9797	2	0.559	4	0.559	0	0	0	1
388	-5	8018	1	0.342	1	0.342	0	0	0	1
2	-5	11689	1	0.234	2	0.234	0	0	1	1
600	-5	14684	1	0.187	1	0.187	0	0	1	1
938	-5	9257	3	0.888	5	0.888	0	0	1	1
97	-5	12547	8	1.747	8	1.747	0	0	1	1
989	-4	11934	0	0.000	1	0.000	0	0	0	1
810	-4	11765	0	0.000	0	0.000	0	0	0	1
900	-4	13635	3	0.603	3	0.603	0	0	0	1
902	-4	7978	1	0.343	2	0.343	0	0	0	1
5	-4	11884	1	0.231	1	0.231	0	0	0	1
68	-4	15208	0	0.000	1	0.000	0	0	1	1
920	-4	12133	1	0.226	3	0.226	0	0	0	1
162	-4	14086	4	0.778	4	0.778	0	0	0	1
342	-4	17119	4	0.640	5	0.640	0	1	0	1
895	-4	14466	2	0.379	3	0.379	0	0	1	1
832	-4	10827	4	1.012	6	1.012	0	0	0	0
966	-4	13130	3	0.626	6	0.626	0	0	1	1
482	-4	18823	11	1.601	13	1.601	0	0	1	1
882	-4	11032	1	0.248	1	0.248	0	0	0	1
82	-4	12100	2	0.453	3	0.453	0	0	0	1
751	-4	6442	2	0.851	2	0.851	0	0	1	1
983	-4	9964	0	0.000	0	0.000	0	0	0	1
388	-4	8154	4	1.344	4	1.344	0	0	0	1
2	-4	11887	4	0.922	6	0.922	0	0	1	1
600	-4	14933	3	0.550	5	0.550	0	0	1	1
938	-4	9414	0	0.000	1	0.000	0	0	1	1
97	-4	12760	2	0.429	4	0.429	0	0	1	1

989	-3	12136	0	0.000	5	0.000	0	0	0	1
810	-3	11965	0	0.000	1	0.000	0	0	0	1
900	-3	13867	7	1.383	8	1.383	0	0	0	1
902	-3	8113	1	0.338	1	0.338	0	0	0	1
5	-3	12085	0	0.000	0	0.000	0	0	0	1
68	-3	15466	2	0.354	2	0.354	0	0	1	1
920	-3	12339	0	0.000	2	0.000	0	0	0	1
162	-3	14325	5	0.956	7	0.956	0	0	0	1
342	-3	17409	2	0.315	4	0.315	0	1	0	1
895	-3	14711	2	0.373	2	0.372	0	0	1	1
832	-3	11011	2	0.498	2	0.498	0	0	0	0
966	-3	13353	3	0.616	7	0.616	0	0	1	1
482	-3	19142	12	1.718	14	1.718	0	0	1	1
882	-3	11219	0	0.000	3	0.000	0	0	0	1
82	-3	12305	4	0.891	5	0.891	0	0	0	1
751	-3	6551	3	1.255	5	1.255	0	0	1	1
983	-3	10133	0	0.000	1	0.000	0	0	0	1
388	-3	8292	0	0.000	3	0.000	0	0	0	1
2	-3	12089	2	0.453	4	0.453	0	0	1	1
600	-3	15186	5	0.902	6	0.902	0	0	1	1
938	-3	9574	1	0.286	1	0.286	0	0	1	1
97	-3	12977	7	1.478	9	1.478	0	0	1	1
989	-2	12342	3	0.666	5	0.666	0	0	0	1
810	-2	12168	2	0.450	3	0.450	0	0	0	1
900	-2	14102	5	0.971	7	0.971	0	0	0	1
902	-2	8251	3	0.996	4	0.996	0	0	0	1
5	-2	12290	3	0.669	3	0.669	0	0	0	1
68	-2	15728	2	0.348	2	0.348	0	0	1	1
920	-2	12548	4	0.873	5	0.873	0	0	0	1
162	-2	14568	12	2.257	16	2.257	0	0	0	1
342	-2	17705	3	0.464	4	0.464	0	1	0	1
895	-2	14961	1	0.183	2	0.183	0	0	1	1
832	-2	11198	2	0.489	3	0.489	0	0	0	0
966	-2	13580	8	1.614	10	1.614	0	0	1	1
482	-2	19467	6	0.844	8	0.844	0	0	1	1
882	-2	11409	2	0.480	3	0.480	0	0	0	1
82	-2	12514	0	0.000	2	0.000	0	0	0	1
751	-2	6663	0	0.000	2	0.000	0	0	1	1
983	-2	10305	2	0.532	3	0.532	0	0	0	1
388	-2	8433	0	0.000	0	0.000	0	0	0	1
2	-2	12294	1	0.223	1	0.223	0	0	1	1
600	-2	15444	2	0.355	3	0.355	0	0	1	1
938	-2	9736	1	0.281	2	0.281	0	0	1	1
97	-2	13197	5	1.038	5	1.038	0	0	1	1
989	-1	12552	1	0.218	2	0.218	0	0	0	1
810	-1	12375	1	0.221	1	0.221	0	0	0	1
900	-1	14341	8	1.528	8	1.528	0	0	0	1

902	-1	8391	1	0.327	3	0.327	0	0	0	1
5	-1	12499	0	0.000	0	0.000	0	0	0	1
68	-1	15995	3	0.514	3	0.514	0	0	1	1
920	-1	12761	4	0.859	5	0.859	0	0	0	1
162	-1	14815	5	0.925	9	0.925	0	0	0	1
342	-1	18005	9	1.370	10	1.369	0	1	0	1
895	-1	15215	3	0.540	5	0.540	0	0	1	1
832	-1	11388	3	0.722	3	0.722	0	0	0	0
966	-1	13810	7	1.389	11	1.389	0	0	1	1
482	-1	19797	8	1.107	13	1.107	0	0	1	1
882	-1	11603	1	0.236	2	0.236	0	0	0	1
82	-1	12726	3	0.646	5	0.646	0	0	0	1
751	-1	6776	4	1.617	5	1.617	0	0	1	1
983	-1	10479	0	0.000	2	0.000	0	0	0	1
388	-1	8576	0	0.000	2	0.000	0	0	0	1
2	-1	12502	1	0.219	2	0.219	0	0	1	1
600	-1	15706	1	0.174	2	0.174	0	0	1	1
938	-1	9902	0	0.000	3	0.000	0	0	1	1
97	-1	13421	2	0.408	3	0.408	0	0	1	1
989	0	12765	5	1.073	6	1.073	0/1	0	0	1
810	0	12585	0	0.000	0	0.000	0/1	0	0	1
900	0	14585	9	1.691	11	1.691	0/1	0	0	1
902	0	8533	0	0.000	0	0.000	0/1	0	0	1
5	0	12711	0	0.000	0	0.000	0/1	0	0	1
68	0	16266	2	0.337	3	0.337	0/1	0	1	1
920	0	12978	1	0.211	4	0.211	0/1	0	0	1
162	0	15067	6	1.091	8	1.091	0/1	0	0	1
342	0	18311	4	0.599	4	0.598	0/1	1	0	1
895	0	15473	5	0.885	6	0.885	0/1	0	1	1
832	0	11581	4	0.946	7	0.946	0/1	0	0	0
966	0	14044	7	1.366	9	1.366	0/1	0	1	1
482	0	20133	6	0.817	8	0.816	0/1	0	1	1
882	0	11800	2	0.464	4	0.464	0/1	0	0	1
82	0	12942	2	0.423	4	0.423	0/1	0	0	1
751	0	6891	2	0.795	2	0.795	0/1	0	1	1
983	0	10657	1	0.257	3	0.257	0/1	0	0	1
388	0	8722	0	0.000	1	0.000	0/1	0	0	1
2	0	12715	0	0.000	1	0.000	0/1	0	1	1
600	0	15973	7	1.201	8	1.201	0/1	0	1	1
938	0	10070	2	0.544	2	0.544	0/1	0	1	1
97	0	13649	8	1.606	9	1.606	0/1	0	1	1
989	1	12981	2	0.422	4	0.422	1	0	0	1
810	1	12798	0	0.000	0	0.000	1	0	0	1
900	1	14832	4	0.739	5	0.739	1	0	0	1
902	1	8678	1	0.316	1	0.316	1	0	0	1
5	1	12927	1	0.212	1	0.212	1	0	0	1
68	1	16543	3	0.497	3	0.497	1	0	1	1

920	1	13198	0	0.000	0	0.000	1	0	0	1
162	1	15322	4	0.715	7	0.715	1	0	0	1
342	1	18622	5	0.736	7	0.736	1	1	0	1
895	1	15735	1	0.174	3	0.174	1	0	1	1
832	1	11778	2	0.465	2	0.465	1	0	0	0
966	1	14283	9	1.726	10	1.726	1	0	1	1
482	1	20475	8	1.071	8	1.070	1	0	1	1
882	1	12000	1	0.228	2	0.228	1	0	0	1
82	1	13162	1	0.208	2	0.208	1	0	0	1
751	1	7007	1	0.391	2	0.391	1	0	1	1
983	1	10838	1	0.253	1	0.253	1	0	0	1
388	1	8870	0	0.000	2	0.000	1	0	0	1
2	1	12930	1	0.212	2	0.212	1	0	1	1
600	1	16244	2	0.337	4	0.337	1	0	1	1
938	1	10241	0	0.000	4	0.000	1	0	1	1
97	1	13880	2	0.395	2	0.395	1	0	1	1
989	2	13201	4	0.830	7	0.830	1	0	0	1
810	2	13015	0	0.000	0	0.000	1	0	0	1
900	2	15084	5	0.908	5	0.908	1	0	0	1
902	2	8825	1	0.310	1	0.310	1	0	0	1
5	2	13146	0	0.000	0	0.000	1	0	0	1
68	2	16823	2	0.326	3	0.326	1	0	1	1
920	2	13422	4	0.817	10	0.816	1	0	0	1
162	2	15582	3	0.528	11	0.527	1	0	0	1
342	2	18938	2	0.289	8	0.289	1	1	0	1
895	2	16002	1	0.171	2	0.171	1	0	1	1
832	2	11978	2	0.458	3	0.457	1	0	0	0
966	2	14525	8	1.509	10	1.509	1	0	1	1
482	2	20822	6	0.790	10	0.789	1	0	1	1
882	2	12204	3	0.674	4	0.673	1	0	0	1
82	2	13385	2	0.409	4	0.409	1	0	0	1
751	2	7126	2	0.769	4	0.769	1	0	1	1
983	2	11022	1	0.249	1	0.249	1	0	0	1
388	2	9020	0	0.000	3	0.000	1	0	0	1
2	2	13150	1	0.208	2	0.208	1	0	1	1
600	2	16519	5	0.829	9	0.829	1	0	1	1
938	2	10414	1	0.263	1	0.263	1	0	1	1
97	2	14116	2	0.388	3	0.388	1	0	1	1
989	3	13426	1	0.204	5	0.204	1	0	0	1
810	3	13236	0	0.000	0	0.000	1	0	0	1
900	3	15340	9	1.607	9	1.607	1	0	0	1
902	3	8975	0	0.000	0	0.000	1	0	0	1
5	3	13369	0	0.000	0	0.000	1	0	0	1
68	3	17109	2	0.320	5	0.320	1	0	1	1
920	3	13650	1	0.201	2	0.201	1	0	0	1
162	3	15847	8	1.383	12	1.383	1	0	0	1
342	3	19259	5	0.711	8	0.711	1	1	0	1

895	3	16274	12	2.020	1	2.020	1	0	1	1
832	3	12181	2	0.450	2	0.450	1	0	0	0
966	3	14771	6	1.113	8	1.113	1	0	1	1
482	3	21176	12	1.553	15	1.553	1	0	1	1
882	3	12411	2	0.442	3	0.441	1	0	0	1
82	3	13612	1	0.201	5	0.201	1	0	0	1
751	3	7247	1	0.378	5	0.378	1	0	1	1
983	3	11209	0	0.000	0	0.000	1	0	0	1
388	3	9173	1	0.299	2	0.299	1	0	0	1
2	3	13373	2	0.410	2	0.410	1	0	1	1
600	3	16800	3	0.489	4	0.489	1	0	1	1
938	3	10591	1	0.259	1	0.259	1	0	1	1
97	3	14355	9	1.718	9	1.718	1	0	1	1
989	4	13653	0	0.000	4	0.000	1	0	0	1
810	4	13461	2	0.407	2	0.407	1	0	0	1
900	4	15600	4	0.703	4	0.702	1	0	0	1
902	4	9127	1	0.300	1	0.300	1	0	0	1
5	4	13596	1	0.202	1	0.202	1	0	0	1
68	4	17399	2	0.315	3	0.315	1	0	1	1
920	4	13881	4	0.790	6	0.789	1	0	0	1
162	4	16116	5	0.850	10	0.850	1	0	0	1
342	4	19586	4	0.560	5	0.560	1	1	0	1
895	4	16550	2	0.331	3	0.331	1	0	1	1
832	4	12387	3	0.664	4	0.664	1	0	0	0
966	4	15022	8	1.459	11	1.459	1	0	1	1
482	4	21535	6	0.763	8	0.763	1	0	1	1
882	4	12621	2	0.434	2	0.434	1	0	0	1
82	4	13843	2	0.396	3	0.396	1	0	0	1
751	4	7370	2	0.743	5	0.743	1	0	1	1
983	4	11399	0	0.000	0	0.000	1	0	0	1
388	4	9329	0	0.000	5	0.000	1	0	0	1
2	4	13600	1	0.202	2	0.201	1	0	1	1
600	4	17085	3	0.481	4	0.481	1	0	1	1
938	4	10771	3	0.763	5	0.763	1	0	1	1
97	4	14599	4	0.751	5	0.751	1	0	1	1
989	5	13885	3	0.197	3	0.592	1	0	0	1
810	5	13689	2	0.200	2	0.400	1	0	0	1
900	5	15865	5	0.864	5	0.863	1	0	0	1
902	5	9282	1	0.295	1	0.295	1	0	0	1
5	5	13827	0	0.000	0	0.000	1	0	0	1
68	5	17694	3	0.465	3	0.465	1	0	1	1
920	5	14117	3	0.194	3	0.582	1	0	0	1
162	5	16389	17	1.337	17	2.842	1	0	0	1
342	5	19918	8	0.825	8	1.100	1	1	0	1
895	5	16831	5	0.814	5	0.814	1	0	1	1
832	5	12598	4	0.652	4	0.870	1	0	0	0
966	5	15277	9	1.435	9	1.614	1	0	1	1

482	5	21900	15	1.501	15	1.877	1	0	1	1
882	5	12835	3	0.427	3	0.640	1	0	0	1
82	5	14078	2	0.389	2	0.389	1	0	0	1
751	5	7495	6	0.000	6	2.193	1	0	1	1
983	5	11593	0	0.000	0	0.000	1	0	0	1
388	5	9487	2	0.000	2	0.578	1	0	0	1
2	5	13831	2	0.198	2	0.396	1	0	1	1
600	5	17375	4	0.473	4	0.631	1	0	1	1
938	5	10954	5	0.500	5	1.251	1	0	1	1
97	5	14847	4	0.369	4	0.738	1	0	1	1
981	-5	6482	0	0.000	1	0.423	0	0	0	1
975	-5	7554	0	0.000	1	0.363	0	0	0	0
970	-5	8164	1	0.336	1	0.336	0	0	0	0
942	-5	3111	1	0.881	1	0.881	0	0	0	0
919	-5	5062	2	1.082	2	1.082	0	0	0	1
870	-5	3857	0	0.000	0	0.000	0	0	1	1
841	-5	18481	6	0.889	9	1.334	0	0	0	1
837	-5	13767	1	0.199	4	0.796	0	0	0	1
797	-5	13932	7	1.377	11	2.163	0	1	0	1
791	-5	13178	0	0.000	0	0.000	0	0	0	1
577	-5	10956	2	0.500	2	0.500	0	0	1	1
499	-5	16430	4	0.667	8	1.334	0	0	1	1
497	-5	8999	4	1.218	4	1.218	0	0	0	1
490	-5	6468	2	0.847	5	2.118	0	0	0	1
469	-5	8598	1	0.319	2	0.637	0	0	1	1
468	-5	10004	0	0.000	0	0.000	0	0	1	1
463	-5	13459	2	0.407	4	0.814	0	0	1	1
389	-5	4090	0	0.000	0	0.000	0	0	0	1
368	-5	12631	1	0.217	1	0.217	0	0	1	1
361	-5	7714	2	0.710	4	1.421	0	0	0	1
345	-5	9240	2	0.593	4	1.186	0	0	1	1
339	-5	23044	1	0.119	1	0.119	0	1	0	1
299	-5	1782	1	1.537	2	3.075	0	0	0	0
268	-5	20756	0	0.000	0	0.000	0	1	0	1
267	-5	13137	0	0.000	0	0.000	0	0	0	1
231	-5	13325	2	0.411	2	0.411	0	0	1	1
227	-5	6428	4	1.705	4	1.705	0	0	0	1
203	-5	25311	6	0.649	9	0.974	0	1	0	1
177	-5	12917	1	0.212	1	0.212	0	0	1	1
176	-5	7477	4	1.466	4	1.466	0	0	1	1
150	-5	8236	1	0.333	3	0.998	0	0	0	1
116	-5	10526	2	0.521	2	0.521	0	0	1	1
112	-5	4741	0	0.000	2	1.156	0	0	0	1
74	-5	16352	3	0.503	6	1.005	0	0	0	1
52	-5	14905	3	0.551	4	0.735	0	0	0	1
34	-5	12213	3	0.673	3	0.673	0	0	1	1
28	-5	9067	1	0.302	4	1.209	0	0	0	1

26	-5	13338	1	0.205	2	0.411	0	0	1	1
115	-5	12615	3	0.652	5	1.086	0	0	1	1
261	-5	15829	6	1.039	10	1.731	0	0	1	1
872	-5	11785	2	0.465	3	0.697	0	0	0	1
9	-5	9562	0	0.000	0	0.000	0	0	0	1
892	-5	8839	0	0.000	0	0.000	0	0	0	0
598	-5	10365	4	1.057	4	1.057	0	0	0	1
736	-5	18917	1	0.145	2	0.290	0	0	1	1
17	-5	10868	4	1.008	7	1.765	0	0	1	1
356	-5	9723	3	0.845	5	1.409	0	0	0	1
981	-4	6592	1	0.416	1	0.416	0	0	0	1
975	-4	7682	1	0.357	2	0.713	0	0	0	0
970	-4	8302	0	0.000	0	0.000	0	0	0	0
942	-4	3164	0	0.000	1	0.866	0	0	0	0
919	-4	5148	0	0.000	2	1.064	0	0	0	1
870	-4	3922	1	0.699	1	0.699	0	0	1	1
841	-4	18794	6	0.875	8	1.166	0	0	0	1
837	-4	14000	0	0.000	3	0.587	0	0	0	1
797	-4	14169	6	1.160	10	1.934	0	1	0	1
791	-4	13401	0	0.000	1	0.204	0	0	0	1
577	-4	11141	4	0.984	4	0.984	0	0	1	1
499	-4	16709	3	0.492	4	0.656	0	0	1	1
497	-4	9152	1	0.299	2	0.599	0	0	0	1
490	-4	6578	2	0.833	2	0.833	0	0	0	1
469	-4	8744	2	0.627	2	0.627	0	0	1	1
468	-4	10174	3	0.808	4	1.077	0	0	1	1
463	-4	13687	2	0.400	3	0.601	0	0	1	1
389	-4	4160	1	0.659	1	0.659	0	0	0	1
368	-4	12845	1	0.213	1	0.213	0	0	1	1
361	-4	7845	1	0.349	4	1.397	0	0	0	1
345	-4	9396	0	0.000	1	0.292	0	0	1	1
339	-4	23435	1	0.117	2	0.234	0	1	0	1
299	-4	1812	0	0.000	0	0.000	0	0	0	0
268	-4	21108	0	0.000	0	0.000	0	1	0	1
267	-4	13360	3	0.615	3	0.615	0	0	0	1
231	-4	13551	1	0.202	2	0.404	0	0	1	1
227	-4	6537	0	0.000	0	0.000	0	0	0	1
203	-4	25740	9	0.958	11	1.171	0	1	0	1
177	-4	13136	2	0.417	2	0.417	0	0	1	1
176	-4	7604	4	1.441	4	1.441	0	0	1	1
150	-4	8376	1	0.327	2	0.654	0	0	0	1
116	-4	10705	3	0.768	3	0.768	0	0	1	1
112	-4	4821	2	1.137	2	1.137	0	0	0	1
74	-4	16629	2	0.330	4	0.659	0	0	0	1
52	-4	15158	2	0.361	5	0.904	0	0	0	1
34	-4	12421	3	0.662	5	1.103	0	0	1	1
28	-4	9221	5	1.486	6	1.783	0	0	0	1

