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Effect of Signing and Lane Markings on the Safety of a Two-Lane Roundabout

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Research Project
Final Report 2014-04

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16. Abstract (Limit: 250 words)

This report presents a study of the impact lane markings and signing have on driving behavior at a two-lane roundabout located in Richfield, Minnesota. After its completion in 2008, this roundabout sustained a suspiciously high amount of crashes. In response, through this study, engineers experimented with changes in the roundabout's signs and lane markings, as roundabout design regulations are relatively lax and non-specific in contrast to those for standard signalized intersections. An observational study was conducted that reduced 216 hours of before and after video records of the roundabout into a database of all the violations committed by drivers. Along with the observational data, crash records were analyzed and demonstrated that improper turns and failing to properly yield account for the majority of collisions. The changes implemented in the approaches to the roundabout and specifically the extension of the solid line seems to have reinforced the message to the drivers that they must select the correct lane before approaching the roundabout entrance. Although choosing the correct lane does not directly address yielding violations, it does reduce the occurrence of drivers conducting an improper turn and to some extent reduces the need for a driver to change lanes within the roundabout. The implemented changes produced a 48% reduction in normalized occurrences of improper turns, and a 53% reduction in normalized occurrences of drivers choosing the incorrect lane a month after the changes, while a year later, these reductions were 44% and 50%, respectively.

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Executive Summary

This report describes the results from a straightforward before and after study of the effect of changes in signs and lane markings on a two–lane roundabout in Richfield, Minnesota. The subject roundabout was designed with the best standards and guidelines available in 2005. For the 35 months following its construction, it exhibited a suspiciously high crash rate for its type and demand. City, county and state engineers, having observed driving behavior in this and other roundabouts as well as having available the more detailed guidelines in the 2009 Manual of Uniform Traffic Control Devices (MUTCD), decided to experiment with changes in the roundabout signs and lane markings. A set of proposed changes on the roundabout signs and lane markings was produced in an attempt to improve roundabout safety and clarify best practices for the industry.

This study followed a more expedient evaluation of the effects of the planned changes. The research team capitalized on prior, unrelated, research conducted in this roundabout by the Minnesota Traffic Observatory to perform an observational study on the effect of the changes in driving violations performed within the roundabout. The earlier research had produced several hundred hours of video records of all the activity around the roundabout. Repeating the same data collection exercise after the changes were implemented as well as a year after that allowed the research team to identify and count all violations performed by vehicles using the roundabout before, after and a year after the changes. Although the value of the exercise would have been greatly increased if data collection had been performed on a control site also, the project budget and timeline made this impossible. Regardless, the produced results display such large differences in the rates of certain violations before and after the changes that the positive effect of the changes can be safely illustrated.

Notable differences between the “before” and “after” data include a reduction in yielding and turning violations, although all types of violations exhibited decreases in their normalized frequencies. These two types of violations account for the majority and most severe crashes. Specifically, 1.04% of vehicles entering the roundabout in “before” committed a yielding violation, whereas “after” only 0.85% did, resulting in a 18% reduction, with a more notable drop in failing to yield to the outer lane than the inner lane. Turning violations were committed by 1.16% of vehicles “before” and 0.60% “after,” boasting an occurrence reduction of 48%. The most common turning violation, making a left turn from the outer lane, was the primary contribution to the overall reduction and exhibits the most significant reduction in both count and rate of occurrence of all the violation types. This observation can be coupled with a decrease in the “Incorrect Lane Choice” for the intended destination, which decreased by 53%.

The “one-year-after” data suggests some behavior has stabilized while other behavior has regressed since the initial changes. Specifically, a 60% increase in instances of yielding violations has taken place between “after” and “one year after.” An overall 31% increase in normalized occurrences of yielding failures were observed between the “before” and the “one-year-after” periods. The volume of vehicles using the roundabout increased by 28% between “before” and “after” and by an additional 1% the year after that. The study has shown a correlation between “failure to yield” violations and traffic volume while the other types of violations do not show such a strong relationship.

Turning violations were committed by 1.16% of vehicles in 2010, 0.6% in 2011, and 0.65 in 2012. The comparison between "before" and "after," which includes the influence from the public relations and enforcement campaign, boasts an occurrence reduction of 48%, while a "year after" this, improvement seems to have retained its level at 44%. Focusing on the most common turning violation, making a left turn from the outer lane, we see that it is the primary contribution to the overall reduction of turning violations and exhibits the most significant reduction in both count and per capita occurrence of all the violation types. Specifically, instances of left turn from the outer lane were reduced by 49% two months after the changes and retained this improvement level a year after at 46%. In contrast to the yielding violations, the turn violations show a lasting improvement over time suggesting that the changes permanently affected driver behavior.

1. Introduction

Distinct from other forms of circular roadways, modern roundabouts require entering traffic to deflect into circular motion parallel to through traffic, and yield the right-of-way to traffic within the circulatory roadway. By deflecting entering traffic, vehicles are forced to reduce their speed, which along with the presence of fewer conflict points, makes the modern roundabout notably safer than a traditional signalized intersection (Retting et al, 2001). With benefits such as improved safety, minimized delays, and reduced vehicle emissions, roundabouts have become an increasingly popular design solution for intersections throughout the United States since the 1990s (Baranowski, 2009). Despite this increase, drivers throughout the country continue to misunderstand the rules of the roundabout, resulting in improper use and avoidable collisions. As reported by several professionals, two-lane, two-lane entrance (2-by-2) roundabouts seem to present a particular problem in regards to low-speed collisions.

In an attempt to minimize collisions associated with confused drivers, numerous engineering design solutions have been suggested and implemented. Before engineering practices and regulations are changed to accommodate the most successful design features, sufficient research must be conducted in order to determine which alternatives are effective, and which are not. Crash statistics are generally used as the basis of such research, but require several years of data preceding and following the changes made. In addition, it is difficult to control for all confounding factors when data are collected over very long periods making difficult the study of incremental improvements. As an alternative to waiting for sufficient crash statistics, observational studies can collect evidence of the changes in driving behavior and use crash surrogates to evaluate the impact of changes. This study attempts to do this in order to evaluate the effect a new sign and road marking layout has on a roundabout that exhibits high crash rates. The evaluation is based on observations of all vehicles using the roundabout for sample periods before, after, and one year after the changes in signs and road markings were implemented.