26	-4	13565	0	0.000	1	0.202	0	0	1	1
115	-4	12829	4	0.854	9	1.922	0	0	1	1
261	-4	16098	8	1.362	12	2.042	0	0	1	1
872	-4	11985	1	0.229	2	0.457	0	0	0	1
9	-4	9724	2	0.564	3	0.845	0	0	0	1
892	-4	8989	1	0.305	1	0.305	0	0	0	0
598	-4	10541	1	0.260	1	0.260	0	0	0	1
736	-4	19238	1	0.142	4	0.570	0	0	1	1
17	-4	11053	3	0.744	5	1.239	0	0	1	1
356	-4	9888	1	0.277	3	0.831	0	0	0	1
981	-3	6704	2	0.817	6	2.452	0	0	0	1
975	-3	7812	1	0.351	1	0.351	0	0	0	0
970	-3	8443	0	0.000	0	0.000	0	0	0	0
942	-3	3217	0	0.000	2	1.703	0	0	0	0
919	-3	5235	1	0.523	1	0.523	0	0	0	1
870	-3	3989	0	0.000	0	0.000	0	0	1	1
841	-3	19113	3	0.430	8	1.147	0	0	0	1
837	-3	14238	2	0.385	4	0.770	0	0	0	1
797	-3	14409	7	1.331	12	2.282	0	1	0	1
791	-3	13629	0	0.000	1	0.201	0	0	0	1
577	-3	11331	1	0.242	1	0.242	0	0	1	1
499	-3	16993	6	0.967	9	1.451	0	0	1	1
497	-3	9307	0	0.000	0	0.000	0	0	0	1
490	-3	6690	1	0.410	2	0.819	0	0	0	1
469	-3	8892	2	0.616	5	1.541	0	0	1	1
468	-3	10346	5	1.324	6	1.589	0	0	1	1
463	-3	13920	4	0.787	6	1.181	0	0	1	1
389	-3	4230	0	0.000	2	1.295	0	0	0	1
368	-3	13063	1	0.210	1	0.210	0	0	1	1
361	-3	7978	1	0.343	2	0.687	0	0	0	1
345	-3	9556	0	0.000	1	0.287	0	0	1	1
339	-3	23832	1	0.115	1	0.115	0	1	0	1
299	-3	1843	0	0.000	2	2.973	0	0	0	0
268	-3	21466	0	0.000	0	0.000	0	1	0	1
267	-3	13587	1	0.202	1	0.202	0	0	0	1
231	-3	13781	1	0.199	3	0.596	0	0	1	1
227	-3	6648	3	1.236	3	1.236	0	0	0	1
203	-3	26177	9	0.942	9	0.942	0	1	0	1
177	-3	13359	1	0.205	1	0.205	0	0	1	1
176	-3	7733	2	0.709	4	1.417	0	0	1	1
150	-3	8518	1	0.322	2	0.643	0	0	0	1
116	-3	10886	0	0.000	2	0.503	0	0	1	1
112	-3	4903	0	0.000	0	0.000	0	0	0	1
74	-3	16911	3	0.486	4	0.648	0	0	0	1
52	-3	15415	3	0.533	4	0.711	0	0	0	1
34	-3	12631	7	1.518	8	1.735	0	0	1	1
28	-3	9377	1	0.292	2	0.584	0	0	0	1

26	-3	13795	0	0.000	1	0.199	0	0	1	1
115	-3	13047	1	0.210	3	0.630	0	0	1	1
261	-3	16371	1	0.167	2	0.335	0	0	1	1
872	-3	12189	0	0.000	0	0.000	0	0	0	1
9	-3	9889	2	0.554	2	0.554	0	0	0	1
892	-3	9141	4	1.199	4	1.199	0	0	0	0
598	-3	10720	3	0.767	3	0.767	0	0	0	1
736	-3	19565	0	0.000	2	0.280	0	0	1	1
17	-3	11240	4	0.975	5	1.219	0	0	1	1
356	-3	10055	2	0.545	4	1.090	0	0	0	1
981	-2	6818	0	0.000	1	0.402	0	0	0	1
975	-2	7945	0	0.000	0	0.000	0	0	0	0
970	-2	8586	0	0.000	0	0.000	0	0	0	0
942	-2	3272	1	0.837	3	2.512	0	0	0	0
919	-2	5324	0	0.000	1	0.515	0	0	0	1
870	-2	4057	0	0.000	0	0.000	0	0	1	1
841	-2	19438	2	0.282	6	0.846	0	0	0	1
837	-2	14479	1	0.189	1	0.189	0	0	0	1
797	-2	14654	9	1.683	12	2.244	0	1	0	1
791	-2	13860	1	0.198	2	0.395	0	0	0	1
577	-2	11523	2	0.476	3	0.713	0	0	1	1
499	-2	17281	6	0.951	11	1.744	0	0	1	1
497	-2	9465	1	0.289	1	0.289	0	0	0	1
490	-2	6803	2	0.805	2	0.805	0	0	0	1
469	-2	9043	2	0.606	3	0.909	0	0	1	1
468	-2	10522	4	1.042	6	1.562	0	0	1	1
463	-2	14156	0	0.000	0	0.000	0	0	1	1
389	-2	4302	1	0.637	2	1.274	0	0	0	1
368	-2	13285	4	0.825	4	0.825	0	0	1	1
361	-2	8113	3	1.013	3	1.013	0	0	0	1
345	-2	9718	1	0.282	2	0.564	0	0	1	1
339	-2	24237	0	0.000	0	0.000	0	1	0	1
299	-2	1874	0	0.000	0	0.000	0	0	0	0
268	-2	21830	2	0.251	2	0.251	0	1	0	1
267	-2	13818	1	0.198	1	0.198	0	0	0	1
231	-2	14015	1	0.195	2	0.391	0	0	1	1
227	-2	6761	2	0.810	2	0.810	0	0	0	1
203	-2	26621	6	0.618	7	0.720	0	1	0	1
177	-2	13586	2	0.403	4	0.807	0	0	1	1
176	-2	7864	2	0.697	2	0.697	0	0	1	1
150	-2	8662	1	0.316	1	0.316	0	0	0	1
116	-2	11071	2	0.495	3	0.742	0	0	1	1
112	-2	4986	0	0.000	1	0.549	0	0	0	1
74	-2	17198	1	0.159	1	0.159	0	0	0	1
52	-2	15677	4	0.699	7	1.223	0	0	0	1
34	-2	12846	0	0.000	2	0.427	0	0	1	1
28	-2	9537	1	0.287	4	1.149	0	0	0	1

26	-2	14029	4	0.781	6	1.172	0	0	1	1
115	-2	13268	5	1.032	7	1.445	0	0	1	1
261	-2	16649	8	1.316	10	1.646	0	0	1	1
872	-2	12396	4	0.884	4	0.884	0	0	0	1
9	-2	10057	0	0.000	0	0.000	0	0	0	1
892	-2	9296	2	0.589	4	1.179	0	0	0	0
598	-2	10902	2	0.503	2	0.503	0	0	0	1
736	-2	19897	1	0.138	2	0.275	0	0	1	1
17	-2	11431	2	0.479	2	0.479	0	0	1	1
356	-2	10226	2	0.536	3	0.804	0	0	0	1
981	-1	6934	1	0.395	2	0.790	0	0	0	1
975	-1	8080	0	0.000	0	0.000	0	0	0	0
970	-1	8732	0	0.000	0	0.000	0	0	0	0
942	-1	3327	2	1.647	2	1.647	0	0	0	0
919	-1	5415	0	0.000	1	0.506	0	0	0	1
870	-1	4125	2	1.328	5	3.321	0	0	1	1
841	-1	19768	8	1.109	8	1.109	0	0	0	1
837	-1	14725	0	0.000	1	0.186	0	0	0	1
797	-1	14903	8	1.471	13	2.390	0	1	0	1
791	-1	14095	0	0.000	1	0.194	0	0	0	1
577	-1	11718	0	0.000	1	0.234	0	0	1	1
499	-1	17574	1	0.156	3	0.468	0	0	1	1
497	-1	9626	1	0.285	3	0.854	0	0	0	1
490	-1	6919	2	0.792	4	1.584	0	0	0	1
469	-1	9196	0	0.000	2	0.596	0	0	1	1
468	-1	10700	4	1.024	4	1.024	0	0	1	1
463	-1	14396	1	0.190	1	0.190	0	0	1	1
389	-1	4375	1	0.626	4	2.505	0	0	0	1
368	-1	13510	2	0.406	2	0.406	0	0	1	1
361	-1	8251	3	0.996	5	1.660	0	0	0	1
345	-1	9883	2	0.554	2	0.554	0	0	1	1
339	-1	24648	1	0.111	1	0.111	0	1	0	1
299	-1	1906	0	0.000	0	0.000	0	0	0	0
268	-1	22201	2	0.247	2	0.247	0	1	0	1
267	-1	14052	1	0.195	2	0.390	0	0	0	1
231	-1	14253	1	0.192	1	0.192	0	0	1	1
227	-1	6876	4	1.594	6	2.391	0	0	0	1
203	-1	27073	12	1.214	15	1.518	0	1	0	1
177	-1	13816	1	0.198	1	0.198	0	0	1	1
176	-1	7998	6	2.055	7	2.398	0	0	1	1
150	-1	8809	2	0.622	2	0.622	0	0	0	1
116	-1	11259	3	0.730	5	1.217	0	0	1	1
112	-1	5071	0	0.000	1	0.540	0	0	0	1
74	-1	17490	0	0.000	0	0.000	0	0	0	1
52	-1	15943	1	0.172	3	0.516	0	0	0	1
34	-1	13064	5	1.049	7	1.468	0	0	1	1
28	-1	9698	3	0.848	6	1.695	0	0	0	1

26	-1	14267	1	0.192	2	0.384	0	0	1	1
115	-1	13494	3	0.609	4	0.812	0	0	1	1
261	-1	16931	2	0.324	7	1.133	0	0	1	1
872	-1	12606	1	0.217	1	0.217	0	0	0	1
9	-1	10228	0	0.000	1	0.268	0	0	0	1
892	-1	9454	3	0.869	6	1.739	0	0	0	0
598	-1	11087	3	0.741	3	0.741	0	0	0	1
736	-1	20234	2	0.271	2	0.271	0	0	1	1
17	-1	11625	2	0.471	3	0.707	0	0	1	1
356	-1	10399	4	1.054	6	1.581	0	0	0	1
981	0	7051	1	0.389	2	0.777	0	0	0	1
975	0	8217	1	0.333	2	0.667	0	0	0	0
970	0	8880	0	0.000	0	0.000	0	0	0	0
942	0	3384	0	0.000	1	0.810	0	0	0	0
919	0	5506	0	0.000	0	0.000	0	0	0	1
870	0	4195	4	2.612	7	4.572	0	0	1	1
841	0	20103	4	0.545	8	1.090	0	0	0	1
837	0	14975	2	0.366	4	0.732	0	0	0	1
797	0	15155	9	1.627	12	2.169	0	1	0	1
791	0	14334	3	0.573	3	0.573	0	0	0	1
577	0	11917	2	0.460	2	0.460	0	0	1	1
499	0	17873	5	0.766	6	0.920	0	0	1	1
497	0	9789	2	0.560	4	1.120	0	0	0	1
490	0	7036	1	0.389	1	0.389	0	0	0	1
469	0	9352	2	0.586	2	0.586	0	0	1	1
468	0	10882	3	0.755	6	1.511	0	0	1	1
463	0	14640	1	0.187	2	0.374	0	0	1	1
389	0	4449	1	0.616	1	0.616	0	0	0	1
368	0	13739	2	0.399	3	0.598	0	0	1	1
361	0	8391	2	0.653	2	0.653	0	0	0	1
345	0	10051	2	0.545	2	0.545	0	0	1	1
339	0	25066	2	0.219	2	0.219	0	1	0	1
299	0	1938	0	0.000	1	1.414	0	0	0	0
268	0	22578	3	0.364	3	0.364	0	1	0	1
267	0	14291	0	0.000	3	0.575	0	0	0	1
231	0	14495	0	0.000	2	0.378	0	0	1	1
227	0	6992	1	0.392	1	0.392	0	0	0	1
203	0	27532	13	1.294	15	1.493	0	1	0	1
177	0	14051	3	0.585	3	0.585	0	0	1	1
176	0	8133	1	0.337	2	0.674	0	0	1	1
150	0	8959	2	0.612	2	0.612	0	0	0	1
116	0	11450	1	0.239	1	0.239	0	0	1	1
112	0	5157	0	0.000	1	0.531	0	0	0	1
74	0	17787	2	0.308	3	0.462	0	0	0	1
52	0	16214	2	0.338	5	0.845	0	0	0	1
34	0	13286	2	0.412	3	0.619	0	0	1	1
28	0	9863	1	0.278	1	0.278	0	0	0	1

26	0	14509	2	0.378	4	0.755	0	0	1	1
115	0	13723	6	1.198	11	2.196	0	0	1	1
261	0	17219	0	0.000	1	0.159	0	0	1	1
872	0	12820	0	0.000	1	0.214	0	0	0	1
9	0	10401	1	0.263	1	0.263	0	0	0	1
892	0	9615	2	0.570	4	1.140	0	0	0	0
598	0	11275	2	0.486	2	0.486	0	0	0	1
736	0	20578	4	0.533	6	0.799	0	0	1	1
17	0	11822	2	0.464	3	0.695	0	0	1	1
356	0	10576	3	0.777	3	0.777	0	0	0	1
981	1	7171	0	0.000	1	0.382	0	0	0	1
975	1	8356	1	0.328	1	0.328	0	0	0	0
970	1	9031	0	0.000	0	0.000	0	0	0	0
942	1	3441	0	0.000	0	0.000	0	0	0	0
919	1	5600	0	0.000	1	0.489	0	0	0	1
870	1	4267	2	1.284	6	3.852	0	0	1	1
841	1	20444	8	1.072	10	1.340	0	0	0	1
837	1	15229	1	0.180	5	0.900	0	0	0	1
797	1	15413	11	1.955	17	3.022	0	1	0	1
791	1	14578	2	0.376	2	0.376	0	0	0	1
577	1	12119	2	0.452	3	0.678	0	0	1	1
499	1	18176	6	0.904	10	1.507	0	0	1	1
497	1	9955	2	0.550	4	1.101	0	0	0	1
490	1	7155	1	0.383	1	0.383	0	0	0	1
469	1	9511	2	0.576	3	0.864	0	0	1	1
468	1	11067	3	0.743	3	0.743	0	0	1	1
463	1	14889	2	0.368	3	0.552	0	0	1	1
389	1	4525	1	0.605	3	1.816	0	0	0	1
368	1	13972	0	0.000	0	0.000	0	0	1	1
361	1	8533	1	0.321	1	0.321	0	0	0	1
345	1	10221	3	0.804	3	0.804	0	0	1	1
339	1	25492	2	0.215	3	0.322	0	1	0	1
299	1	1971	0	0.000	1	1.390	0	0	0	0
268	1	22961	1	0.119	1	0.119	0	1	0	1
267	1	14533	2	0.377	2	0.377	0	0	0	1
231	1	14741	0	0.000	1	0.186	0	0	1	1
227	1	7111	3	1.156	4	1.541	0	0	0	1
203	1	28000	5	0.489	7	0.685	0	1	0	1
177	1	14289	2	0.383	4	0.767	0	0	1	1
176	1	8271	1	0.331	1	0.331	0	0	1	1
150	1	9111	1	0.301	1	0.301	0	0	0	1
116	1	11644	3	0.706	5	1.176	0	0	1	1
112	1	5244	0	0.000	0	0.000	0	0	0	1
74	1	18089	1	0.151	5	0.757	0	0	0	1
52	1	16489	2	0.332	4	0.665	0	0	0	1
34	1	13511	0	0.000	0	0.000	0	0	1	1
28	1	10030	2	0.546	2	0.546	0	0	0	1

26	1	14755	1	0.186	1	0.186	0	0	1	1
115	1	13955	4	0.785	5	0.982	0	0	1	1
261	1	17511	4	0.626	10	1.565	0	0	1	1
872	1	13037	2	0.420	2	0.420	0	0	0	1
9	1	10578	2	0.518	2	0.518	0	0	0	1
892	1	9778	3	0.841	4	1.121	0	0	0	0
598	1	11467	3	0.717	3	0.717	0	0	0	1
736	1	20927	4	0.524	4	0.524	0	0	1	1
17	1	12023	2	0.456	3	0.684	0	0	1	1
356	1	10755	1	0.255	2	0.509	0	0	0	1
981	2	7293	4	1.503	4	1.503	0	0	0	1
975	2	8498	1	0.322	2	0.645	0	0	0	0
970	2	9184	0	0.000	0	0.000	0	0	0	0
942	2	3500	0	0.000	0	0.000	0	0	0	0
919	2	5695	1	0.481	2	0.962	0	0	0	1
870	2	4339	0	0.000	1	0.631	0	0	1	1
841	2	20791	6	0.791	8	1.054	0	0	0	1
837	2	15488	1	0.177	2	0.354	0	0	0	1
797	2	15674	3	0.524	6	1.049	0	1	0	1
791	2	14825	0	0.000	1	0.185	0	0	0	1
577	2	12325	0	0.000	2	0.445	0	0	1	1
499	2	18484	13	1.927	14	2.075	0	0	1	1
497	2	10124	1	0.271	2	0.541	0	0	0	1
490	2	7277	2	0.753	2	0.753	0	0	0	1
469	2	9672	1	0.283	3	0.850	0	0	1	1
468	2	11254	4	0.974	5	1.217	0	0	1	1
463	2	15141	4	0.724	4	0.724	0	0	1	1
389	2	4602	0	0.000	2	1.191	0	0	0	1
368	2	14209	1	0.193	1	0.193	0	0	1	1
361	2	8678	0	0.000	3	0.947	0	0	0	1
345	2	10395	2	0.527	2	0.527	0	0	1	1
339	2	25924	2	0.211	2	0.211	0	1	0	1
299	2	2004	0	0.000	0	0.000	0	0	0	0
268	2	23350	0	0.000	1	0.117	0	1	0	1
267	2	14780	2	0.371	2	0.371	0	0	0	1
231	2	14991	0	0.000	1	0.183	0	0	1	1
227	2	7232	2	0.758	3	1.137	0	0	0	1
203	2	28475	10	0.962	14	1.347	0	1	0	1
177	2	14531	3	0.566	4	0.754	0	0	1	1
176	2	8412	2	0.651	3	0.977	0	0	1	1
150	2	9266	0	0.000	3	0.887	0	0	0	1
116	2	11842	2	0.463	2	0.463	0	0	1	1
112	2	5333	0	0.000	0	0.000	0	0	0	1
74	2	18396	2	0.298	4	0.596	0	0	0	1
52	2	16769	2	0.327	3	0.490	0	0	0	1
34	2	13740	1	0.199	2	0.399	0	0	1	1
28	2	10201	1	0.269	4	1.074	0	0	0	1

26	2	15006	1	0.183	1	0.183	0	0	1	1
115	2	14192	4	0.772	10	1.930	0	0	1	1
261	2	17808	1	0.154	7	1.077	0	0	1	1
872	2	13259	0	0.000	0	0.000	0	0	0	1
9	2	10757	3	0.764	3	0.764	0	0	0	1
892	2	9944	3	0.827	5	1.378	0	0	0	0
598	2	11661	2	0.470	3	0.705	0	0	0	1
736	2	21282	4	0.515	6	0.772	0	0	1	1
17	2	12227	5	1.120	6	1.344	0	0	1	1
356	2	10938	3	0.751	4	1.002	0	0	0	1
981	3	7416	3	1.108	4	1.478	0	0	0	1
975	3	8642	0	0.000	0	0.000	0	0	0	0
970	3	9340	0	0.000	1	0.293	0	0	0	0
942	3	3559	1	0.770	1	0.770	0	0	0	0
919	3	5792	2	0.946	2	0.946	0	0	0	1
870	3	4413	0	0.000	3	1.862	0	0	1	1
841	3	21144	4	0.518	12	1.555	0	0	0	1
837	3	15750	0	0.000	2	0.348	0	0	0	1
797	3	15940	5	0.859	10	1.719	0	1	0	1
791	3	15077	1	0.182	1	0.182	0	0	0	1
577	3	12534	1	0.219	2	0.437	0	0	1	1
499	3	18798	6	0.874	8	1.166	0	0	1	1
497	3	10296	3	0.798	6	1.597	0	0	0	1
490	3	7400	2	0.740	2	0.740	0	0	0	1
469	3	9837	0	0.000	0	0.000	0	0	1	1
468	3	11445	1	0.239	3	0.718	0	0	1	1
463	3	15398	0	0.000	3	0.534	0	0	1	1
389	3	4680	0	0.000	1	0.585	0	0	0	1
368	3	14451	1	0.190	1	0.190	0	0	1	1
361	3	8825	0	0.000	2	0.621	0	0	0	1
345	3	10571	2	0.518	3	0.778	0	0	1	1
339	3	26364	3	0.312	3	0.312	0	1	0	1
299	3	2038	0	0.000	0	0.000	0	0	0	0
268	3	23747	5	0.577	5	0.577	0	1	0	1
267	3	15031	1	0.182	2	0.365	0	0	0	1
231	3	15245	1	0.180	2	0.359	0	0	1	1
227	3	7354	6	2.235	8	2.980	0	0	0	1
203	3	28958	13	1.230	15	1.419	0	1	0	1
177	3	14778	1	0.185	1	0.185	0	0	1	1
176	3	8554	1	0.320	1	0.320	0	0	1	1
150	3	9423	0	0.000	1	0.291	0	0	0	1
116	3	12043	2	0.455	2	0.455	0	0	1	1
112	3	5424	1	0.505	1	0.505	0	0	0	1
74	3	18708	0	0.000	3	0.439	0	0	0	1
52	3	17053	2	0.321	2	0.321	0	0	0	1
34	3	13973	1	0.196	1	0.196	0	0	1	1
28	3	10374	0	0.000	2	0.528	0	0	0	1

26	3	15260	4	0.718	5	0.898	0	0	1	1
115	3	14433	6	1.139	9	1.708	0	0	1	1
261	3	18110	7	1.059	10	1.513	0	0	1	1
872	3	13484	1	0.203	1	0.203	0	0	0	1
9	3	10940	2	0.501	2	0.501	0	0	0	1
892	3	10112	1	0.271	2	0.542	0	0	0	0
598	3	11859	4	0.924	9	2.079	0	0	0	1
736	3	21643	6	0.760	12	1.519	0	0	1	1
17	3	12434	5	1.102	5	1.102	0	0	1	1
356	3	11124	0	0.000	0	0.000	0	0	0	1
981	4	7542	3	1.090	6	2.180	0	0	0	1
975	4	8789	0	0.000	0	0.000	0	0	0	0
970	4	9499	0	0.000	0	0.000	0	0	0	0
942	4	3620	0	0.000	0	0.000	0	0	0	0
919	4	5890	1	0.465	2	0.930	0	0	0	1
870	4	4488	2	1.221	3	1.831	0	0	1	1
841	4	21503	6	0.764	11	1.402	0	0	0	1
837	4	16018	2	0.342	5	0.855	0	0	0	1
797	4	16211	5	0.845	9	1.521	0	1	0	1
791	4	15332	1	0.179	2	0.357	0	0	0	1
577	4	12747	2	0.430	5	1.075	0	0	1	1
499	4	19117	9	1.290	15	2.150	0	0	1	1
497	4	10471	1	0.262	2	0.523	0	0	0	1
490	4	7526	2	0.728	2	0.728	0	0	0	1
469	4	10003	2	0.548	2	0.548	0	0	1	1
468	4	11640	2	0.471	5	1.177	0	0	1	1
463	4	15660	3	0.525	5	0.875	0	0	1	1
389	4	4759	1	0.576	5	2.878	0	0	0	1
368	4	14696	2	0.373	2	0.373	0	0	1	1
361	4	8975	1	0.305	3	0.916	0	0	0	1
345	4	10750	3	0.765	5	1.274	0	0	1	1
339	4	26812	1	0.102	2	0.204	0	1	0	1
299	4	2073	0	0.000	0	0.000	0	0	0	0
268	4	24150	0	0.000	0	0.000	0	1	0	1
267	4	15286	4	0.717	4	0.717	0	0	0	1
231	4	15504	1	0.177	1	0.177	0	0	1	1
227	4	7479	2	0.733	3	1.099	0	0	0	1
203	4	29450	8	0.744	10	0.930	0	1	0	1
177	4	15029	1	0.182	2	0.365	0	0	1	1
176	4	8700	4	1.260	4	1.260	0	0	1	1
150	4	9583	1	0.286	2	0.572	0	0	0	1
116	4	12247	2	0.447	3	0.671	0	0	1	1
112	4	5516	0	0.000	0	0.000	0	0	0	1
74	4	19025	2	0.288	5	0.720	0	0	0	1
52	4	17342	4	0.632	6	0.948	0	0	0	1
34	4	14211	1	0.193	1	0.193	0	0	1	1
28	4	10550	0	0.000	2	0.519	0	0	0	1

26	4	15519	2	0.353	2	0.353	0	0	1	1
115	4	14678	1	0.187	5	0.933	0	0	1	1
261	4	18418	4	0.595	6	0.893	0	0	1	1
872	4	13713	0	0.000	0	0.000	0	0	0	1
9	4	11125	3	0.739	4	0.985	0	0	0	1
892	4	10284	1	0.266	2	0.533	0	0	0	0
598	4	12060	1	0.227	1	0.227	0	0	0	1
736	4	22010	1	0.124	1	0.124	0	0	1	1
17	4	12645	2	0.433	2	0.433	0	0	1	1
356	4	11312	1	0.242	3	0.727	0	0	0	1
981	5	7670	3	1.072	4	1.429	0	0	0	1
975	5	8938	0	0.000	0	0.000	0	0	0	0
970	5	9660	0	0.000	0	0.000	0	0	0	0
942	5	3681	1	0.744	2	1.489	0	0	0	0
919	5	5990	2	0.915	3	1.372	0	0	0	1
870	5	4564	1	0.600	1	0.600	0	0	1	1
841	5	21868	8	1.002	10	1.253	0	0	0	1
837	5	16290	0	0.000	1	0.168	0	0	0	1
797	5	16486	5	0.831	13	2.160	0	1	0	1
791	5	15593	0	0.000	0	0.000	0	0	0	1
577	5	12963	1	0.211	1	0.211	0	0	1	1
499	5	19442	1	0.141	2	0.282	0	0	1	1
497	5	10649	3	0.772	3	0.772	0	0	0	1
490	5	7654	1	0.358	1	0.358	0	0	0	1
469	5	10173	1	0.269	2	0.539	0	0	1	1
468	5	11837	0	0.000	1	0.231	0	0	1	1
463	5	15925	5	0.860	7	1.204	0	0	1	1
389	5	4840	0	0.000	3	1.698	0	0	0	1
368	5	14945	0	0.000	1	0.183	0	0	1	1
361	5	9127	2	0.600	2	0.600	0	0	0	1
345	5	10933	1	0.251	2	0.501	0	0	1	1
339	5	27267	4	0.402	4	0.402	0	1	0	1
299	5	2108	0	0.000	0	0.000	0	0	0	0
268	5	24559	4	0.446	4	0.446	0	1	0	1
267	5	15545	5	0.881	6	1.057	0	0	0	1
231	5	15767	1	0.174	1	0.174	0	0	1	1
227	5	7606	0	0.000	3	1.081	0	0	0	1
203	5	29949	21	1.921	24	2.196	0	1	0	1
177	5	15284	1	0.179	1	0.179	0	0	1	1
176	5	8847	4	1.239	5	1.548	0	0	1	1
150	5	9745	3	0.843	6	1.687	0	0	0	1
116	5	12455	1	0.220	2	0.440	0	0	1	1
112	5	5610	0	0.000	1	0.488	0	0	0	1
74	5	19348	0	0.000	1	0.142	0	0	0	1
52	5	17637	5	0.777	7	1.087	0	0	0	1
34	5	14452	2	0.379	2	0.379	0	0	1	1
28	5	10729	0	0.000	1	0.255	0	0	0	1

26	5	15783	2	0.347	4	0.694	0	0	1	1
115	5	14927	3	0.551	5	0.918	0	0	1	1
261	5	18730	4	0.585	7	1.024	0	0	1	1
872	5	13945	0	0.000	4	0.786	0	0	0	1
9	5	11314	3	0.726	5	1.211	0	0	0	1
892	5	10458	4	1.048	5	1.310	0	0	0	0
598	5	12265	1	0.223	3	0.670	0	0	0	1
736	5	22384	6	0.734	6	0.734	0	0	1	1
17	5	12860	2	0.426	5	1.065	0	0	1	1
356	5	11504	3	0.714	5	1.191	0	0	0	1

Appendix B
Additional Graphs and Trends

B.1. Cross-Section Study

B.1.1. Total Crashes

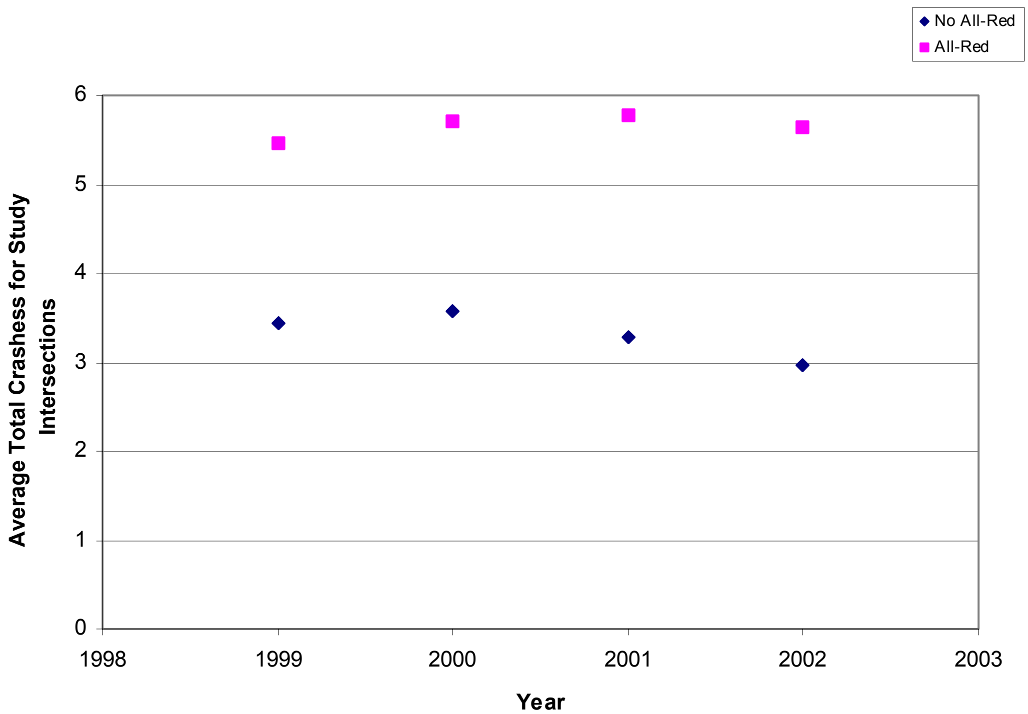


Figure B-1 Average Total Crashes for Cross-Section Study Intersections

Table B-1 Descriptive Statistics for Total Crashes at Cross-Section Study Intersections

	1999		2000		2001		2002		1999-2002	
	No A-R	A-R	No A-R	A-R	No A-R	A-R	No A-R	A-R	No A-R	A-R
Average	3.45	5.58	3.58	5.82	3.29	5.89	2.97	5.74	3.32	5.76
Minimum	0	0	0	0	0	0	0	0	0	0
Maximum	24	22	21	21	18	23	17	20	24	23
Median	2	5	3	5	3	4	2	4	2	4
Standard Deviation	4.43	5.40	3.58	5.10	3.34	5.28	3.49	4.82	3.71	5.10
Variance	19.66	29.12	12.79	25.99	11.18	27.88	12.19	23.28	13.72	26.05

No A-R: Intersections without the all-red clearance interval
A-R: Intersections with the all-red clearance interval

B.1.2. Total Crash Rate

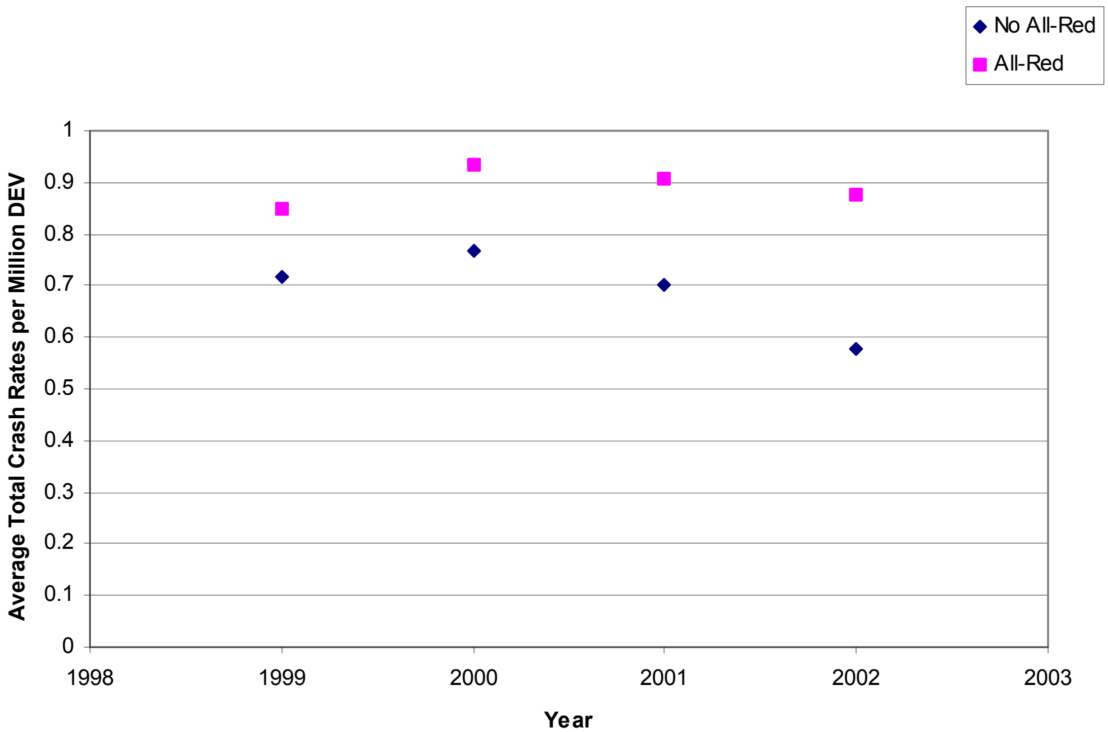


Figure B-2: Average Total Crash Rates for Cross-Section Study Intersections

Table B-2: Descriptive Statistics for Total Crash Rates at Cross-Section Study Intersections

	1999		2000		2001		2002		1999-2002	
	No A-R	A-R	No A-R	A-R	No A-R	A-R	No A-R	A-R	No A-R	A-R
Average	0.719	0.86	0.766	0.941	0.702	0.922	0.578	0.88	0.691	0.901
Minimum	0	0	0	0	0	0	0	0	0	0
Maximum	2.195	2.7	1.89	2.41	2.16	2.01	1.71	1.87	2.2	2.7
Median	0.495	0.803	0.692	0.874	0.613	0.848	0.452	0.921	0.582	0.863
Standard Deviation	0.624	0.63	0.483	0.608	0.534	0.595	0.505	0.533	0.538	0.587
Variance	0.389	0.396	0.233	0.369	0.285	0.354	0.255	0.284	0.29	0.345

No A-R: Intersections without the all-red clearance interval
A-R: Intersections with the all-red clearance interval
Crash Rate: Per million Daily Entering Vehicle

B.2. Before-and-after Study

B.2.1. Total Crashes

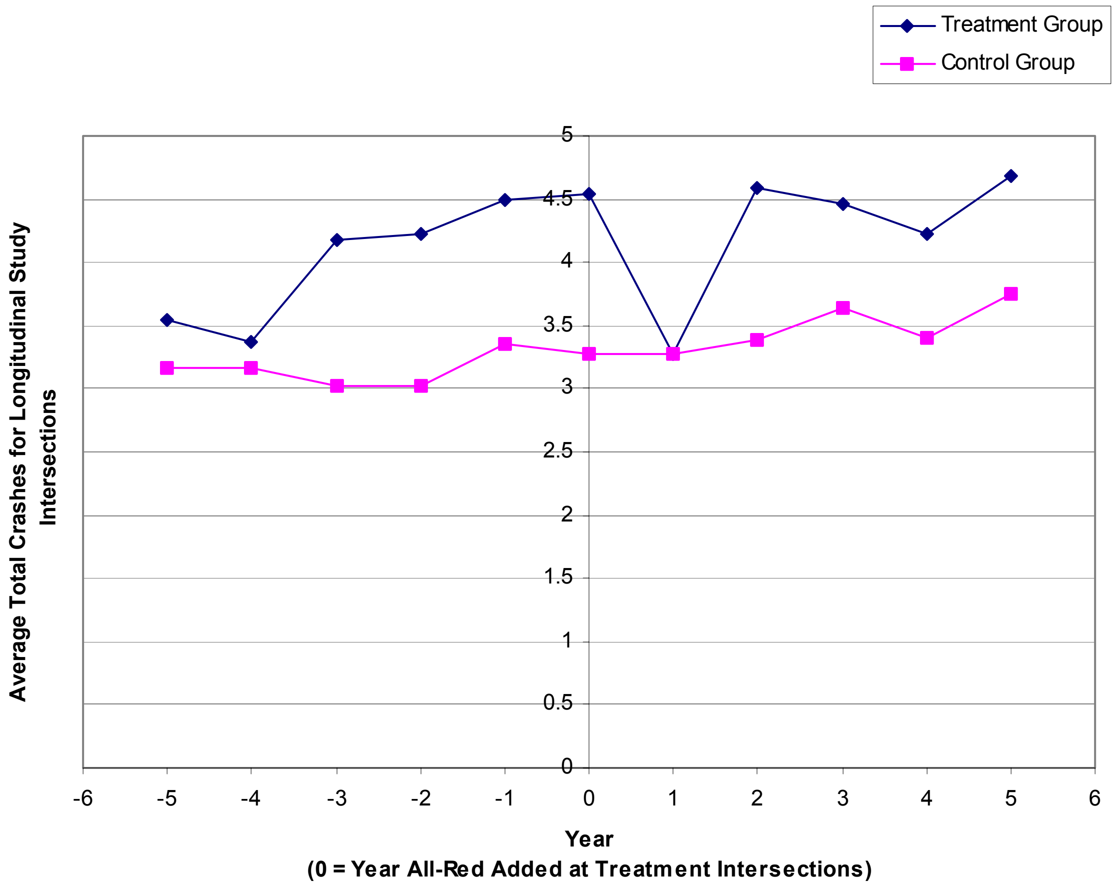


Figure B-3: Average Total Crashes at Treatment and Control Group Intersections

Table B-3: Descriptive Statistics for Total Crashes at Treatment and Control Group Intersections