This study focuses on changes made to a 2-by-2 roundabout located on East 66th Street & Portland Avenue South in Richfield, Minnesota. As a signalized intersection that was crash-prone and congested prior to its reconstruction in 2008, conversion into a roundabout was a practical solution (Richfield 2012). However, after its completion, this roundabout exhibited an abnormal amount of crashes. In response to this fact, local engineers from the City of Richfield, Hennepin County and the Minnesota Department of Transportation (MnDOT) expressed the desire to experiment with changes in the roundabout's signs and road markings. The research team of the Minnesota Traffic Observatory (MTO) of the University of Minnesota was called to develop and execute a before/after study in order to evaluate the effect these changes have on this roundabout's crash potential.

This report starts with a short description of the design regulations involved in the construction of this roundabout as well as how they have changed and evolved during recent years. Chapter 2 introduces the concept of driving violations as a surrogate measure of safety as well as presents a safety evaluation based on traditional crash record analysis. Chapter 3 presents the changes introduced in the signs and road markings in the effort of reducing crash potential. Chapter 4 describes the data collection methodology and schedule involved in this study starting with the specialized equipment developed by the MTO, their deployment, and the subsequent data reduction process. Chapter 5 presents the results of the studies three phases and offers a final opinion on the efficacy of the measures taken in reducing crash potential. Finally chapter 6 offers some conclusions and describes the need for further research.

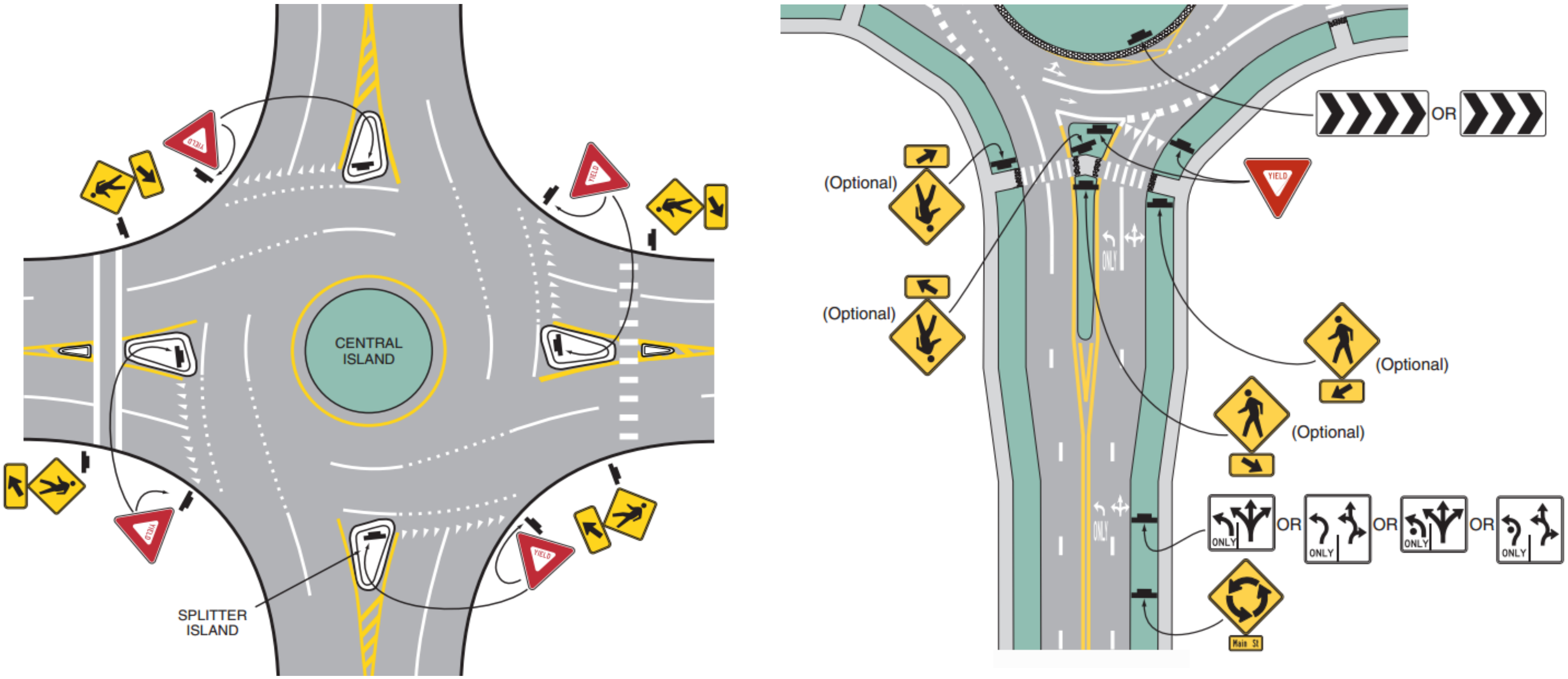
2. Design Regulations

As the roundabout is still a fairly new intersection design concept, relatively few standards exist pertaining to the signs and pavement markings. These standards, set forth by the Federal Highway Administration (FHWA) via the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2003 and FHWA, 2009), have exhibited significant changes in the past several years. Minnesota is one of eight states that uses its state version, the MNMUTCD (MnDOT, 2011) instead of the federal. However, in regards to roundabouts any differences between the MUTCD and the MNMUTCD are negligible.

During the design of the roundabout in Richfield, the 2003 MUTCD was in effect. No revisions were made to roundabout regulations until the 2009 MUTCD, in which roundabout pavement markings received their own chapter. The 2003 version contains limited amount of resources for roundabouts. Section 3B.24 (2003): Markings for Roundabout Intersections contains a single example each of road markings for one- and two-lane roundabouts, along with several options and guidelines. Options include the use of a yellow edge line around the inner edge, use of lane lines, and yield lines. Guidelines suggest that crosswalks be located 25 ft upstream from the yield line, line extensions not be used across exits, and the outer portion of the roundabout should contain a line that extends from the splitter island, where it remains solid, to across entrances, where it should be dotted (refer to Figure 1.a). Sections 2B.09 (2003) and 2B.10 (2003) discuss the only content related to regulatory signs in roundabouts, citing a standard that yield signs must be present at both the right and left sides of approaches in two-lane roundabouts. The aforementioned three sections are the only ones that pertain to roundabouts specifically.

The current version of the MUTCD is the 2009 Edition with Revision Numbers 1 and 2 incorporated, dated May 2012. This version of the MUTCD manual contains significantly more content regarding roundabouts than its predecessor. Roundabout sign requirements appended in this edition include movement prohibition signs (Section 2B.18 (2009)), intersection lane control signs (Section 2B.19 (2012)), one way signs (Section 2B.20 (2009)), roundabout directional arrow signs (Section 2B.43 (2009)), circulation plaques (Section 2B.44 (2009)), and destination signs (Section 2D.38 (2009)). Refer to Figure 1 for a general presentation of the differences in sign requirements between 2003 (a) and 2009 (b).