	-5		-4		-3		-2	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	3.55	3.17	3.36	3.17	4.18	3.02	4.23	3.02
Minimum	0	0	0	0	0	0	0	0
Maximum	10	11	13	12	14	12	16	12
Median	3	2	3	2	3.5	2	3	2
Standard Deviation	2.65	2.82	2.89	2.83	3.35	2.75	3.50	2.88
Variance	7.02	7.93	8.34	8.01	11.20	7.59	12.28	8.28

	-1		0		1	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	4.50	3.36	4.55	3.28	3.27	3.28
Minimum	0	0	0	0	0	0
Maximum	13	15	11	15	10	17
Median	3	2	4	2	2	3
Standard Deviation	3.52	3.14	3.33	3.08	2.66	3.24
Variance	12.36	9.84	11.12	9.47	7.06	10.47

	2		3		4		5	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	4.59	3.38	4.45	3.64	4.23	3.40	4.68	3.74
Minimum	0	0	0	0	0	0	0	0
Maximum	11	14	15	15	11	15	17	24
Median	3.5	3	3.5	2	4	2	3.5	3
Standard Deviation	3.59	3.12	4.17	3.67	2.74	3.09	4.30	4.05
Variance	12.92	9.72	17.40	13.50	7.52	9.55	18.51	16.41

Trt: **Treatment group intersections that received the all-red at year 0**

Ctrl: **Control group intersections that do not have the all-red**

Table B-4: Average Total Crashes at Treatment and Control Group Intersections

Time Period	Treatment Group	Control Group
-5 to -1	3.96	3.15
0	4.55	3.28
1 to 5	4.25	3.49

B.2.2. Total Crash Rate

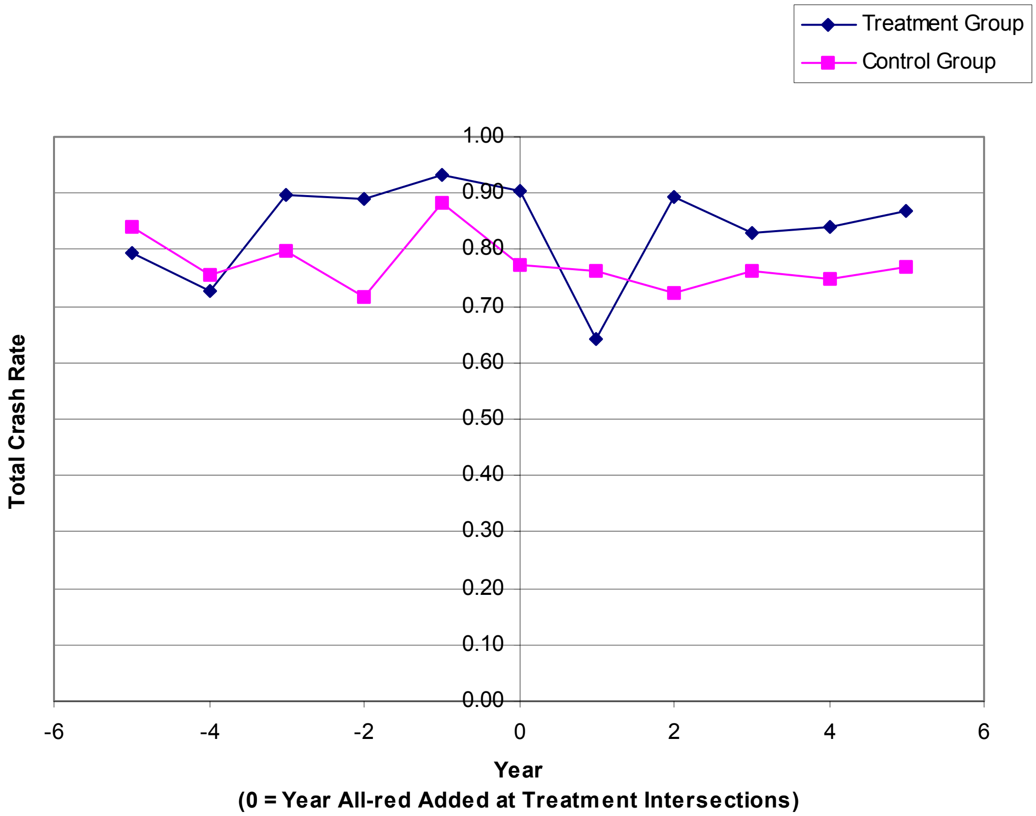


Figure B-4: Average Total Crash Rates for Treatment and Control Group Intersections

Table B-5: Descriptive Statistics for Total Crash Rates at Treatment and Control Group Intersections

	-5		-4		-3		-2	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	0.794	0.841	0.727	0.756	0.897	0.798	0.890	0.716
Minimum	0	0	0	0	0	0	0	0
Maximum	2.122	3.076	1.892	2.042	2.091	2.974	3.009	2.512
Median	0.712	0.796	0.683	0.659	0.820	0.643	0.727	0.697
Standard Deviation	0.565	0.686	0.510	0.516	0.622	0.695	0.648	0.588
Variance	0.320	0.471	0.260	0.266	0.386	0.483	0.420	0.346

	-1		0		1	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	0.932	0.885	0.905	0.773	0.643	0.763
Minimum	0	0	0	0	0	0
Maximum	2.182	3.321	2.066	4.571	1.918	3.853
Median	0.776	0.596	0.846	0.612	0.510	0.552
Standard Deviation	0.609	0.803	0.612	0.733	0.447	0.735
Variance	0.371	0.645	0.375	0.537	0.199	0.540

	2		3		4		5	
	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl	Trt	Ctrl
Average	0.895	0.724	0.831	0.762	0.840	0.748	0.870	0.771
Minimum	0	0	0	0	0	0	0	0
Maximum	2.041	2.075	2.075	2.980	2.006	2.878	2.842	2.195
Median	0.858	0.724	0.657	0.534	0.701	0.717	0.636	0.670
Standard Deviation	0.629	0.501	0.691	0.652	0.544	0.633	0.706	0.578
Variance	0.396	0.251	0.478	0.426	0.296	0.400	0.498	0.334

Trt: Treatment group intersections that received the all-red at year 0

Ctrl: Control group intersections that do not have the all-red

Crash Rate: Per million Daily Entering Vehicles

Table B-6: Average Total Crash Rates for Treatment and Control Group Intersections

Time Period	Treatment Group	Control Group
-5 to -1	0.85	0.80
0	0.91	0.77
1 to 5	0.82	0.75

B.2.3. Relevant Crash Rate Graphs for Treatment Group Intersections

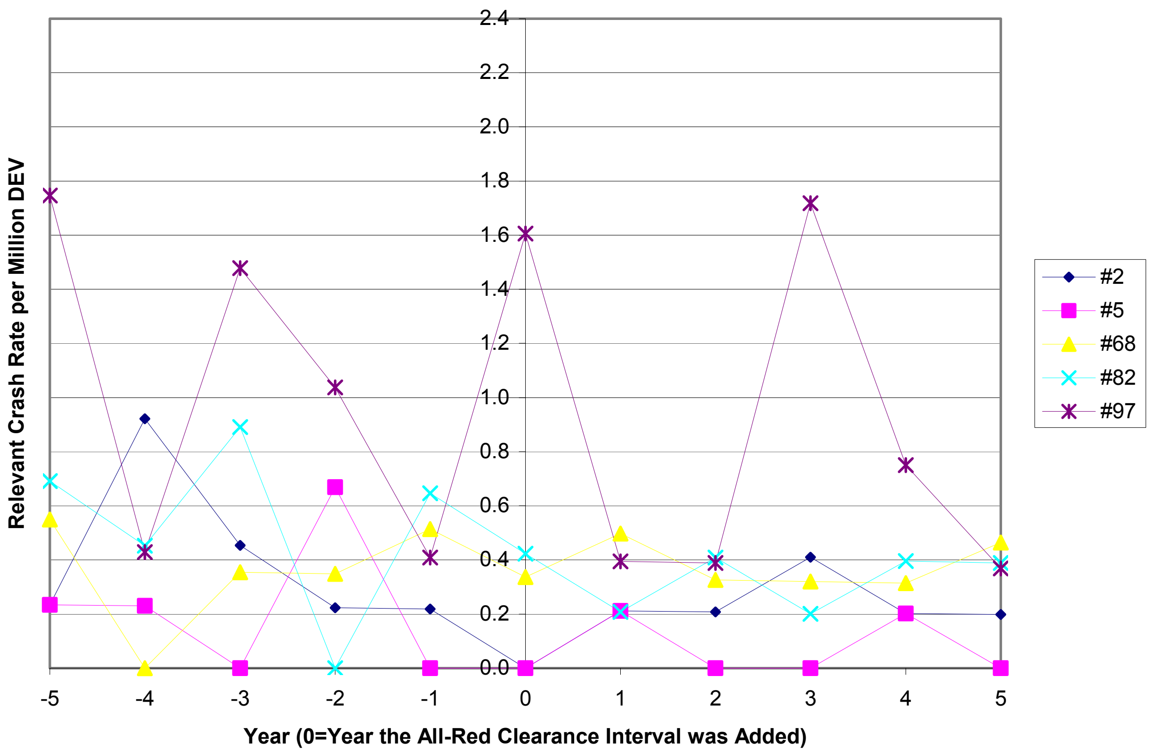


Figure B-5: Relevant Crash Rates for Treatment Group Intersections (#2, #5, #68, #82, #97)

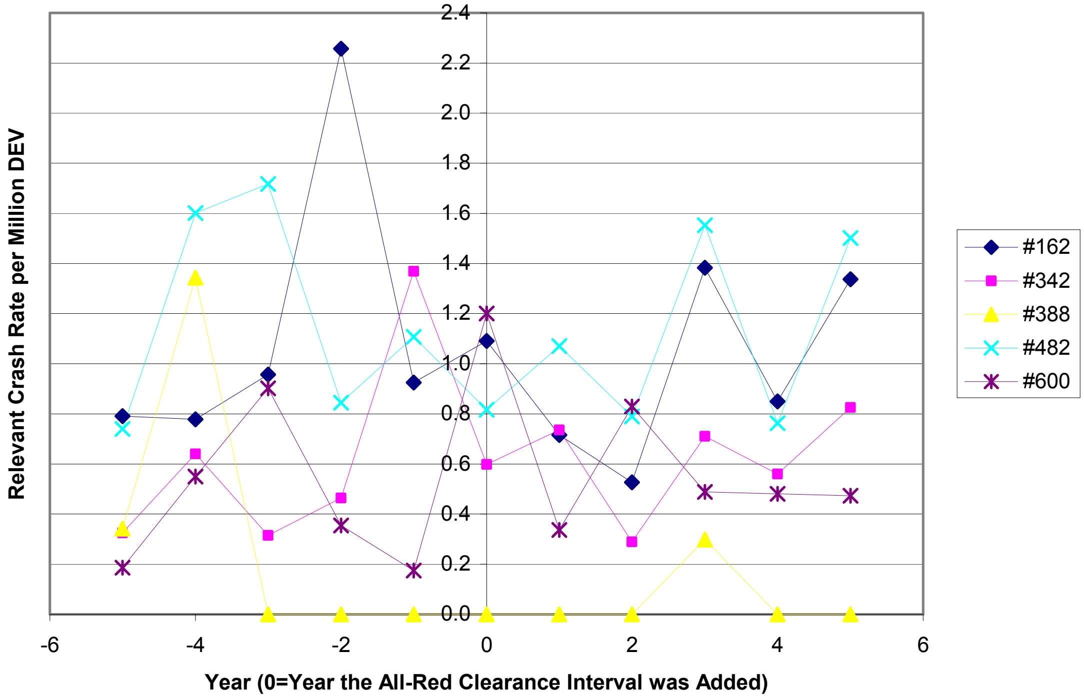


Figure B-6: Relevant Crash Rates for Treatment Group Intersections (#162, #342, #388, #482, #600)

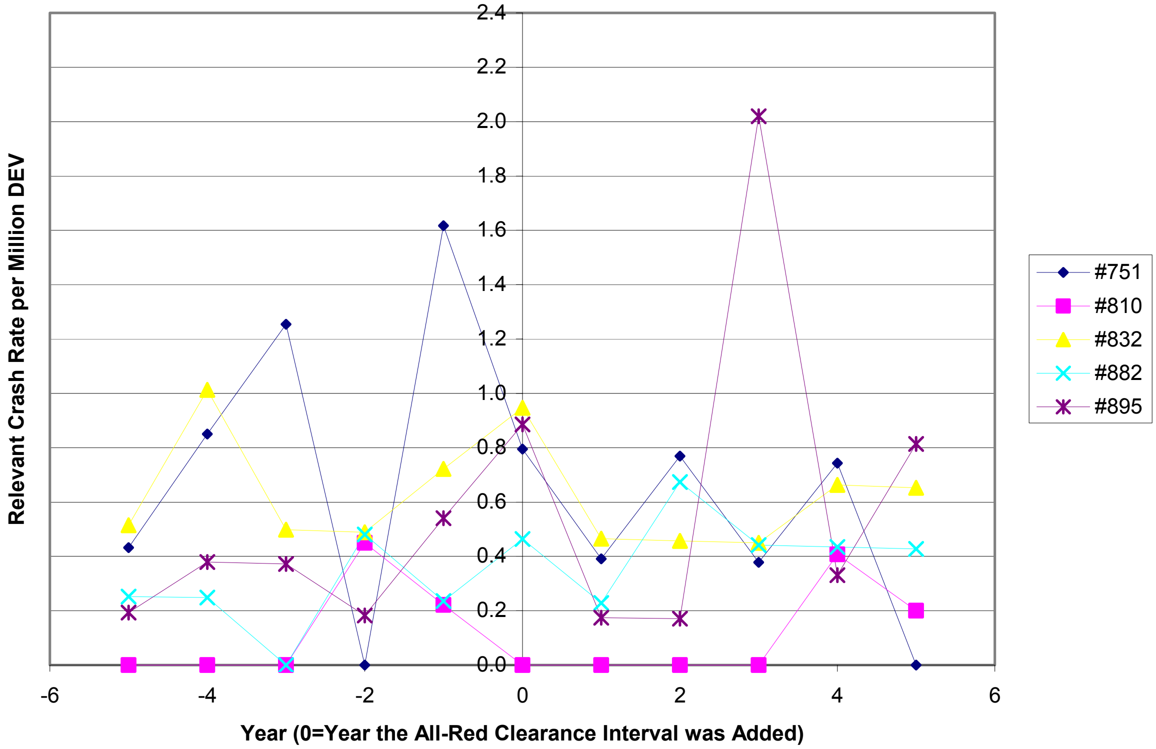


Figure B-7: Relevant Crash Rates for Treatment Group Intersections (#751, #810, #832, #882, #895)

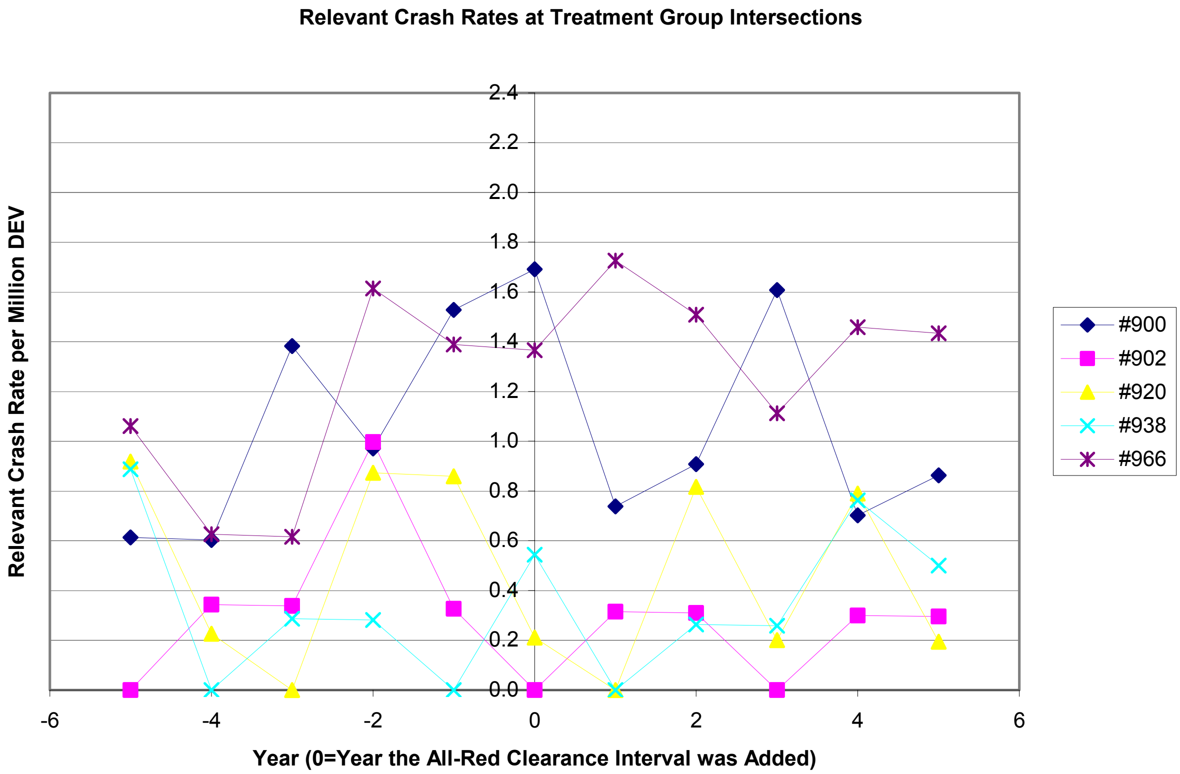


Figure B-8: Relevant Crash Rates for Treatment Group Intersections (#900, #902, #920, #938, #966)

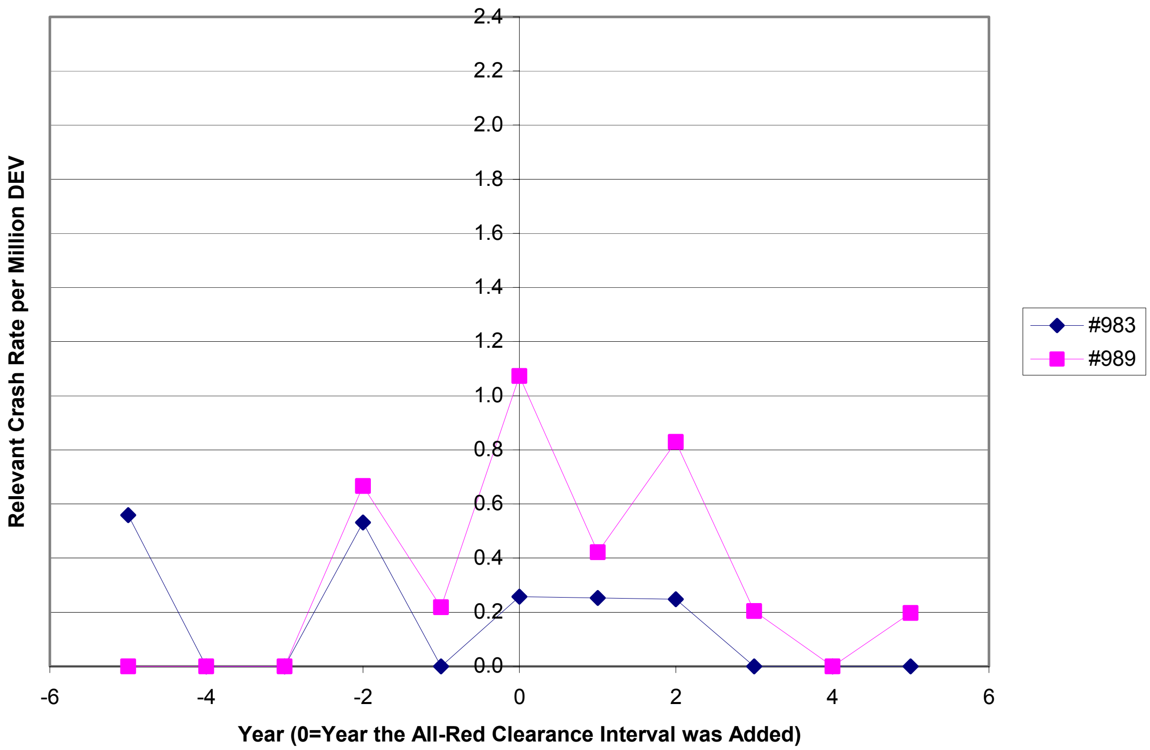


Figure B-9: Relevant Crash Rates for Treatment Group Intersections (#983, #989)

Appendix C
Statistical Model Information and Results

Linear mixed models were developed for this project. A linear mixed model is a regression model with fewer limitations than simple linear regression. Linear mixed models are used to analyze correlated, non-normally distributed data. The models use a curve fitting approach to account for "within-subject dependence" meaning that measurements on the same intersections are more similar than measurements on different intersections. Four different types of linear mixed models were developed:

- Generalized linear mixed model with an "unstructured" covariance structure
- Generalized linear mixed model with a compound symmetric covariance structure
- Linear mixed model with an "unstructured" covariance structure
- Linear mixed model with a compound symmetric covariance structure

C.1. Generalized Linear Mixed Models

The following models employed a generalized linear mixed model with a Poisson error distribution model, and a link function of the natural logarithm. The response variable was count data (relevant intersection crashes). Rather than using DEV as a covariate, all of the DEV values were centered on their mean. That is, the mean of all DEV values was subtracted from the predicted DEV value to create a new variable cDEV. The generalized linear mixed model was run two different times, the first using an "unstructured" covariance structure and the second using a compound symmetric covariance structure.

First, variables and their interactions were entered into the model. Equation C-1 depicts the original generalized linear mixed model.

Equation C-1: Original Generalized Linear Mixed Model with all Variables and their Interactions

$$\text{IMP\_CR} \sim \text{POISSON}\begin{bmatrix} \text{TRT, D1, D2, INT\_LIGHTS, cDEV, TRT} \times \text{INT\_LIGHTS,} \\ \text{TRT} \times \text{cDEV, D1} \times \text{cDEV, D2} \times \text{cDEV,} \\ \text{INT\_LIGHTS} \times \text{cDEV} \end{bmatrix}$$

$$\begin{aligned}
&\text{Where:}\\
&\text{IMP_CR} = \text{Relevant Crashes}\\
&\text{TRT} = \text{Treatment (1 for All-red, 0 for No All-Red)}\\
&\text{D1} = \text{Signal Visibility (1 for Overhead Both Directions, 0 for Otherwise)}\\
&\text{D2} = \text{Signal Visibility (1 for Overhead One Direction, 0 for Otherwise)}\\
&\text{INT_LIGHTS} = \text{Presence of Lighting at the Intersection (1 for Yes, 0 for No)}\\
&\text{cDEV} = \text{Centered DEV}
\end{aligned}$$

Because this was an observational study, when main effects and interactions were not significant at a reasonable significance level (α=0.05), they were dropped from the model. This resulted in a reduced model, shown as Equation C-2.

Equation C-2: Reduced Generalized Linear Mixed Model

$$\text{IMP\_CR} \sim \text{POISSON}\left[\text{TRT},\ \text{D2}, \text{cDEV}\right]$$

Where :

IMP_CR = Relevant Crashes

TRT = Treatment (1 for All - red, 0 for No All - Red)

D2 = Signal Visibility (1 for Overhead One Direction, 0 for Otherwise)

cDEV = Centered DEV

To facilitate comparison of this model to a linear mixed model (developed in the next section), the model were then expanded to include the variables for the presence of lighting at the intersection and the interaction between treatment and centered DEV, one at a time. The final model is shown as Equation C-3.

Equation C-3: Final Generalized Linear Mixed Model

$$\text{IMP\_CR} \sim \text{POISSON}\begin{bmatrix}\text{TRT},\ \text{D2}, \text{INT\_LIGHTS}, \text{cDEV}, \\ \text{TRT} \times \text{cDEV}\end{bmatrix}$$

Where :

IMP_CR = Relevant Crashes

TRT = Treatment (1 for All - red, 0 for No All - Red)

D2 = Signal Visibility (1 for Overhead One Direction, 0 for Otherwise)

INT_LIGHTS = Presence of Lighting at the Intersection (1 for Yes, 0 for No)

cDEV = Centered DEV

Finally, two generalized linear mixed models were created: one with an "unstructured" covariance structure and one with a compound symmetric covariance structure (definitions of covariance structures to follow).

C.1.1. Generalized Linear Mixed Model with an "Unstructured" Covariance Structure

An "unstructured" covariance structure was used between the time points within a subject (here an intersection). This type of covariance matrix is a completely general (unstructured) covariance matrix using only variance and covariance parameters, and is depicted in Table C-1. In this structure, all variances are nonnegative and covariances can be either negative or positive. An "unstructured" covariance structure allowed variances of crashes at each intersection to be different for each year. This covariance structure also implies that the covariance and correlations of crashes at an intersection can differ depending on which two years are being considered. The "unstructured" covariance parameter estimates for the generalized linear mixed model for the cross-section study are shown in Table C-2. Each row and column in the 4x4 matrix represents an analysis year (1999, 2000, 2001, and 2002).

In the "unstructured" covariance matrix, Table C-2, the elements along the rows, from the diagonal outwards, are decreasing. This is because from 1999 to 2000 there is a higher correlation in a particular intersection than there is from 1999 to 2002.

Table C-1: "Unstructured" Covariance Structure

$$
\begin{array}{c}
 \\
1999 \\
2000 \\
2001 \\
2002
\end{array}
\begin{array}{c}
\begin{array}{cccc} 1999 & 2000 & 2001 & 2001 \end{array} \\
\begin{bmatrix}
\sigma_1^2 & \sigma_{21} & \sigma_{31} & \sigma_{41} \\
\sigma_{21} & \sigma_2^2 & \sigma_{32} & \sigma_{42} \\
\sigma_{31} & \sigma_{32} & \sigma_3^2 & \sigma_{43} \\
\sigma_{41} & \sigma_{42} & \sigma_{43} & \sigma_4^2
\end{bmatrix}
\end{array}
$$

Table C-2: "Unstructured" Covariance Structure for the Generalized Linear Mixed Model

$$
\begin{bmatrix}
2.13 & 1.10 & 1.02 & 0.76 \\
1.10 & 1.53 & 0.72 & 0.57 \\
1.02 & 0.72 & 1.73 & 0.74 \\
0.76 & 0.57 & 0.74 & 1.43
\end{bmatrix}
$$

Table C-3 shows the solution vector for the fixed effects. Equation C-4 gives the expected number of relevant crashes. If the value of X_1, X_2, X_3, or X_1X_4 is 1, it does not affect the number of expected intersection crashes. If the value is 0, the variable will have the following effects: a negative regression coefficient means that the variable causes a reduction in expected intersection crashes and a positive regression coefficient means that the variable causes an increase in expected intersection crashes. In this model, the safest intersection (intersection with the least expected crashes) would have the following characteristics: no all-red clearance interval ($X_1 = 0$), overhead signals in all directions or neither direction (X_2=0), and no intersection lighting (X_3=0). All SAS results for the generalized linear mixed model with the "unstructured" covariance structure are located in Appendix D.

If there is an intersection that has an all-red clearance interval (X_1=1), overhead signals in one direction (X_2=1), intersection lighting (X_3=1), and DEV is one more than average (X_4=1), the expected number of crashes at that intersection would be 2.32 per year. If an intersection has all of the same parameters as the previous example, but operates without an all-red clearance interval (X_1=0), the expected number of intersection crashes is 1.46 per year.

Table C-3: Solution Vector for Fixed Effects of the Generalized Linear Mixed Model with an "Unstructured" Covariance Structure

Effect	X_1	X_2	X_3	Estimate	Standard Error	DF	t Value	$\Pr > \lvert t \rvert$
Intercept				0.8447	0.1481	72	5.70	< 0.0001
X_1	0			-0.4700	0.1592	72	-2.95	0.0043
X_1	1			0	.	.	.	.
X_2		0		0.3874	0.1482	72	2.61	0.0109
X_2		1		0	.	.	.	.
X_3			0	-0.3477	0.2841	72	-1.22	0.2251
X_3			1	0	.	.	.	.
X_4				0.000094	0.000012	72	7.93	< 0.0001
$X_1 \times X_4$	0			-6.58×10^{-6}	0.000019	72	-0.35	0.7301
$X_1 \times X_4$	1			0	.	.	.	.

Where :

X_1 = Treatment (1 = All - Red, 0 = No All - Red)

X_2 = Signal Visibility (1 = Overhead Signals One Direction, 0 = Otherwise)

X_3 = Presence of Street Lights at the Intersecti on (1 = Yes, 0 = No)

X_4 = Centered DEV

Equation C-4: Equation to Determine Expected Number of Relevant Crashes Using the Generalized Linear Mixed Model with an "unstructured" Covariance Structure

$$\text{Expected Number of Relevant Crashes} = e^{\begin{pmatrix} 0.8447\text{-}0.4700(1\text{-}X_1)+0.3847(1\text{-}X_2) \\ \text{-}0.3447(1\text{-}X_3)+0.000094\times X_4 \\ -6.58\times10^{-6}\times X_4(1-X_1) \end{pmatrix}}$$

Where :

X_1 = Treatment (1 = All - Red, 0 = No All - Red)

X_2 = Signal Visibility (1 = Overhead Signals One Direction, 0 = Otherwise)

X_3 = Presence of Street Lights at the Intersection (1 = Yes, 0 = No)

X_4 = Centered DEV

C.1.2. Generalized Linear Mixed Model with a Compound Symmetric Covariance Structure

After the "unstructured" covariance structure was explored, a compound symmetric covariance structure was used in the generalized linear mixed model. These two different covariance structures were explored to determine which one produced a better-fit model. A compound symmetric covariance structure has constant variance and constant covariance. This means that the variance of crashes at an intersection is the same for all four years. This covariance structure also implies that covariance and correlation between any two years is the same. The compound symmetric covariance structure is depicted in Table C-4. The compound symmetric covariance structure for the generalized linear mixed model is shown in Table C-5.

Table C-4: Compound Symmetric Covariance Structure

$$\begin{array}{c} \\ 1999 \\ 2000 \\ 2001 \\ 2002 \end{array} \begin{array}{c} \begin{array}{cccc} 1999 & 2000 & 2001 & 2002 \end{array} \\ \begin{bmatrix} \sigma^2+\sigma_1 & \sigma_1 & \sigma_1 & \sigma_1 \\ \sigma_1 & \sigma^2+\sigma_1 & \sigma_1 & \sigma_1 \\ \sigma_1 & \sigma_1 & \sigma^2+\sigma_1 & \sigma_1 \\ \sigma_1 & \sigma_1 & \sigma_1 & \sigma^2+\sigma_1 \end{bmatrix} \end{array}$$

Table C-5: Compound Symmetric Covariance Structure for the Generalized Linear Mixed Model

$$\begin{bmatrix} 1.69 & 0.79 & .79 & 0.79 \\ 0.79 & 1.69 & 0.79 & 0.79 \\ 0.79 & 0.79 & 1.69 & 0.79 \\ 0.79 & 0.79 & 0.79 & 1.69 \end{bmatrix}$$

Table C-6 shows the solution vector for the fixed effects of the generalized linear mixed model with a compound symmetric covariance structure. Equation C-5 gives the expected number of relevant crashes. If the value of X_1, X_2, X_3, or $X_1 x X_4$ is 1, the variable does not affect the number of expected intersection crashes. If the value is 0, the variable will have the following effects: a negative regression coefficient means that the variable causes a reduction in expected intersection crashes and a positive regression coefficient means that the variable causes an increase in expected intersection crashes. In this model, the safest intersection (intersection with the least expected crashes) would have the following characteristics: no all-red clearance interval ($X_1 = 0$), overhead signals in all directions or neither direction ($X_2=0$), and no intersection lighting ($X_3=0$). All SAS results for the generalized linear mixed model with compound symmetric covariance structure are located in Appendix D.

For an intersection that has an all-red clearance interval (X_1=1), overhead signals in one direction (X_2=1), intersection lighting (X_3=1), and DEV is one more than average (X_4=1), the expected number of crashes at that intersection would be 2.18 per year. If an intersection has all of the same parameters as the previous example, but operates without an all-red clearance interval (X_1=0), the expected number of intersection crashes is 1.43 per year.

Table C-6: Solution Vector for Fixed Effects of the Generalized Linear Mixed Model with a Compound Symmetric Covariance Structure

Effect	X_1	X_2	X_3	Estimate	Standard Error	DF	t Value	$\Pr > \lvert t \rvert$
Intercept				0.7793	0.1554	72	5.01	< 0.0001
X_1	0			−0.4206	0.1642	72	−2.56	0.0125
X_1	1			0	.	.	.	.
X_2		0		0.4392	0.1545	72	2.84	0.0058
X_2		1		0	.	.	.	.
X_3			0	−0.3250	0.2900	72	−1.12	0.2661
X_3			1	0	.	.	.	.
X_4				0.000100	0.000012	226	8.11	< 0.0001
$X_1 \times X_2$	0			-8.54×10^{-6}	0.000020	226	−0.44	0.6622
$X_1 \times X_2$	1			0	.	.	.	.

Where:

X_1 = Treatment (1 = All-Red, 0 = No All-Red)

X_2 = Signal Visibility (1 = Overhead Signals One Direction, 0 = Otherwise)

X_3 = Presence of Street Lights at the Intersection (1 = Yes, 0 = No)

X_4 = Centered DEV

Equation C-5: Equation to Determine Expected Number of Relevant Crashes Using the Generalized Linear Mixed Model with a Compound Symmetric Covariance Structure

$$\text{Expected Number of Relevant Crashes} = e^{\begin{pmatrix} 0.7793\text{-}0.4206(1\text{-}X_1)+0.4392(1\text{-}X_2) \\ \text{-}0.3250(1\text{-}X_3)+0.000100\times X_4 \\ -8.54\times10^{-6}\times X_4(1-X_1) \end{pmatrix}}$$

Where:

X_1 = Treatment (1 = All - Red, 0 = No All - Red)

X_2 = Signal Visibility (1 = Overhead Signals One Direction, 0 = Otherwise)

X_3 = Presence of Street Lights at the Intersection (1 = Yes, 0 = No)

X_4 = Centered DEV

While a generalized linear model with random effects offers a more correct way of modeling non normally distributed count data, the difficulty of using cumbersome nonlinear equations should be noted.

C.2. Linear Mixed Models

It is easier to use a standard normal analysis (such as a linear mixed model) than using a the complicated generalized mixed linear model. Linear mixed models also require fewer assumptions than ordinary least squares regression models. These models also use curve fitting to account for "within-subject dependence," meaning that measurements on the same intersections are more similar than measurements on different intersections.

However, one of the three primary assumptions of mixed linear models is that the data are normally distributed, or that the dependent variable be transformed into something that is approximately normal. As the raw count data are not normally distributed, relevant crash histograms were created using the log of crashes, square root of crashes, and cubic root of crashes at the study intersections over the four-year study period. The square root of crashes produced an approximately normally distributed histogram, and is shown in Figure C-1. A normal linear mixed model was therefore fitted to the square root of crash data.

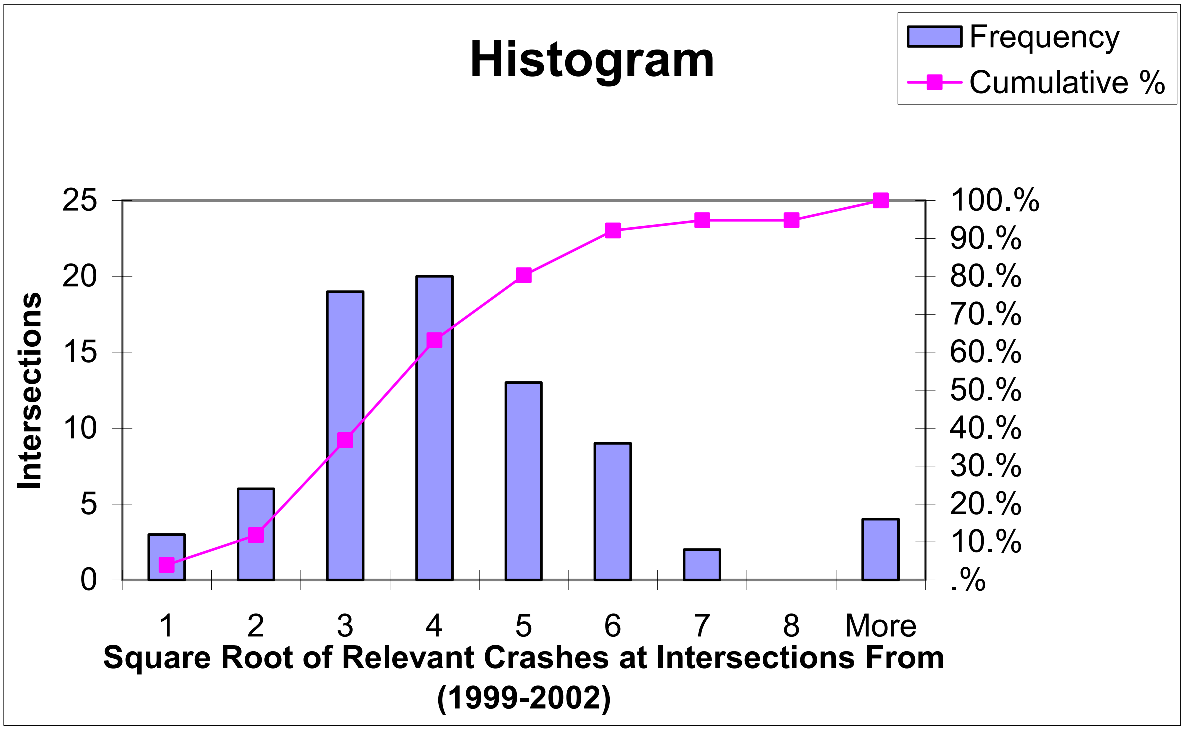


Figure C-1: Square Root Transformation of the Data

As in the previous models, the response variable was relevant intersection crashes (counts). DEV values were normalized and centered about their mean. Two linear mixed models were developed: one using an "unstructured" covariance structure and one using a compound symmetric covariance structure.

All variables and their interactions were entered into the model. Equation C-6 depicts the original linear mixed model.

Equation C-6: Original Linear Mixed Model with all Variables and their Interactions

$$\text{Square Root (IMP\_CR)} \sim \text{Normal}\begin{bmatrix} \mu(\text{TRT, D1, D2, INT\_LIGHTS, cDEV,} \\ \text{TRT} \times \text{INT\_LIGHTS,} \\ \text{TRT} \times \text{cDEV, D1} \times \text{cDEV, D2} \times \text{cDEV,} \\ \text{INT\_LIGHTS} \times \text{cDEV}), \sigma \end{bmatrix}$$

Where :

IMP_CR = Relevant Crashes

TRT = Treatment (1 for All - red, 0 for No All - Red)

D1 = Signal Visibility (1 for Overhead Both Directions, 0 for Otherwise)

D2 = Signal Visibility (1 for Overhead One Direction, 0 for Otherwise)

INT_LIGHTS = Presence of Lighting at the Intersection (1 for Yes, 0 for No)

cDEV = Centered DEV

Interactions that were not significant at a reasonable significance level were dropped from the model. All main effects were entered into the model, and are shown in Equation C-7.