In addition to the sign requirement content, the 2012 version of the MUTCD manual includes additional recommendations pertaining to lane-use arrows on approaches and markings within the circular roadway (Chapter 3C). Lane-use arrows deemed acceptable for approaches are demonstrated in Figure 2. They include normal (standard) arrows that would be located at a signalized intersection, as well as fish-hook arrows, which exhibit additional curvature that represents the radial direction of the circular roadway. Fish-hook arrows may be used with signs on the approach as well. An additional dot representing the central island for left turns and U-turns is an optional feature. Within the circular roadway, standard arrows must be used. Other markings within the circular roadway have also been addressed more specifically. It is now required that multi-lane approaches to roundabouts have lane lines (3C.02-1 (2012)), within the circulatory roadway continuous concentric lane lines may not be used (3C.02-4 (2012)), and exits cannot contain edge lines from the circulatory roadway (3C.03-3 (2012)), among other added recommendations and options for roundabout design. Differences between the Minnesota and federal MUTCD manuals are negligible pertaining to roundabout design regulations.



2003 MUTCD

(a)

2009 MUTCD

(b)

Figure 1 MUTCD Example Signs & Markings for a Two-Lane Roundabout

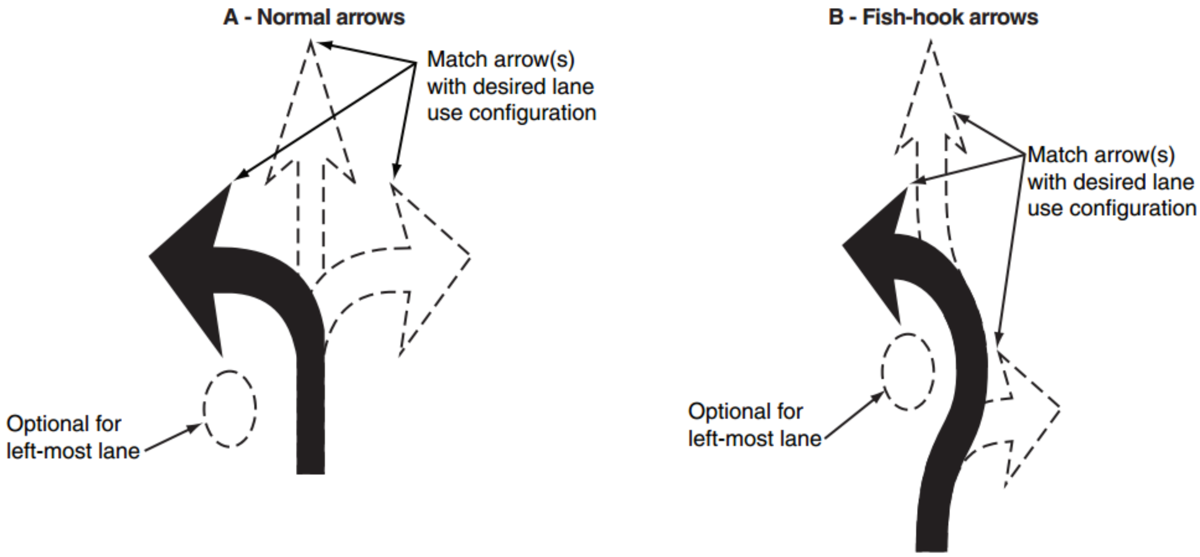


Figure 2 Turn Arrow Options. © 2009 MUTCD

3. Roundabout Safety Analysis

Crash frequency and severity are direct measures of road safety. Therefore, road safety analysis has traditionally been undertaken using crash data. However, there are well-recognized availability and quality problems associated with crash data. Crash data are not always sufficient due to:

1. Small sample sizes leading to inconclusive results, and
2. The lack of details to improve our understanding of crash failure mechanism and especially the driver crash avoidance behavior.

Furthermore, the use of crash records for safety analysis is a reactive approach: a significant number of crashes need to be recorded before an action can be taken. This also reduces the ability to examine the safety effects of a recently implemented safety countermeasure. Because of these issues, road safety analysis can benefit from reliable analysis methods that utilize observable non-crash traffic events and other surrogate data instead of the accumulation of crashes.

In the case of this study, the goal was to examine the safety effects of the proposed changes and determine how these changes affect driving behavior. In addition to the above arguments, crashes are rare events. In an environment like a roundabout where severe crashes are almost non-existent, some crash types would require many years of crash history records in order to produce credible results. This does not fit well with the quick expansion of roundabouts locally and nationally and the need of better design standards. For this reasons, in this study, we followed a path based on observation of events that can serve as surrogates to crashes. Common traffic violations that can lead to crashes.

Direct observation of vehicles traversing the roundabout provides an invaluable insight on the effect traffic control strategies have on driver behavior. Modern urban roundabouts have well defined and concrete driving rules, regardless if drivers don't understand them or follow them. When these instructions are followed, the number of conflicts between vehicles is much lower than traditional intersections. When these rules are violated crashes happen. In the next section we show that all traffic related crashes in a roundabout are the result of a violation of traffic rules. This study is based on the argument that observations of traffic violations can serve as an indicator of the safety of the roundabout and allow an evaluation of before and after conditions in a much more expedient way than the traditional analysis based on crash frequencies.

3.1 Roundabout Violations

The Richfield roundabout, host to more than 30,000 vehicles a day, is a two-lane roundabout in which for all approaches the inner lane may proceed straight, turn left, or perform a U-turn, and the outer lane may proceed straight or turn right. Despite this straightforward configuration, 129 crashes have been recorded with the Richfield Police Department between September 2008 and November 2012. Additional crashes have been reported at the roundabout, including those caused by drunk driving, distracted driving, and environmental conditions, but are left out for the purposes of this study. This study is focusing on crashes that are the result of violations of the roundabout driving rules. Therefore, all relevant crashes can be categorized into one of the following three types: **Yield Violations**, **Lane Change Violations**, and **Turn Violations**. For consistency, these categorizations are used in the data reduction process as well, including sub classifications. In addition, **Wrong Way** and **Stopping** events are also noted and recorded during data reduction. Finally, whether or not the offending driver exhibited an **Incorrect Lane Choice** is also recorded for each crash and each violation. Refer to categorization definitions below.

Yielding Violation

A yielding violation denotes an instance in which, upon entering, a vehicle fails to yield to one or more vehicles already in the roundabout. The rules of driving in roundabouts require the entering vehicle to yield to vehicles in all lanes of the roundabout, in this case two. For the purposes of this project we differentiate. The classifications of yielding violations specify whether the offending vehicle failed to yield to traffic in the inner lane (Figure 3.a), outer lane (Figure 3.b), or both lanes (Figure 3.c) of the roundabout, as demonstrated respectively below. The entry lane of the subject vehicle is separately recorded.

Lane Change Violations

For the purposes of this study a lane change within the circulatory roadway is considered to be a violation of roundabout driving rules. This regulation is not explicitly defined in the MUTCD, but in general lane changes are generally discouraged. There exist several different cases in which vehicles commonly perform a lane change violation. Some of the observed cases are common as compared to others and are mostly harmless. Each instance of a lane change is recorded with the classification of either being an entrance lane change (Figure 3.d), which denotes a lane change occurring in the first quadrant of a vehicle's path through the roundabout, or an exit lane change (Figure 3.e), which indicates that the lane change occurs at any point afterwards. There are also two special classifications: one in which a vehicle is simultaneously occupying or straddling both lanes (Figure 3.f), and the other in which a vehicle going straight through the roundabout cuts across both lanes to minimize the curvature of the turn (Figure 3.g). The latter is an issue in this particular roundabout. More recent ones have increased the angle of the approaches virtually eliminating such a behavior as well as minimize wrong way cases.

Turn Violations

Turning violations are the causes of the most severe crashes and are the subject of greater scrutiny in this project. Basically, always following the official rules of driving in a roundabout, turning violations indicate that the turning maneuver a vehicle makes is not allowed in the lane in which the vehicle proceeds through the roundabout. For the two-lane roundabout investigated in this study, the turning violation classifications include turning right from the inner lane of the roundabout (Figure 3.h), turning left from the outer lane (Figure 3.i), and turning more than 270 degrees from the outer lane (Figure 3.j).

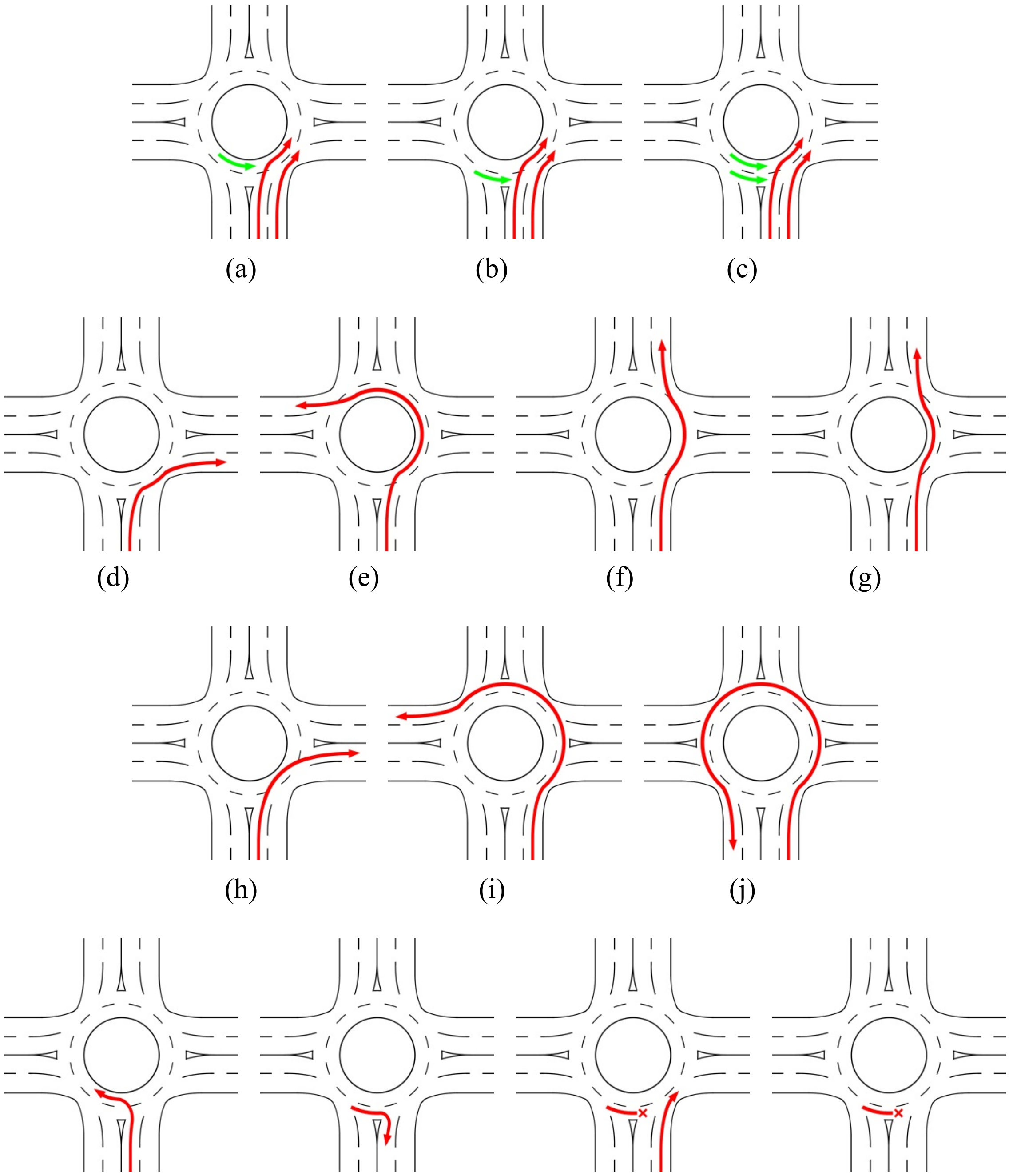


Figure 3 Categories of Violations

Wrong Way Violations

For completeness, although not of particular interest in this project, instances of vehicles driving the wrong way were detect and noted. Wrong way violations pertain to clockwise vehicular procession through the roundabout, with classifications comprising entering the roundabout against the direction of traffic (Figure 3.k), and utilizing the entrance lanes to exit the roundabout (Figure 3.l).

Stop Violations

A stopping violation denotes an instance in which, after entering the roundabout, a vehicle comes to a stop or otherwise impedes traffic without proper justification. Two classifications of stopping violations were created based of trends from previous observation: stopping to yield to vehicles entering the roundabout unnecessarily (Figure 3.m), and stopping for other general and unjustified purposes (Figure 3.n).