Equation C-7. Reduced Linear Mixed Model

$$\text{Square Root (IMP\_CR)} \sim \text{Normal}\left[\mu(\text{TRT, D2, INT\_LIGHTS, cDEV, CDEV} \times \text{TRT}), \sigma\right]$$

Where :

IMP_CR = Relevant Crashes

TRT = Treatment (1 for All - red, 0 for No All - Red)

D2 = Signal Visibility (1 for Overhead One Direction, 0 for Otherwise)

INT_LIGHTS = Presence of Lighting at the Intersection (1 for Yes, 0 for No)

cDEV = Centered DEV

C.2.1. Linear Mixed Model with an "Unstructured" Covariance Structure

As in the case of the generalized linear mixed model, an "unstructured" covariance structure was used for the linear mixed model. The "unstructured" covariance structure is shown in Table C-7, and Table C-8 shows the solution vector for fixed effects. Equation C-8 gives the expected number of relevant crashes. If the value of X_1, X_2, X_3, or X_1xX_4 is 1, the variable does not affect the number of expected intersection crashes. If the value is 0, the variable will have the following effects: a negative regression coefficient means that the variable causes a reduction in expected intersection crashes and a positive regression coefficient means that the variable causes an increase in expected intersection crashes. In this model, the safest intersection (intersection with the least expected crashes) would have the following characteristics: no all-red clearance interval ($X_1 = 0$), overhead signals in all directions or neither direction (X_2=0), and no intersection lighting (X_3=0). All SAS results for the linear mixed model with the "unstructured" covariance structure are located in Appendix D.

In order to determine the expected number of crashes, the estimated expected number of crashes in the transformed scale (in our case, square root scale) needs to be transformed back to the original scale. In this case, simply squaring the square root of estimated expected crashes is not correct due to a bias correction which needs to be corrected. The back transformation for the expected number of crashes is shown in the second portion of Equation 6-8. This correction can be derived using a Taylor expansion of the non-linear function on expected crashes that results from the power transformation. The term that is added to the naïve back-transformation is one half of the second derivative of the inverse transformation with respect to $\hat{X}$ (the expected number of intersection crashes in the transformed scale) times the within intersection variance. Since an "unstructured" covariance structure was used in this model, the within-intersection variance was approximated for each year. For 1999, the within intersection variance is 0.40. (From Table C-7. 0.40 = 0.6712 – (0.2917 + 0.2801 + 0.2440)/3.)

If there is an intersection that has an all-red clearance interval (X_1=1), overhead signals in one direction (X_2=1), intersection lighting (X_3=1), and DEV of one more than average (X_4=1), the expected number of crashes would be 2.24 per year. If an intersection has all of the same parameters as the previous example, but operates without an all-red clearance interval (X_1=0), the expected number of crashes would be1.50 per year.

Table C-7: "Unstructured" Covariance Structure for the Linear Mixed Model.
(Data are the square root of crashes.)

$$\begin{bmatrix} 0.67 & 0.29 & 0.28 & 0.24 \\ 0.29 & 0.52 & 0.20 & 0.15 \\ 0.28 & 0.20 & 0.52 & 0.20 \\ 0.24 & 0.15 & 0.20 & 1.43 \end{bmatrix}$$

Table C-8: Solution Vector for Fixed Effects of the Linear Mixed Model with an "Unstructured" Covariance Structure

Effect	X_1	X_2	X_3	Estimate	Standard Error	DF	t Value	$\Pr > \lvert t \rvert$
Intercept				1.3584	0.1252	72	10.85	< 0.0001
X_1	0			-0.3083	0.1273	72	-2.42	0.0180
X_1	1			0	.	.	.	.
X_2		0		0.3727	0.1340	72	2.78	0.0069
X_2		1		0	.	.	.	.
X_3			0	-0.5276	0.2309	72	−2.29	0.0252
X_3			1	0	.	.	.	.
X_4				0.000113	0.000014	72	7.90	< 0.0001
$X_1 \times X_2$	0			-0.00004	0.000020	72	−2.19	0.0317
$X_1 \times X_2$	1			0	.	.	.	.

Where:

X_1 = Treatment (1 = All-Red, 0 = No All-Red)

X_2 = Signal Visibility (1 = Overhead Signals One Direction, 0 = Otherwise)

X_3 = Presence of Street Lights at the Intersection (1 = Yes, 0 = No)

X_4 = Centered DEV

Equation C-8: Equation to Determine Expected Number of Relevant Crashes Using the Linear Mixed Model with an "Unstructured" Covariance Structure

$$\sqrt{\text{Expected Number of Relevant Crashes}} = \begin{pmatrix} 1.3584 - 0.3083(1-X_1) + 0.3727(1-X_2) \\ -0.5276(1-X_3) + 0.000113 \times X_4 \\ -0.00004 \times X_4(1-X_1) \end{pmatrix}$$

$$\text{Expected Number of Relevant Crashes} = \sqrt{\text{Expected Number of Relevant Crashes}} + \frac{1}{2} \times 2 \times \sigma^2_{\text{within}}$$

Where:

X_1 = Treatment (1 = All-Red, 0 = No All-Red)

X_2 = Signal Visibility (1 = Overhead Signals One Direction, 0 = Otherwise)

X_3 = Presence of Street Lights at the Intersection (1 = Yes, 0 = No)

X_4 = Centered DEV

C.2.2. Linear Mixed Model with a Compound Symmetric Covariance Structure

In this linear mixed model, a compound symmetric covariance structure was used to account for the "within-subject dependence" meaning that measurements at the same intersections were more similar than measurements at different intersections. For example, relevant crashes at intersection "A" for year 1999 and 2000 are more similar than relevant crashes at intersection "A" for 1999 and intersection "Z" for 2002 because intersection "A" and "Z" are inherently different intersections and have different characteristics affecting the number of relevant intersection crashes.

The compound symmetric covariance structure for the linear mixed model is in Table C-9.

Table C-9 Compound Symmetric Covariance Structure for the Linear Mixed Model
(Data are the square root of crashes.)

$$\begin{bmatrix} 0.56 & 0.23 & 0.23 & 0.23 \\ 0.23 & 0.56 & 0.23 & 0.23 \\ 0.23 & 0.23 & 0.56 & 0.20 \\ 0.23 & 0.23 & 0.23 & 0.56 \end{bmatrix}$$

Table C-10 shows the solution vector for fixed effects of the linear mixed model with a compound symmetric covariance structure. If the value of X_1, X_2, X_3, or $X_1 x X_4$ is 1, it does not affect the number of expected intersection crashes. If the value is 0, the variable will have the following effects: a negative regression coefficient means that the variable causes a reduction in expected intersection crashes and a positive regression coefficient means that the variable causes an increase in expected intersection crashes. In this model, the safest intersection (intersection with the least expected crashes) would have the following characteristics: no all-red clearance interval ($X_1 = 0$), overhead signals in all directions or neither direction (X_2=0), and no intersection lighting (X_3=0). All SAS results for the linear mixed model with the compound symmetric covariance structure are located in Appendix D.

In order to determine the expected number of crashes, the estimated expected number of crashes in the transformed scale (in this case, square root scale) needs to be transformed back to the original scale. The back transformation for the expected number of crashes is shown in the second portion of Equation C-9. In this model the within intersection variance is 0.33 (From Table C-9, 0.33 = 0.56 - 0.23.)

If there is an intersection that has an all-red clearance interval (X_1=1), overhead signals in one direction (X_2=1), has intersection lighting (X_3=1), and the DEV is one more than the average DEV (X_4=1), the expected number of crashes at that intersection would be 2.07 per year. If an intersection has all of the same parameters as the previous example, but operates without an all-red clearance interval (X_1=0), the expected number of intersection crashes is 1.41 per year.

Table C-10 Solution Vector for Fixed Effects of the Linear Mixed Model with a Compound Symmetric Covariance Structure

Effect	X_1	X_2	X_3	Estimate	Standard Error	DF	t Value	$\Pr > \lvert t \rvert$
Intercept				1.3192	0.1286	72	10.26	< 0.0001
X_1	0			-0.2784	0.1310	72	-2.13	0.0370
X_1	1			0	.	.	.	.
X_2		0		0.3958	0.1379	72	2.87	0.0054
X_2		1		0	.	.	.	.
X_3			0	−0.5157	0.2377	72	−2.17	0.0333
X_3			1	0	.	.	.	.
X_4				0.000119	0.000015	226	7.98	< 0.0001
$X_1 \times X_2$	0			−0.00005	0.000021	226	−2.26	0.0248
$X_1 \times X_2$	1			0	.	.	.	.

Where:

X_1 = Treatment (1 = All-Red, 0 = No All-Red)

X_2 = Signal Visibility (1 = Overhead Signals One Direction, 0 = Otherwise)

X_3 = Presence of Street Lights at the Intersection (1 = Yes, 0 = No)

X_4 = Centered DEV

Equation C-9 Equation to Determine Expected Number of Relevant Crashes Using the Linear Mixed Model with a Compound Symmetric Covariance Structure

$$\sqrt{\text{Expected Number of Relevant Crashes}} = \begin{pmatrix} 1.3192 - 0.2784(1-X_1) + 0.3958(1-X_2) \\ -0.5157(1-X_3) + 0.000119 \times X_4 \\ -0.00005 \times X_4(1-X_1) \end{pmatrix}$$

$$\text{Expected Number of Relevant Crashes} = \sqrt{\text{Expected Number of Relevant Crashes}} + \frac{1}{2} \times 2 \times \sigma^2_{\text{within}}$$

Where:

X_1 = Treatment (1 = All-Red, 0 = No All-Red)

X_2 = Signal Visibility (1 = Overhead Signals One Direction, 0 = Otherwise)

X_3 = Presence of Street Lights at the Intersection (1 = Yes, 0 = No)

X_4 = Centered DEV

Parameters in the normal linear mixed model can be estimated by solving a set of linear equations, once the variance components have been obtained. Thus, in general, computations are less intensive (and results are more stable) than in the case of the generalized linear mixed model. In this study, relatively smaller standard errors associated to the regression coefficient resulted in a larger set of statistically significant effects on crashes. In addition, when possible, it is always preferred to use a linear model because it is easier to understand and interpret.

All four models had relatively similar solutions. Estimates for the effects of intersections characteristics were all in the same direction and similar in magnitude. The major difference between the generalized linear mixed models and the linear mixed models is that neither generalized linear mixed model found the effects of the presence of street lighting and the interaction of treatment and centered DEV to be significant. Although these effects were not significant, they were kept in the models in order to compare the models to the linear mixed models. Out of the four models investigated, the linear mixed model with a compound symmetric covariance structure ended up being the best model because it had the smallest Akaike's Information Criterion (AIC) and Schwarz's Bayesian Criterion (BIC) values, as shown in Table C-11. Table C-12 shows the predicted number of intersection crashes using the different models. The average of intersections refers to the average of predicted values for all intersections with and without the all-red clearance interval.

Table C-11 Summary of Fit Statistics

Model	-2 Res Log Likelihood	AIC (Smaller is Better)	AICC (Smaller is Better)	BIC (Smaller is Better)
Generalized Linear Mixed Model with an "Unstructured" Covariance Structure	724.2	744.2	745.0	767.5
Generalized Linear Mixed Model with a Compound Symmetric Covariance Structure	735.3	739.3	739.3	744.0
Linear Mixed Model with an "Unstructured" Covariance Structure	663.4	683.4	684.1	706.7
Linear Mixed Model with a Compound Symmetric Covariance Structure	669.0	673.0	673.0	677.7

Table C-12 Predicted Number of Intersection Crashes Using Models

	Average of Intersections			
	All-red	All-red	No all-red	Diff.
GLMM (UN)	3.33	3.99	2.04	1.95
GLMM (CS)	3.27	4.00	2.07	1.93
LMM (UN)	3.36	3.77	1.92	1.85
LMM (CS)	3.24	3.78	1.92	1.86
SLR	4.02	4.02	2.09	1.93
Actual	Na	4.02	2.09	1.93

Appendix D
SAS Code and Results

D.1. SAS Code

```
PROC IMPORT DATAFILE='D:\06-13 Reid\Molly\X_Sec_Data_with_NUM.xls' OUT=data0
REPLACE;
RUN;

data DATA1;
 set DATA0;
 MERGER=777;
 run;
*** EXPLORATION OF THE DATA;
*** THE FOLLOWING IS TO EXAMINE SOME BASIC SUMMARY STATISTICS
    OF THE CRASH RATE RESPONSE VARIABLES;
proc sort data=DATA1;
 by TRT;
 run;
proc means mean data=DATA1;
 var DEV;
 ods output summary=out1;
 run;
data out1;
 set out1;
 MERGER=777;
data DATA2;
 merge DATA1 OUT1;
 by MERGER;
 cDEV=DEV-DEV_MEAN;
 SqrtIMP=sqrt(imp_cr);
 SqrtTOT=sqrt(tot_cr);
 drop MERGER;
run;


/***************** START GENERALIZED LINEAR MIXED MODEL SEARCH
*********************/
/*
 MODEL 1: IMP_CR ~ POISSON[Lambda(TRT,D1,D2,INT_LIGHTS,TRT*INT_LIGHTS,
                                  CDEV,TRT*CDEV,D1*CDEV,D2*CDEV,INT_LIGHTS*CDEV)]
 MODEL 2: IMP_CR ~ POISSON[Lambda(TRT,D1,D2,INT_LIGHTS,TRT*INT_LIGHTS,CDEV)]
 MODEL 3: IMP_CR ~ POISSON[Lambda(TRT,D1,D2,INT_LIGHTS,CDEV)]
 MODEL 4: IMP_CR ~ POISSON[Lambda(TRT,D1,D2,CDEV)]
 MODEL 5: IMP_CR ~ POISSON[Lambda(TRT,CDEV)]
 MODEL 6: IMP_CR ~ POISSON[Lambda(TRT,CDEV,TRT*CDEV)]
 MODEL 7: IMP_CR ~ POISSON[Lambda(TRT,D2,CDEV,TRT*CDEV)]
 MODEL 8: IMP_CR ~ POISSON[Lambda(TRT,D2,INT_LIGHTS,CDEV,TRT*CDEV)]
               Types: A ~ UN, B ~ CS, C~ TOEP, D ~ CSH
*/
%include "D:\glmm800.sas" / nosource;

title 'MODEL 1';
title2 'type=UN';
%glimmix(
       data=DATA2,
       stmts=%str(
                    class TRT NUM D1 D2 INT_LIGHTS;
                    model IMP_CR = TRT D1 D2 INT_LIGHTS TRT*INT_LIGHTS CDEV
TRT*CDEV
                        D1*CDEV D2*CDEV INT_LIGHTS*CDEV;
                    repeated / subject=NUM type=UN;
               ),
               error=poisson,
```

```
                        link=log
                );
run;
title 'MODEL 2';
title2 'type=UN';
%glimmix(
      data=DATA2,
      stmts=%str(
                              class TRT NUM D1 D2 INT_LIGHTS;
                              model IMP_CR = TRT D1 D2 INT_LIGHTS TRT*INT_LIGHTS CDEV;
                              repeated / subject=NUM type=UN;
                        ),
                        error=poisson,
                        link=log
                );
run;
title 'MODEL 3';
title2 'type=UN';
%glimmix(
      data=DATA2,
      stmts=%str(
                              class TRT NUM D1 D2 INT_LIGHTS;
                              model IMP_CR = TRT D1 D2 INT_LIGHTS CDEV;
                              repeated / subject=NUM type=UN;
                        ),
                        error=poisson,
                        link=log
                );
run;
title 'MODEL 4';
title2 'type=UN';
%glimmix(
      data=DATA2,
      stmts=%str(
                              class TRT NUM D1 D2 ;
                              model IMP_CR = TRT D1 D2 CDEV;
                              repeated / subject=NUM type=UN;
                        ),
                        error=poisson,
                        link=log
                );
run;
title 'MODEL 5';
title2 'type=UN';
%glimmix(
      data=DATA2,
      stmts=%str(
                              class TRT NUM ;
                              model IMP_CR = TRT CDEV;
                              repeated / subject=NUM type=UN;
                        ),
                        error=poisson,
                        link=log
                );
run;
title 'MODEL 6';
title2 'type=UN';
%glimmix(
      data=DATA2,
      stmts=%str(
                              class TRT NUM ;
```

```
                    model IMP_CR = TRT CDEV TRT*CDEV;
                    repeated / subject=NUM type=UN;
                ),
                error=poisson,
                link=log
        );
run;
title 'MODEL 7';
title2 'type=UN';
%glimmix(
      data=DATA2,
      stmts=%str(
                    class TRT NUM D2;
                    model IMP_CR = TRT D2 CDEV TRT*CDEV;
                    repeated / subject=NUM type=UN;
                ),
                error=poisson,
                link=log
        );
run;
title 'MODEL 8A';
title2 'type=UN';
%glimmix(
      data=DATA2,
      stmts=%str(
                    class TRT NUM D2 INT_LIGHTS;
                    model IMP_CR = TRT D2 INT_LIGHTS CDEV TRT*CDEV;
                    repeated / subject=NUM type=UN r;
                ),
                error=poisson,
                link=log
        );
run;
title 'MODEL 8B';
title2 'type=CS';
%glimmix(
      data=DATA2,
      stmts=%str(
                    class TRT NUM D2 INT_LIGHTS;
                    model IMP_CR = TRT D2 INT_LIGHTS CDEV TRT*CDEV;
                    repeated / subject=NUM type=CS r;
                ),
                error=poisson,
                link=log
        );
run;
title 'MODEL 8C';
title2 'type=TOEP';
%glimmix(
      data=DATA2,
      stmts=%str(
                    class TRT NUM D2 INT_LIGHTS;
                    model IMP_CR = TRT D2 INT_LIGHTS CDEV TRT*CDEV;
                    repeated / subject=NUM type=TOEP r;
                ),
                error=poisson,
                link=log
        );
run;
title 'MODEL 8D';
title2 'type=CSH';
```

```
%glimmix(
       data=DATA2,
       stmts=%str(
                            class TRT NUM D2 INT_LIGHTS;
                            model IMP_CR = TRT D2 INT_LIGHTS CDEV TRT*CDEV;
                            repeated / subject=NUM type=CSH r;
                       ),
                       error=poisson,
                       link=log
              );
run;
/*
                                        MODEL 1: Fit Statistics

                              -2 Res Log Likelihood           796.3
                              AIC (smaller is better)         816.3
                              AICC (smaller is better)        817.1
                              BIC (smaller is better)         839.6

                                        MODEL 2: Fit Statistics

                              -2 Res Log Likelihood           721.1
                              AIC (smaller is better)         741.1
                              AICC (smaller is better)        741.9
                              BIC (smaller is better)         764.4

                                        MODEL 3: Fit Statistics

                              -2 Res Log Likelihood           706.6
                              AIC (smaller is better)         726.6
                              AICC (smaller is better)        727.4
                              BIC (smaller is better)         749.9

                                        MODEL 4: Fit Statistics

                              -2 Res Log Likelihood           704.5
                              AIC (smaller is better)         724.5
                              AICC (smaller is better)        725.3
                              BIC (smaller is better)         747.8

                                        MODEL 5: Fit Statistics

                              -2 Res Log Likelihood           702.5
                              AIC (smaller is better)         722.5
                              AICC (smaller is better)        723.3
                              BIC (smaller is better)         745.8

                                        MODEL 6: Fit Statistics

                              -2 Res Log Likelihood           723.5
                              AIC (smaller is better)         743.5
                              AICC (smaller is better)        744.3
                              BIC (smaller is better)         766.8

                                        MODEL 7: Fit Statistics

                              -2 Res Log Likelihood           722.2
                              AIC (smaller is better)         742.2
                              AICC (smaller is better)        742.9
                              BIC (smaller is better)         765.5
```

```
                     MODEL 8A: Fit Statistics

          -2 Res Log Likelihood           724.2
          AIC (smaller is better)         744.2
          AICC (smaller is better)        745.0
          BIC (smaller is better)         767.5

                     MODEL 8B: Fit Statistics

          -2 Res Log Likelihood           735.3
          AIC (smaller is better)         739.3
          AICC (smaller is better)        739.3
          BIC (smaller is better)         744.0

                     MODEL 8C: Fit Statistics

          -2 Res Log Likelihood           734.6
          AIC (smaller is better)         742.6
          AICC (smaller is better)        742.7
          BIC (smaller is better)         751.9

                     MODEL 8D: Fit Statistics

          -2 Res Log Likelihood           729.9
          AIC (smaller is better)         739.9
          AICC (smaller is better)        740.1
          BIC (smaller is better)         751.6

*/

/***************** START LINEAR MIXED MODEL SEARCH *********************/
/*
 MODEL 1: SqrtIMP ~ NORMAL[MU(TRT,D1,D2,INT_LIGHTS,TRT*INT_LIGHTS,
                             CDEV,TRT*CDEV,D1*CDEV,D2*CDEV,INT_LIGHTS*CDEV),
SIGMA]
 MODEL 2: SqrtIMP ~ NORMAL[MU(TRT,D1,D2,INT_LIGHTS,TRT*INT_LIGHTS,CDEV,TRT*CDEV),
SIGMA]
 MODEL 3: SqrtIMP ~ NORMAL[MU(TRT,D1,D2,INT_LIGHTS,CDEV,TRT*CDEV), SIGMA]
 MODEL 4: SqrtIMP ~ NORMAL[MU(TRT,D2,INT_LIGHTS,CDEV,TRT*CDEV), SIGMA]
 MODEL 5: SqrtIMP ~ NORMAL[MU(TRT,D2,INT_LIGHTS,TRT*CDEV), SIGMA]
*/

title 'LMM MODEL 1';
title2 'type=UN';
proc mixed data=DATA2;
                          class TRT NUM D1 D2 INT_LIGHTS;
                          model SqrtIMP = TRT D1 D2 INT_LIGHTS TRT*INT_LIGHTS CDEV
                               TRT*CDEV D1*CDEV D2*CDEV INT_LIGHTS*CDEV/
outp=OUTLMM1;
                          repeated / subject=NUM type=UN;
run;
title 'LMM MODEL 2';
title2 'type=UN';
proc mixed data=DATA2;
                          class TRT NUM D1 D2 INT_LIGHTS;
                          model SqrtIMP = TRT D1 D2 INT_LIGHTS TRT*INT_LIGHTS CDEV
TRT*CDEV/ outp=OUTLMM2;
                          repeated / subject=NUM type=UN;
run;
title 'LMM MODEL 3';
```

```
title2 'type=UN';
proc mixed data=DATA2;
                          class TRT NUM D1 D2 INT_LIGHTS;
                          model SqrtIMP = TRT D1 D2 INT_LIGHTS CDEV TRT*CDEV/
outp=OUTLMM3;
                          repeated / subject=NUM type=UN;
run;

title 'LMM MODEL 4A';
title2 'type=UN';
proc mixed data=DATA2;
                          class TRT NUM D2 INT_LIGHTS;
                          model SqrtIMP = TRT D2 INT_LIGHTS CDEV TRT*CDEV/
outp=OUTLMM4;
                          repeated / subject=NUM type=UN r;
run;
title 'LMM MODEL 4B';
title2 'type=CS';
proc mixed data=DATA2;
                          class TRT NUM D2 INT_LIGHTS;
                          model SqrtIMP = TRT D2 INT_LIGHTS CDEV TRT*CDEV/
outp=OUTLMM4;
                          repeated / subject=NUM type=CS r;
run;
title 'LMM MODEL 4C';
title2 'type=CSH';
proc mixed data=DATA2;
                          class TRT NUM D2 INT_LIGHTS;
                          model SqrtIMP = TRT D2 INT_LIGHTS CDEV TRT*CDEV/
outp=OUTLMM4;
                          repeated / subject=NUM type=CSH r;
run;

title 'LMM MODEL 5';
title2 'type=UN';
proc mixed data=DATA2;
                          class TRT NUM D2 INT_LIGHTS;
                          model SqrtIMP = TRT D2 INT_LIGHTS TRT*CDEV/ outp=OUTLMM5
;
                          repeated / subject=NUM type=UN r;
run;
title 'LMM MODEL 5';
title2 'type=CS';
proc mixed data=DATA2;
                          class TRT NUM D2 INT_LIGHTS;
                          model SqrtIMP = TRT D2 INT_LIGHTS TRT*CDEV/ outp=OUTLMM5
solution ;
                          repeated / subject=NUM type=CS r;
run;
proc univariate data=OUTLMM4 normal plots;
 var resid;
 ods listing select plots testsfornormality;
 run;
```

D.2. Generalized Linear Mixed Model Results

MODEL 8A

type=UN

The Mixed Procedure

Model Information

Data Set	WORK._DS
Dependent Variable	_z
Weight Variable	_w
Covariance Structure	Unstructured
Subject Effect	NUM
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Between-Within

Class Level Information

Class	Levels	Values
TRT	2	0 1
NUM	76	26 28 34 43 51 52 74 75 109 112 116 121 125 150 176 177 203 227 231 233 237 265 267 268 272 298 299 339 345 349 355 361 368 389 412 439 441 459 463 467 468 469 478 486 490 497 499 572 577 582 783 791 797 809 837 841 851 855 860 861 864 865 870 873 886 897 898 914 919 942 943 969 970 975 980 981
D2	2	0 1
INT_LIGHTS	2	0 1

Dimensions

Covariance Parameters	10
Columns in X	10
Columns in Z	0
Subjects	76
Max Obs Per Subject	4
Observations Used	304
Observations Not Used	0
Total Observations	304

The Mixed Procedure

Parameter Search

CovP1	CovP2	CovP3	CovP4	CovP5	CovP6	CovP7	CovP8	CovP9
2.1286	1.0980	1.5260	1.0166	0.7218	1.7261	0.7589	0.5727	0.7358

Parameter Search

CovP10	Res Log Like	-2 Res Log Like
1.4329	-362.1210	724.2419

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
1	1	724.24192054	0.00000000

Convergence criteria met.

Estimated R Matrix for NUM 26/Weighted by _w

Row	Col1	Col2	Col3	Col4
1	1.3296	0.6778	0.6201	0.4574
2	0.6778	0.9311	0.4351	0.3411
3	0.6201	0.4351	1.0283	0.4330
4	0.4574	0.3411	0.4330	0.8331

Covariance Parameter Estimates

Cov Parm	Subject	Estimate
UN(1,1)	NUM	2.1286
UN(2,1)	NUM	1.0980
UN(2,2)	NUM	1.5260
UN(3,1)	NUM	1.0166
UN(3,2)	NUM	0.7218
UN(3,3)	NUM	1.7261
UN(4,1)	NUM	0.7589
UN(4,2)	NUM	0.5727
UN(4,3)	NUM	0.7358
UN(4,4)	NUM	1.4329

MODEL 8A
type=UN

The Mixed Procedure

Fit Statistics

-2 Res Log Likelihood	724.2
AIC (smaller is better)	744.2
AICC (smaller is better)	745.0
BIC (smaller is better)	767.5

PARMS Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
10	0.00	1.0000

Solution for Fixed Effects

Effect	TRT	D2	INT_ LIGHTS	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept				0.8447	0.1481	72	5.70	<.0001
TRT	0			-0.4700	0.1595	72	-2.95	0.0043
TRT	1			0	.	.	.	.
D2		0		0.3874	0.1482	72	2.61	0.0109
D2		1		0	.	.	.	.
INT_LIGHTS			0	-0.3477	0.2841	72	-1.22	0.2251
INT_LIGHTS			1	0	.	.	.	.
cDEV				0.000094	0.000012	72	7.93	<.0001
cDEV*TRT	0			-6.58E-6	0.000019	72	-0.35	0.7301
cDEV*TRT	1			0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
TRT	1	72	8.69	0.0043
D2	1	72	6.83	0.0109
INT_LIGHTS	1	72	1.50	0.2251
cDEV	1	72	94.14	<.0001
cDEV*TRT	1	72	0.12	0.7301

MODEL 8A

type=UN

The Mixed Procedure

GLIMMIX Model Statistics

Description	Value
Deviance	567.9791
Scaled Deviance	567.9791
Pearson Chi-Square	495.4177
Scaled Pearson Chi-Square	495.4177
Extra-Dispersion Scale	1.0000

MODEL 8B
type=CS

The Mixed Procedure

Model Information

Data Set	WORK._DS
Dependent Variable	_z
Weight Variable	_w
Covariance Structure	Compound Symmetry
Subject Effect	NUM
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Between-Within

Class Level Information

Class	Levels	Values
TRT	2	0 1
NUM	76	26 28 34 43 51 52 74 75 109 112 116 121 125 150 176 177 203 227 231 233 237 265 267 268 272 298 299 339 345 349 355 361 368 389 412 439 441 459 463 467 468 469 478 486 490 497 499 572 577 582 783 791 797 809 837 841 851 855 860 861 864 865 870 873 886 897 898 914 919 942 943 969 970 975 980 981
D2	2	0 1
INT_LIGHTS	2	0 1

Dimensions

Covariance Parameters	2
Columns in X	10
Columns in Z	0
Subjects	76
Max Obs Per Subject	4
Observations Used	304
Observations Not Used	0
Total Observations	304

MODEL 8B
type=CS

The Mixed Procedure

Parameter Search

CovP1	CovP2	Variance	Res Log Like	-2 Res Log Like
0.7927	0.8934	0.8934	-367.6462	735.2924

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
1	1	735.29243116	0.00000000

Convergence criteria met.

Estimated R Matrix for NUM 26/Weighted by _w

Row	Col1	Col2	Col3	Col4
1	1.0656	0.4949	0.4887	0.4825
2	0.4949	1.0397	0.4827	0.4766
3	0.4887	0.4827	1.0140	0.4707
4	0.4825	0.4766	0.4707	0.9886

Covariance Parameter Estimates

Cov Parm	Subject	Estimate
CS	NUM	0.7927
Residual		0.8934

Fit Statistics

-2 Res Log Likelihood	735.3
AIC (smaller is better)	739.3
AICC (smaller is better)	739.3
BIC (smaller is better)	744.0

MODEL 8B
type=CS

The Mixed Procedure

PARMS Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
1	0.00	1.0000

Solution for Fixed Effects

Effect	TRT	D2	INT_ LIGHTS	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept				0.7793	0.1554	72	5.01	<.0001
TRT	0			-0.4206	0.1642	72	-2.56	0.0125
TRT	1			0	.	.	.	.
D2		0		0.4392	0.1545	72	2.84	0.0058
D2		1		0	.	.	.	.
INT_LIGHTS			0	-0.3250	0.2900	72	-1.12	0.2661
INT_LIGHTS			1	0	.	.	.	.
cDEV				0.000100	0.000012	226	8.11	<.0001
cDEV*TRT	0			-8.54E-6	0.000020	226	-0.44	0.6622
cDEV*TRT	1			0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
TRT	1	72	6.56	0.0125
D2	1	72	8.07	0.0058
INT_LIGHTS	1	72	1.26	0.2661
cDEV	1	226	99.29	<.0001
cDEV*TRT	1	226	0.19	0.6622

GLIMMIX Model Statistics

Description	Value
Deviance	535.4398
Scaled Deviance	599.2999
Pearson Chi-Square	488.3641
Scaled Pearson Chi-Square	546.6097
Extra-Dispersion Scale	0.8934

D.3. Linear Mixed Model Results

```
LMM MODEL 4A        10:02 Monday, November 3, 2003
   type=UN

The Mixed Procedure

Model Information

Data Set                     WORK.DATA2
Dependent Variable           SqrtIMP
Covariance Structure         Unstructured
Subject Effect               NUM
Estimation Method            REML
Residual Variance Method     None
Fixed Effects SE Method      Model-Based
Degrees of Freedom Method    Between-Within


Class Level Information

Class         Levels    Values

TRT                2    0 1
NUM               76    26 28 34 43 51 52 74 75 109
                        112 116 121 125 150 176 177
                        203 227 231 233 237 265 267
                        268 272 298 299 339 345 349
                        355 361 368 389 412 439 441
                        459 463 467 468 469 478 486
                        490 497 499 572 577 582 783
                        791 797 809 837 841 851 855
                        860 861 864 865 870 873 886
                        897 898 914 919 942 943 969
                        970 975 980 981
D2                 2    0 1
INT_LIGHTS         2    0 1


Dimensions

Covariance Parameters           10
Columns in X                    10
Columns in Z                     0
Subjects                        76
Max Obs Per Subject              4
Observations Used              304
Observations Not Used            0
Total Observations             304
```

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	725.64799374	
1	2	663.36737099	0.00000007
2	1	663.36736702	0.00000000

Convergence criteria met.

Estimated R Matrix for NUM 26

Row	Col1	Col2	Col3	Col4
1	0.6712	0.2917	0.2801	0.2440
2	0.2917	0.5190	0.1970	0.1475
3	0.2801	0.1970	0.5165	0.2039
4	0.2440	0.1475	0.2039	0.5148

Covariance Parameter Estimates

Cov Parm	Subject	Estimate
UN(1,1)	NUM	0.6712
UN(2,1)	NUM	0.2917
UN(2,2)	NUM	0.5190
UN(3,1)	NUM	0.2801
UN(3,2)	NUM	0.1970
UN(3,3)	NUM	0.5165
UN(4,1)	NUM	0.2440
UN(4,2)	NUM	0.1475
UN(4,3)	NUM	0.2039
UN(4,4)	NUM	0.5148

Fit Statistics

-2 Res Log Likelihood	663.4
AIC (smaller is better)	683.4
AICC (smaller is better)	684.1
BIC (smaller is better)	706.7

The Mixed Procedure

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
9	62.28	<.0001

Solution for Fixed Effects

Effect	TRT	D2	INT_ LIGHTS	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept				1.3584	0.1252	72	10.85	<.0001
TRT	0			-0.3083	0.1273	72	-2.42	0.0180
TRT	1			0	.	.	.	.
D2		0		0.3727	0.1340	72	2.78	0.0069
D2		1		0	.	.	.	.
INT_LIGHTS			0	-0.5276	0.2309	72	-2.29	0.0252
INT_LIGHTS			1	0	.	.	.	.
cDEV				0.000113	0.000014	72	7.90	<.0001
cDEV*TRT	0			-0.00004	0.000020	72	-2.19	0.0317
cDEV*TRT	1			0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
TRT	1	72	5.86	0.0180
D2	1	72	7.74	0.0069
INT_LIGHTS	1	72	5.22	0.0252
cDEV	1	72	83.70	<.0001
cDEV*TRT	1	72	4.80	0.0317

The Mixed Procedure

Model Information

Data Set	WORK.DATA2
Dependent Variable	SqrtIMP
Covariance Structure	Compound Symmetry
Subject Effect	NUM
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Between-Within

Class Level Information

Class	Levels	Values
TRT	2	0 1
NUM	76	26 28 34 43 51 52 74 75 109 112 116 121 125 150 176 177 203 227 231 233 237 265 267 268 272 298 299 339 345 349 355 361 368 389 412 439 441 459 463 467 468 469 478 486 490 497 499 572 577 582 783 791 797 809 837 841 851 855 860 861 864 865 870 873 886 897 898 914 919 942 943 969 970 975 980 981
D2	2	0 1
INT_LIGHTS	2	0 1

Dimensions

Covariance Parameters	2
Columns in X	10
Columns in Z	0
Subjects	76
Max Obs Per Subject	4
Observations Used	304
Observations Not Used	0
Total Observations	304

The Mixed Procedure

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	725.64799374	
1	2	668.99784335	0.00000000

Convergence criteria met.

Estimated R Matrix for NUM 26

Row	Col1	Col2	Col3	Col4
1	0.5559	0.2279	0.2279	0.2279
2	0.2279	0.5559	0.2279	0.2279
3	0.2279	0.2279	0.5559	0.2279
4	0.2279	0.2279	0.2279	0.5559

Covariance Parameter Estimates

Cov Parm	Subject	Estimate
CS	NUM	0.2279
Residual		0.3281

Fit Statistics

-2 Res Log Likelihood	669.0
AIC (smaller is better)	673.0
AICC (smaller is better)	673.0
BIC (smaller is better)	677.7

Null Model Likelihood Ratio Test

DF	Chi-Square	Pr > ChiSq
1	56.65	<.0001

Solution for Fixed Effects

Effect	TRT	D2	INT_ LIGHTS	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept				1.3192	0.1286	72	10.26	<.0001
TRT	0			-0.2784	0.1310	72	-2.13	0.0370
TRT	1			0	.	.	.	.
D2		0		0.3958	0.1379	72	2.87	0.0054
D2		1		0	.	.	.	.

INT_LIGHTS		0	-0.5157	0.2377	72	-2.17	0.0333
INT_LIGHTS		1	0	.	.	.	.
cDEV			0.000119	0.000015	226	7.98	<.0001
cDEV*TRT	0		-0.00005	0.000021	226	-2.26	0.0248
cDEV*TRT	1		0	.	.	.	.

The Mixed Procedure

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
TRT	1	72	4.52	0.0370
D2	1	72	8.24	0.0054
INT_LIGHTS	1	72	4.71	0.0333
cDEV	1	226	84.65	<.0001
cDEV*TRT	1	226	5.11	0.0248

Appendix E
All-Red Policies

All-red Clearance Policies

Bloomington, MN: All controllers in town use all-red except a few old mid block ped controllers that are being replaced. They use MNDOT guidelines, R=(w+L)/(1.467v), to time the interval.

Illinois DOT: Refers to Bureau of Operations Traffic Policies and Procedures Manual, 1992, section 4B-15:

4B-15 Vehicle Change (Clearance) Interval In determining the duration of a yellow clearance interval, the following formula should be used.

$$Y + AR = t + \frac{v}{2a} + \frac{w + l}{v}$$

Where Y = length of yellow in seconds

AR = length of all-red in seconds

t = perception - reaction time of driver in seconds; the standard value is 1 second

v = approach speed in feet per second

a = deceleration rate in feet per second per second; the value 10 feet per second per second should be used.

w = width of intersection in feet.

l = length of vehicle in feet; the standard value is 20 feet.

The final determination of the appropriateness of any yellow/all-red ratio should be determined by field observation. However, consideration should be given to making the initial yellow setting equal to the time obtained from the first two terms of the above equation rounded up to the next 0.5 second with the all-red setting equal to the remainder of the time. Yellow intervals less than 3 seconds or more than 5 seconds in length should normally not be used. Clearance intervals computed to be in excess of 5 seconds should have 5 seconds of the yellow and the remainder of the time as an all-red interval.

This formula does not take into consideration the effect of grades on stopping distances. Adjustments should be made if field observation indicates a change is needed.

Illinois has also adopted MUTCD which includes Section 4D.10 Yellow Change and Red Clearance Intervals.

Section 4D.10 Yellow Change and Red Clearance Intervals

Standard:
A yellow signal indication shall be displayed following every CIRCULAR GREEN or GREEN ARROW signal indication.

The exclusive function of the yellow change interval shall be to warn traffic of an impending change in the right-of-way assignment.

The duration of a yellow change interval shall be predetermined.

Guidance:
A yellow change interval should have a duration of approximately 3 to 6 seconds. The longer intervals should be reserved for use on approaches with higher speeds.

Option:
The yellow change interval may be followed by a red clearance interval to provide additional time before conflicting traffic movements are released.