Incorrect Entrance Lane Choice

In addition to the aforementioned violations, the correctness of the entrance lane depending on the destination is recorded. In most cases the selection of the wrong entrance lane also involves a lane change and/or turn violation later on in the path of the vehicle. The entrance lane selection is independently noted to assist in the more refined data mining and comparison of the "after" conditions. Figures 3.h, 3.i, and 3.d are common examples of incorrect lane choices.

Crash Statistics

Before the changes were made to the roundabout, a total of 89 relevant crashes were reported over the course of 35 months. Of these crashes, 38 were caused by yielding violations, 7 caused by lane changes, 44 caused by turning violations. Associations with the aforementioned definitions were accomplished through scrutiny of the actual crash reports provided to the research team by the City of Richfield. Specific numbers are as follows:

- Yielding violations: 38
    - Failing to yield to the inner lane (Figure 3.a): 24
    - Failing to yield to the outer lane (Figure 3.b): 14
- Lane changes: 7
    - Lane change at entrance (Figure 3.d): 3
    - Lane change at exit (Figure 3.e): 2
    - Straddling both lanes (Figure 3.f): 1
    - Cutting straight across (Figure 3.g): 1
- Turn violations: 44
    - Right turn from the inner lane (Figure 3.h): 6
    - Left turn from the outer lane (Figure 3.i): 38

Immediately after the changes were implemented, for a duration of six months between August 2011 and January 2012, a total of 14 relevant crashes occurred. Of these crashes, 12 resulted from yielding violations and two from turning violations. Specific categorizations are as follows:

- Yielding violations: 12
    - Failing to yield to the inner lane (Figure 3.a): 6
    - Failing to yield to the outer lane (Figure 3.b): 6
- Turn violations: 2
    - Left turn from the outer lane (Figure 3.i): 2

Long after the changes were implemented, with 10 months of records from February 2012 through November 2012, a total of 26 relevant crashes were reported. Of these crashes, 13 were caused by yielding violations, one caused by a lane change, and 12 caused by turning violations.

- Yielding violations: 13
    - Failing to yield to the inner lane (Figure 3.a): 11
    - Failing to yield to the outer lane (Figure 3.b): 2
- Lane changes: 1
    - Lane change at exit (Figure 3.e): 1
- Turn violations: 12
    - Right turn from the inner lane (Figure 3.h): 1
    - Left turn from the outer lane (Figure 3.i): 11

Below, Figure 4 presents the preceding crash breakdown chronologically alongside estimated traffic volumes. Due to the large variance in traffic volumes over time, counts of reported instances alone are not relevant. Volumes are affected by time of year, weather, construction, etc. Specifically, in the case of the subject roundabout, various portions of the nearby I-35W/Hwy 62 Crosstown reconstruction project significantly affected traffic intermittently from the time of the roundabout's commencement through the completion of the nearby reconstruction project in November 2010. The estimated traffic volumes illustrated in Figure 4 were calculated to ultimately approximate crash rates (Figure 8) as opposed to counts in order to provide a more significant demonstration of crash trends over the course of the subject roundabout's existence.