Standard:
The duration of a red clearance interval shall be predetermined.

Guidance:
A red clearance interval should have a duration not exceeding 6 seconds.

Indiana DOT: each district decides how it will handle a specific location. However as a general rule, the districts have settled on a general means that is used in many cases. There are variations in actual practice; however, this is the general method of determining the all-red interval.

See next pages for Indiana policy/procedure.

A. THE PURPOSE OF THE VEHICLE CLEARANCE INTERVAL IS TWO FOLD:

1. To advise drivers that the green interval has ended and to allow them to come to a safe stop,
2. To allow vehicles which are too close to the intersection to either stop safely, or, clear the intersection.
3. Vehicles which are already legally in the intersection to clear the intersection.

The VEHICLE CLEARANCE INTERVAL will consist of yellow and all-red intervals according to the two categories:

1. Through traffic, and
2. Left turning traffic.

B. MAINLINE AND MINOR APPROACH STREET THROUGH TRAFFIC YELLOW INTERVAL

The yellow interval for through vehicular traffic is established from Table 2.3.1 (Yellow and All-Red Intervals). This table relates the total clearance interval (sum of yellow and any required all red intervals) to vehicle approach speed and critical width of the intersection. The vehicular approach speed to be used in Table 2.3.1 is one of the following:

1. Established speed by radar studies,
2. Posted speed limit or
3. Observed approach speed.

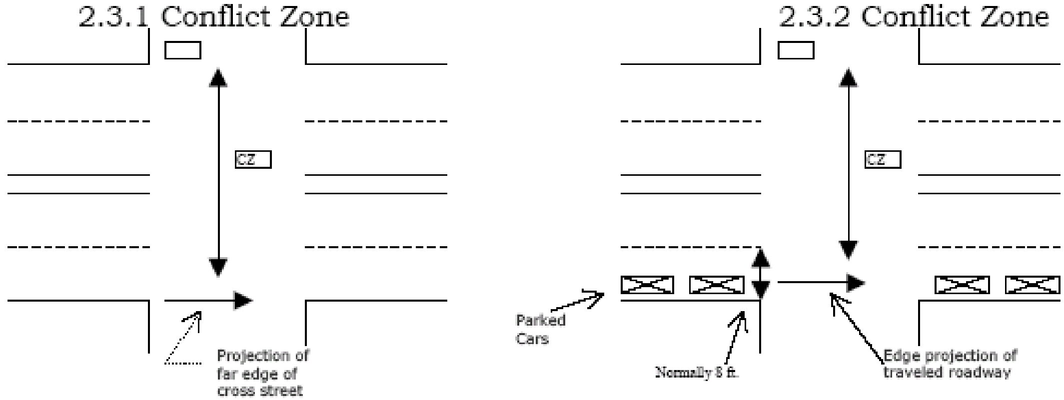
The critical width of the intersection to be used in Table 2.3.1 is considered the distance from the stop bar to a point across the intersection where the vehicle is no longer subject to a vehicular conflict (The CONFLICT ZONE). This point is:

1. the projection of the cross traffic far edge of traveled pavement (see drawing 2.3.1), or,
2. eight (8) feet from the projection of the cross street traffic far edge of pavement, IN THE CASE OF PARKING ALONG THE ROAD EDGE. (see drawing 2.3.2)
3. in very wide intersections, you might want to consider subtracting reaction time for the first opposing vehicle

1. DETERMINING WIDTH OF INTERSECTION, TO BE USED FOR TABLE 2.3.1

2.3.1 Conflict Zone

2.3.2 Conflict Zone



clearing vehicle f 100 v_c=velocity
vehicle clears ft/sec

Table 2.3.2
YELLOW & ALL RED INTERVALS (METRIC SYSTEMS)

Approach Speed (mph)	Velocity (ft/sec)	Yellow Interval (Y)		All red clearance interval ® Critical Width + Vehicle Length													
				18.3	21.3	24.4	27.4	30.5	33.5	33.5	36.6	42.7	45.7	48.8	51.8	54.9	57.9
35	9.72	3.0[1]	R=	1.9	2.2	2.5	2.8	3.1	3.5	3.8	4.1	4.4	4.7	5.0	5.3	5.5	6.0
			Y+R=	4.9	5.2	5.5	5.8	6.1	6.5	6.8	7.1	7.4	7.7	8.0	8.3	8.5	9.0
40	11.11	3.0[1]	R=	1.7	1.9	2.2	2.5	2.8	3.0	3.3	3.6	3.9	4.1	4.4	4.7	5.0	5.2
			Y+R=	4.7	4.9	5.2	5.5	5.8	6.0	6.3	6.6	6.9	7.1	7.4	7.7	8.0	8.2
50	13.89	3.3	R=	1.3	1.5	1.8	2.0	2.2	2.4	2.6	2.9	3.1	3.3	3.5	3.7	4.0	4.2
			Y+R=	4.6	4.8	5.1	5.3	5.5	5.7	5.9	6.2	6.5	6.6	6.8	7.0	7.3	7.5
55	15.28	3.6	R=	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8
			Y+R=	4.8	5.0	5.2	5.4	5.6	5.8	6.0	6.2	6.4	6.6	6.8	7.0	7.2	7.4
60	16.67	3.8	R=	1.1	1.3	1.5	1.7	1.8	2.0	2.2	2.4	2.6	2.8	2.9	3.1	3.3	3.5
			Y+R=	4.9	5.1	5.3	5.5	5.6	5.8	6.0	6.2	6.4	6.6	6.7	6.9	7.1	7.3
65	18.06	4.0	R=	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.2	2.4	2.5	2.7	2.9	3.0	3.2
			Y+R=	5.0	5.2	5.4	5.5	5.7	5.9	6.0	6.2	6.4	6.5	6.7	6.9	7.0	7.2
70	19.44	4.3	R=	1.0	1.1	1.3	1.4	1.6	1.7	1.9	2.0	2.2	2.4	2.5	2.7	2.8	3.0
			Y+R=	5.3	5.4	5.6	5.7	5.9	6.0	6.2	6.3	6.5	6.7	6.8	7.0	7.1	7.3
75	22.83	4.5	R=	0.9	1.0	1.2	1.3	1.5	1.6	1.8	1.9	2.1	2.2	2.4	2.5	2.6	2.7
			Y+R=	5.4	5.5	5.7	5.8	6.0	6.1	6.3	6.4	6.6	6.7	6.9	7.0	7.1	7.3
80	22.22	4.7	R=	0.8	1.0	1.1	1.2	1.4	1.5	1.7	1.8	1.9	2.1	2..2	2.3	2.5	2.6
			Y+R=	5.5	5.7	5.8	5.9	6.1	6.2	6.4	6.5	6.6	6.8	6.9	7.0	7.2	7.3
90	25.00	5.2	R=	0.7	0.9	1.1	1.1	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.3
			Y+R=	5.9	6.1	6.2	6.3	6.4	6.5	6.7	6.8	6.9	7.0	7.2	7.3	7.4	7.5
95	26.39	5.4	R=	0.7	0.8	0.9	1.0	1.2	1.3	1.4	1.5	1.6	1.7	1.9	2.0	2.1	2.2
			Y+R=	6.1	6.2	6.3	6.4	6.6	6.7	6.8	6.9	7.0	7.1	7.3	7.4	7.5	7.6

1. For ease of setting controller 3 seconds has been chosen as the minimum yellow interval.

NOTE: Values rounded (>0.04 + 0.1). Values derived from eq: $Y=tp+\frac{v_i}{2a}+\frac{W+l}{v_c}$ where: Y=

t=

If grades are involved use

v_i=initial m/sec.

$a=3.0 m/sec^2$

where $g=9.81 m/sec^2$

w=critical m

$\frac{G=Grade}{100}$

l=length m

v_c=m/sec.

1. DISCUSSION ABOUT YELLOW INTERVAL

The exclusive function of the steady yellow interval shall be to warn traffic of an impending change in the right-of-way assignment. Yellow vehicle change intervals should have a range of 3 to 6 seconds. Generally, the longer intervals are appropriate to high approach speeds. A clearance interval shall be provided between the termination of a GREEN ARROW indication and the showing of a green indication to any conflicting traffic movement. A YELLOW ARROW shall bot be terminated by a GREEN ARROW. It may be terminated by a CIRCULAR GREEN if the movement controlled by the arrow is to coninue on a permissive basis, or by a CIRCULAR YELLOW or CIRCULAR RED. The yellow vehicle change interval may be folloed by a red clearance interval of sufficient duration to permit traffic to clear the intersection before conflicting traffic movements are released.

2. MINIMUM VEHICULAR CHANGE INTERVALS FOR THROUGH MOVEMENTS

The minimum vehicular change intervals shown in table 2.3.1 for thru movements.

1. Excessively short or long yellow intervals tend to encourage driver disrespect, therefore the yellow interval is confined to values between three (3.0) and five and on-tenth (5.1) seconds with the remainder of the clearance interval taken up in the all red interval. The distribution between the two intervals will be discussed in the section on all red clearance intervals.
2. The primary difference between Table 2.3.1 and similar tables utilized previously is the deceleration rate used. Previous tables used a deceleration rate of 15 ft/sec/sec while Table 2/3/1 uses 10 ft/sec/sec. This change is based upon published literature relating to clearance intervals which indicates a rate of 10 ft/sec/sec is more realistic and acceptable to the driver.

3. LEFT TURNING TRAFFIC YELLOW INTERVAL (LEFT TURN ARROW)

1. This controller time setting is established as follows:
   a. 3.5 seconds – Initial trial setting
   b. 1.0 - All Red
   c. 3.0 seconds – Minimum allowable setting. This minimum value is never to be violated.
2. Field Adjusted Setting
3. Normally an all red interval would not be included with the left turn yellow interval for exclusive left turn phases. The all red clearance interval may be considered if an accident analysis indicates a need.

4. ALL RED CLEARANCE INTERVAL

As indicated previously, the setting of the all red interval is dependent upon the total vehicle clearance interval required. The yellow clearance time is kept at or below 5.1 seconds with the remainder of the total clearance interval required timed as all red clearance. See Table 2.3.1

NOTE: When there is heavy truck volume, the formula for Yellow and all red intervals' changes, since (1) the length of clearing vehicle increases from 20 to 55.

Minnesota DOT:

Yellow and Red Timing

The MMUTCD states that the exclusive function of the steady yellow interval shall be to warn traffic of an impending change of right-of-way assignment. The yellow vehicle change interval should have a range of approximately 3 to 6 seconds. Generally the longer intervals are appropriate to higher approach speeds. The yellow vehicle change interval should be followed by a short all-way red clearance interval, of sufficient duration to permit the intersection to clear before cross traffic is released.

Minnesota Traffic Laws state that vehicular traffic facing a yellow indication are warned that the related green movement is being terminated or that the red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. Therefore, the yellow and all-red intervals advises that the green interval is about to end and either;

- permits the vehicle to come too a safe stop at the stop line, or
- allows vehicles that are to near the intersection to stop to safely clear the intersection.

Yellow Timing

The following formulas may be used to determine the yellow time.

$$Y = t + \frac{1.467v}{2(a + 64.4p)} \qquad Y = t + \frac{0.447v}{2(a + 9.81p)}$$

English **Metric**

Y = Yellow Interval in seconds

t = perception-reaction time, assumed to be 1 second

v = approach speed, 85th percentile in miles per hour

a = deceleration rate, assumed to be 10 feet/sec/sec(English), or 3 meters/sec^2

p = + or - grade of approach in percent/100

85th Percentile Speed	Percent Grade							Mn/DOT
	+3	+2	+1	Level	-1	-2	-3	
25	2.7	2.7	2.8	2.8	2.9	3.0	3.0	**3.0**
30	3.0	3.1	3.1	3.2	3.3	3.4	3.4	**3.5**
35	3.3	3.4	3.5	3.6	3.7	3.7	3.8	**4.0**
40	3.7	3.8	3.8	3.9	4.0	4.1	4.3	**4.0**
45	4.0	4.1	4.2	4.3	4.4	4.5	4.7	**4.5**
50	4.4	4.5	4.6	4.7	4.8	4.9	5.1	**5.0**
55	4.7	4.8	4.8	5.0	5.2	5.3	5.5	**5.5**
60	5.0	5.1	5.1	5.4	5.6	5.7	5.9	**6.0**
65	5.4	5.5	5.5	5.8	5.9	6.1	6.3	**6.0**

All Red

$$R = \frac{w + L}{1.467v}$$

English

$$R = \frac{w + L}{0.447v}$$

Metric

R = All red clearance interval in seconds

w = width of intersection, stop line to center of farthest conflicting lane

l = length of vehicle, assumed to be 20 feet or 6.1 meters

v = 85th percentile speed in mile per hour

85th Percentile Speed	Width of Intersection								
	30	40	50	60	70	80	90	100	110
25	1.4	1.6	1.9	2.2	2.5	2.7	3.0	3.3	3.5
30	1.1	1.4	1.6	1.8	2.0	2.3	2.5	2.7	3.0
35	1.0	1.2	1.4	1.6	1.8	1.9	2.1	2.3	2.5
40	0.9	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.2
45	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.8	2.0
50	0.7	0.8	1.0	1.1	1.2	1.4	1.5	1.6	1.8
55	0.6	0.7	0.9	1.0	1.1	1.2	1.4	1.5	1.6
60	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.5

These formulas are general and should only be used as a guide. Other factors at an intersection (such as approach grades, visibility, truck traffic and local traffic characteristics) should be considered. It is important that approach grades and truck traffic are considered in determining the yellow and red intervals. The yellow interval must not be too short (causing quick stops and/or red violations) nor too long (causing regular "driving of the yellow").

Slower vehicles traveling at the 15th percentile speed, particularly at wide intersections, may require longer yellow and red time. Therefore, for special situations it may be desirable to compute the equation using both the 85th and 15th percentile speeds and use the longer on the two computed values.

The all-red should be in the range of 1 to 5 seconds.

Missouri DOT: The Missouri DOT provided the following document excerpt to explain their use of all-red phasing:

6.3.2 Clearance and Change Intervals (Change Period)

The change interval (yellow indication) and clearance interval (all indications displaying red, if used) are required in order to prepare the intersection for the transfer of right-of-way. These intervals permit vehicles which are either within the intersection or so close to it that they cannot comfortably stop to clear the intersection, and to permit those vehicles which can come to a comfortable stop to do so. The total time of the yellow change interval and the red clearance interval (if used) is the change period.

According to the MUTCD, the yellow change intervals should have a range of 3 to 6 seconds. To develop statewide consistency and to prevent excessive yellow times that may lead to red light violations, yellow change intervals should be between 4 and 5 seconds. Tighter local consistency is also recommended where possible . If a phase change period longer than the selected yellow change interval is needed then the additional time is provided by an all-red interval.

The addition of an all-red clearance interval should not be automatically provided after every movement. The all-red time has become nearly automatic at intersections, and with this has come increased driver expectancy of an all-red. Over-use may lead to drivers incorrectly assuming a change will be timed out with all-red and failing to clear the intersection in time. The use of an all-red should be reserved for phases where either a phase change period longer than the selected yellow change interval is needed or where observations show a need. A common need is for unusually wide intersections. Proper application of the following formula should eliminate most cases of needless all-red intervals.

The duration of change and clearance intervals, as well as the appropriateness of red clearance intervals, is a topic with no clear consensus. The following formula is developed based on a kinematic model of stopping behavior to determine the duration of the yellow and red indications, and is in common use throughout the country.

Change Period:

$$CP = t + \frac{V}{2a + 64.4g} + \frac{W + L}{V}$$

CP = nondilemma change period (yellow plus all-red), seconds

t = perception-reaction time, recommended as 1.0 sec.

V = approach speed, feet/second

g = percent grade (positive for upgrade, negative for downgrade)

a = deceleration rate, recommended values as follows:

10 feet/second^2 - low speed approaches, i.e. CBD
12.5 feet/second^2 - typical arterial approaches

15 feet/second^2 - high speed approaches

W = width of intersection, feet

L = length of vehicle, recommended as 20 ft

NOTE: **CP greater than 7 seconds not recommended.**

A spot-speed study on an approach to an intersection will produce a range (or distribution) of speeds. Typically, the 85th percentile speed or the prevailing speed limit has been used to determine the yellow change interval. It is important, however, to also consider slower traffic going through the intersection at the 15th percentile speed. Low speeds and wide intersections or large left turn radii are a combination that may require a longer change periods (yellow plus all-red). It may be necessary, therefore, to calculate the equation using both the 85th and 15th percentile speeds and to employ the longer of the two calculations.

Using this equation for approaches with steep downgrades yields such long intervals that they appear unreasonable to drivers as well as the engineer. The remedy is not to ignore the physics of the situation when an unusually long phase change period results from a steep grade or from high approach speeds. The remedy may come from other devices, such as warning signs, or other countermeasures.

Nebraska Department of Roads (NDOR) (including references to policies of Grand Island and Lincoln): Source: Discussion with NDOR staff

The policy of the Nebraska Department of Roads regarding clearance intervals for thru phases is to use 4.5 to 5 seconds of yellow and 0.5 to 1.0 second of all-red. This does not correspond to the ITE recommended practice, as state law requires a driver to stop for yellow signals. The city of Grand Island uses the ITE recommended practice for their signals. The city of Lincoln has used three second all-red intervals in the central business district (CBD) for many years. Anecdotal observation of this indicates that the drivers may have learned to expect the long all-red interval. Additional anecdotal information indicates an alarming development: these drivers may also expect long all-reds on all intersections.

Staff indicated that in order for a vehicle to be struck by another vehicle that is running a red light, they must first get into position to be hit. To move from the stopbar to the middle of the first through lane requires 5 to 7 seconds. This means that a vehicle running a red light that strikes another vehicle entered the intersection 5 to 7 seconds after the end of the existing all-red interval. When viewed in this light, an argument about whether all-reds should be one second or three seconds may be irrelevant.

Ohio DOT: Below is an excerpt from Ohio's Traffic Engineering Manual (TEM). The entire manual can be found on the ODOT web site; on the Office of Traffic Engineering page. (From the Traffic page; choose manuals and publications from the selections on the left.)

ODOT usually provides an all-red clearance interval. The TEM is ODOT's rules; not necessarily a local jurisdiction's. The local jurisdictions are only required to follow the OMUTCD so the "may be followed by a red clearance interval" allows them some flexibility in deciding their own policies.

403-2 Vehicle Change Interval

The vehicle change interval (or phase change interval) described in OMUTCD Section 6B-15 consists of the yellow change interval and the all-red clearance interval. The yellow change interval advises drivers that their phase has expired and that they should stop or proceed through the intersection if they are too close to stop. The yellow change interval should be followed by a red clearance interval (all-red interval) of sufficient duration to permit traffic to clear the intersection before conflicting traffic movements are released. For more efficient operations, start-up time for the conflicting movements may be considered when setting the length of the all-red.

The length of the phase change interval can be determined using the following equation, in which $[(W+L)/V]$ represents the all-red interval:

$Y + AR = t + V/(2a + 64.4g) + [(W + L) / V]$ (for English units)

$Y + AR = t + V/(2a + 19.6g) + [(W + L) / V]$ (for metric)

Where:

$Y + AR$ = Sum of the yellow and all-red,

t = perception/reaction time of driver, (typically assumed to be 1 second)

V = approach speed, ft/s (m/s)

a = deceleration rate, ft/s2 (m/s2) (typically assumed to be 10 ft/s2 (3.0 m/s2))

W = width of intersection, ft (m) (measured from the near side Stop Line to the far edge of the conflicting traffic lane, along the actual vehicular path)

L = length of vehicle, ft (m) (typically assumed to be 20 feet (6.0 meters))

g = approach grade, percent of grade divided by 100 (plus for upgrade, minus for downgrade)

Yellow change intervals typically are in the range of three to six seconds, and the typical maximum all-red interval is two seconds.

- Provided by Dave Holstein, ODOT Office of Traffic Engineering