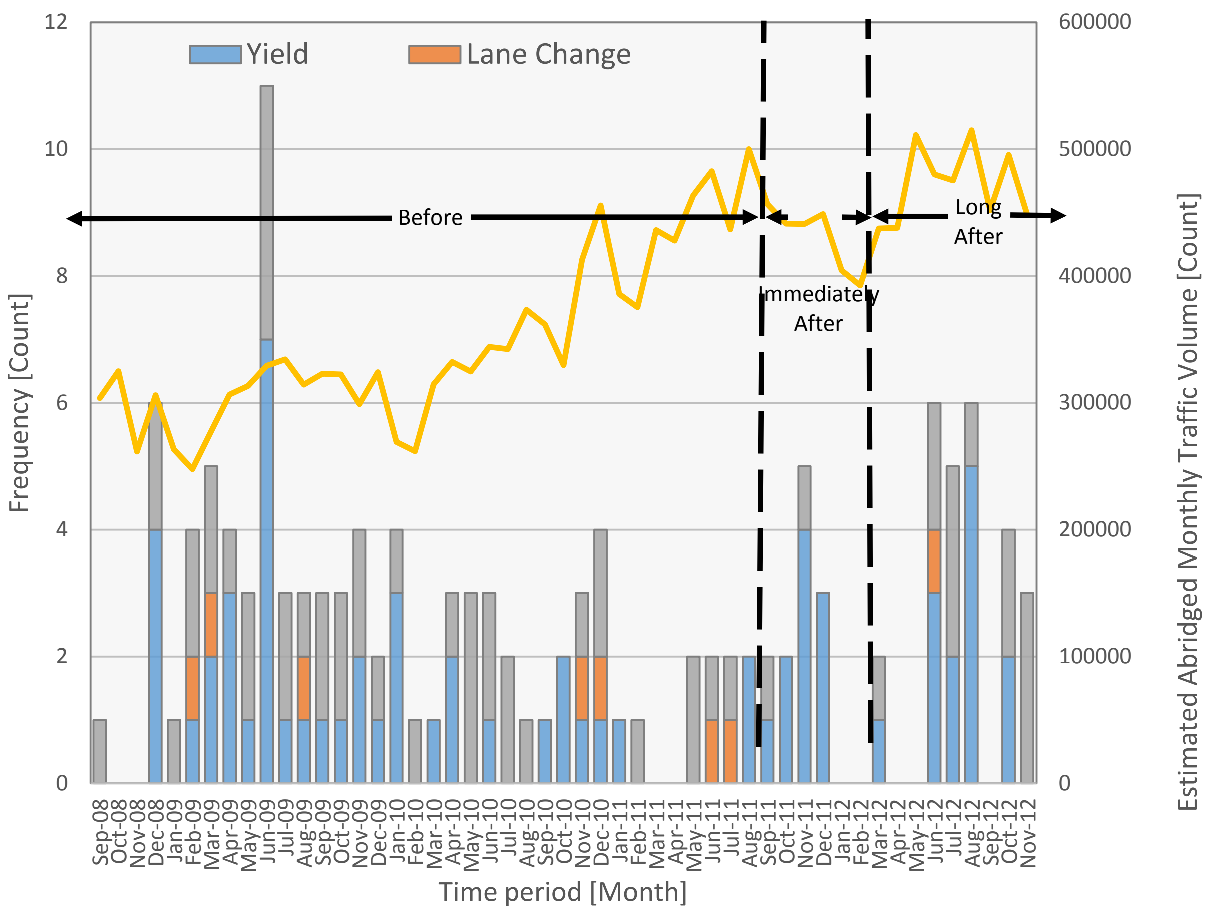


Figure 4: Distribution of Reported Crashes per Month

Through analysis of the crash reports, it was determined that 84% of reported crashes occurred on a weekday and 95% of reported crashes occurred between the hours of 07:00 and 19:00. With these time periods representing the traffic conditions that coincide with the majority of crashes, models were created that estimate the total volume on weekdays between 07:00 and 19:00 over the course of the month for each month between September 2008 and November 2012. Estimated counts are used as opposed to averages because as the number of weekdays in a month vary between 20 and 23, total traffic volumes are subject to notable differences from month to month. For instance, September 2012 contained 20 weekdays and October 2012 contained 23 weekdays, and for each of those weekdays the traffic conditions over the 12-hour period between 07:00-19:00 were analyzed to result in a total of 240 hours for the month of September 2012 and 276 hours for the month of October 2012, a difference of 36 hours, or tens of thousands of vehicles.

To create a model, manual counts collected in conjunction with recording occurrences of violations were used alongside highway detector data from highway exits near the subject roundabout. Relationships between the amount of traffic detected on the highway exits and corresponding approaches to the roundabout were subsequently determined. The sum of the northbound and southbound exits from Minnesota State Highway 77 (Hwy 77) onto East 66th Street was found to correspond linearly to the westbound entrance of the subject roundabout. Similar relationships were found between exits on Interstate 494, Interstate 35W, Minnesota State Highway 62, and their respective corresponding approaches.

Using the relationships, estimates of traffic volumes entering from all approaches to the roundabout were calculated and then summed to produce estimated volumes for the roundabout. However, during the aforementioned interchange reconstruction project, the only detectors with consistent data throughout were those along Hwy 77. Traffic entering from the westbound approach was found to comprise approximately 40% of all traffic over the course of the applicable 12-hour day during construction. Consequently, during this period estimated volumes for the westbound approach were calculated normally and total roundabout volume was estimated assuming the westbound approach represented 40% of the roundabout’s traffic. The final volume estimates are presented in Table 1.

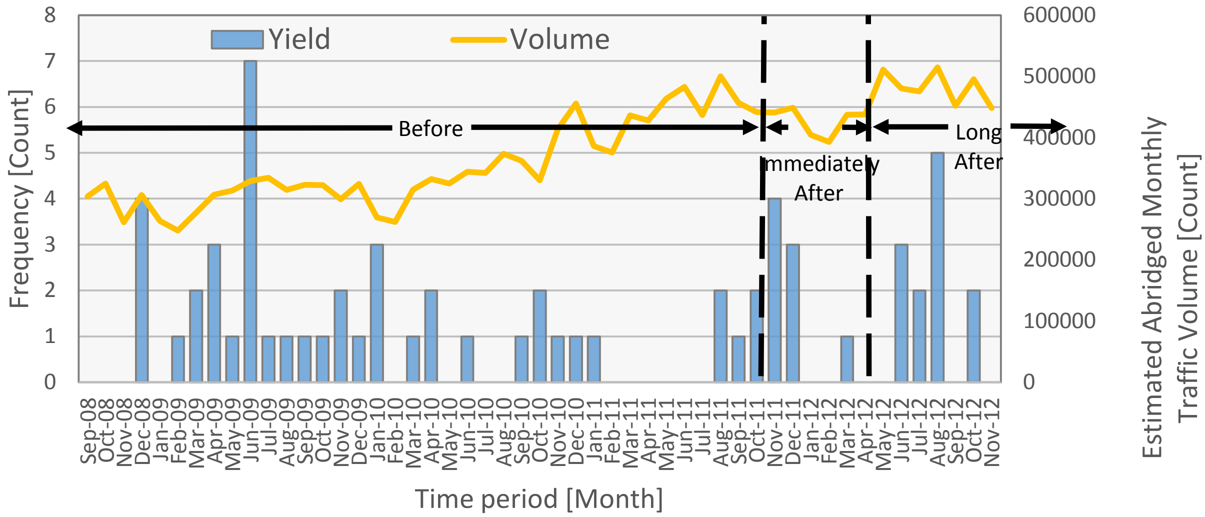


Figure 5 Distribution of Reported Yield Crashes per Month

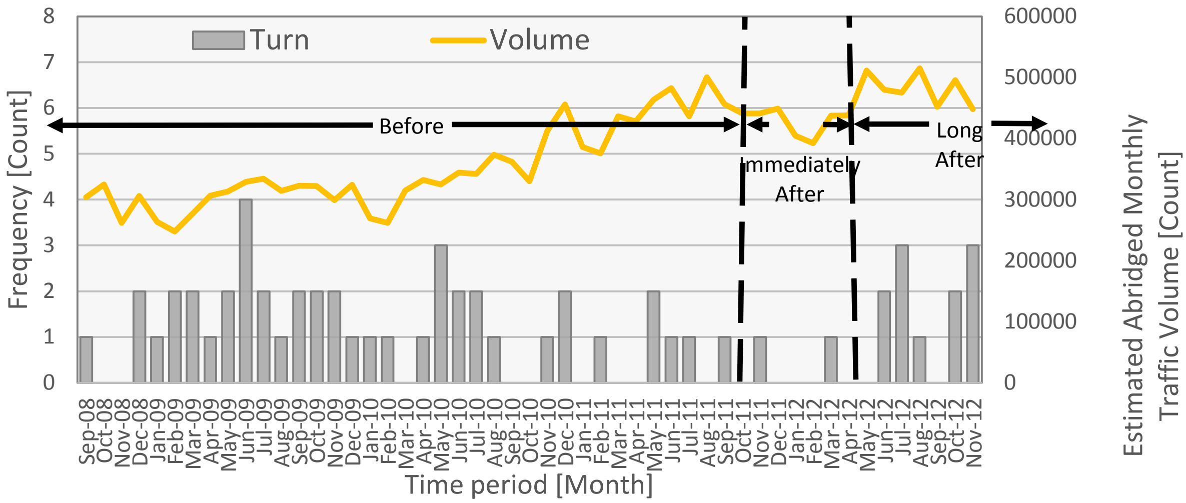


Figure 6 Distribution of Reported Turn Crashes per Month

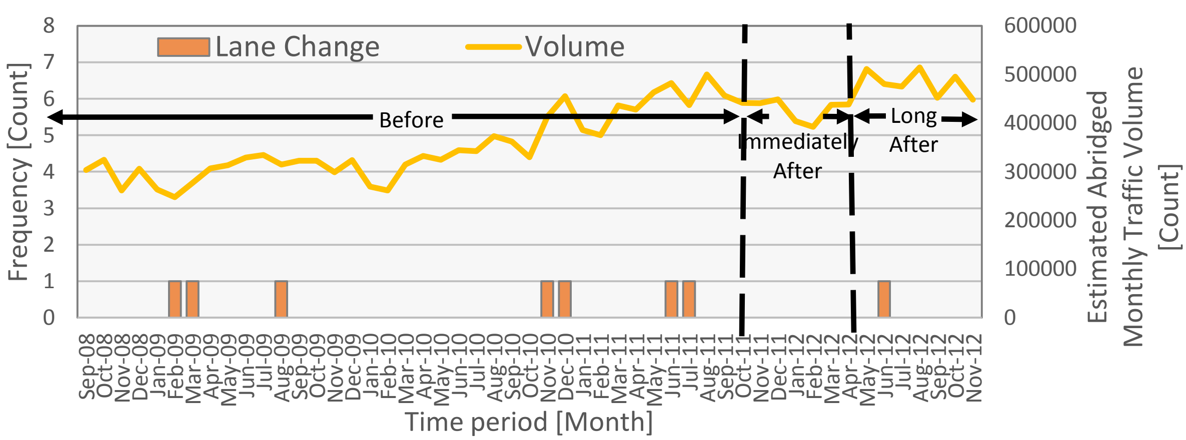


Figure 7 Distribution of Reported Lane Change Crashes per Month

Table 1: Estimated Applicable Traffic Volumes by Month

Month	Estimated Applicable Volume	Month	Estimated Applicable Volume
Sep-08	13803	**Jan-11**	18374
Oct-08	14125	**Feb-11**	18773
Nov-08	13082	**Mar-11**	18965
Dec-08	13302	**Apr-11**	20375
Jan-09	11970	**May-11**	21064
Feb-09	12392	**Jun-11**	21935
Mar-09	12607	**Jul-11**	20791
Apr-09	13933	**Aug-11**	21745
May-09	14919	**Sep-11**	20751
Jun-09	14961	**Oct-11**	21010
Jul-09	14537	**Nov-11**	20042
Aug-09	14973	**Dec-11**	20403
Sep-09	14678	**Jan-12**	18377
Oct-09	14655	**Feb-12**	18691
Nov-09	14236	**Mar-12**	19880
Dec-09	14093	**Apr-12**	20856
Jan-10	12819	**May-12**	22222
Feb-10	13089	**Jun-12**	22857
Mar-10	13683	**Jul-12**	21607
Apr-10	15105	**Aug-12**	22382
May-10	15463	**Sep-12**	22594
Jun-10	15644	**Oct-12**	21538
Jul-10	15557	**Nov-12**	20366
Aug-10	16968	***Dec-12****	*19972*
Sep-10	16447	***Jan-13****	*18574*
Oct-10	15704	***Feb-13****	*19632*
Nov-10	18772	***Mar-13****	*19494*
Dec-10	19807	***Apr-13****	*20290*

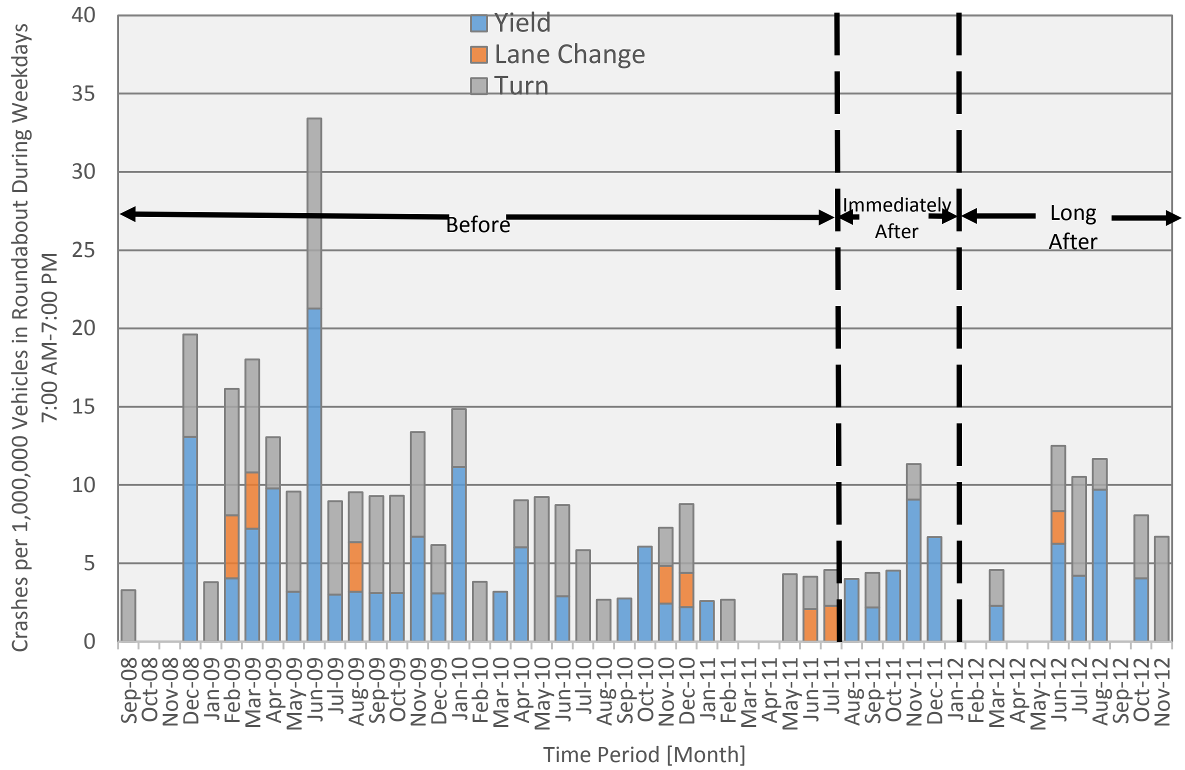


Figure 8: Crashes per 1,000,000 Vehicles from September 2008-November 2012

Figure 8 alters Figure 4 by dividing each monthly crash count by its corresponding estimated volume to produce a crash rate. Refer to January 2010 and October 2012, both of which demonstrate four reported crashes. However, due to a significant difference in the estimated volume, January 2010 exhibits a crash rate of approximately 15 per 1,000,000 vehicles versus eight per 1,000,000 in October 2012.

Seasonal trends are present within the data, with summers exhibiting a tendency to produce local maxima and winters tending to produce local minima, although this cannot be universally applied to the data.

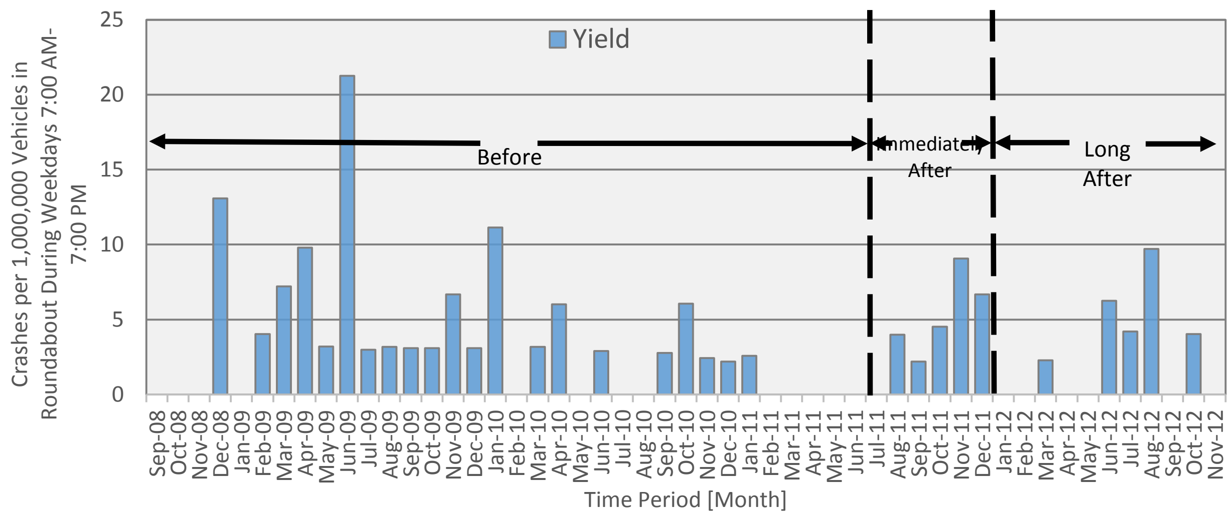


Figure 9 Yield Crashes per 1,000,000 Vehicles from September 2008-November 2012

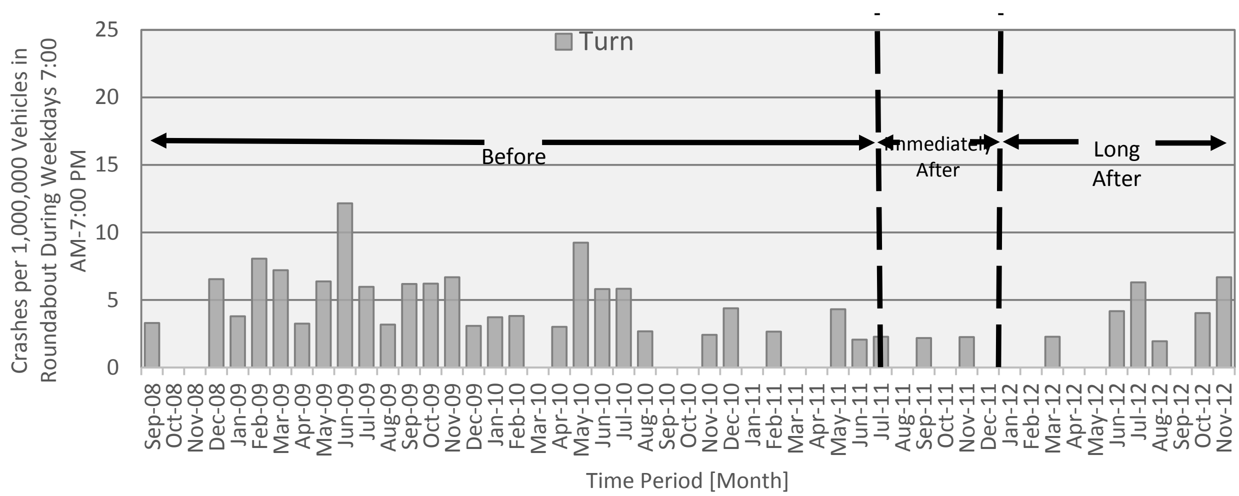


Figure 10 Turn Crashes per 1,000,000 Vehicles from September 2008-November 2012

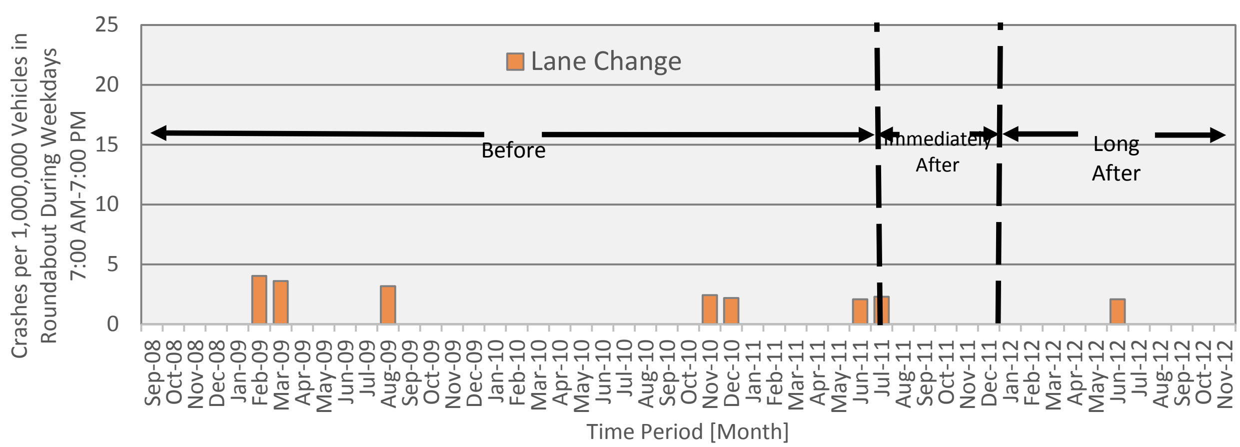


Figure 11 Lane Change Crashes per 1M Vehicles from September 2008-November 2012

4. Roundabout Signs and Lane Marking Changes

During this project, the City of Richfield and Hennepin County took steps to improve the roundabout's safety by implementing changes in the roundabout signs as well as pavement and lane markings. During early August 2011, the following changes were made to the roundabout.

Pavement Markings

- Turn arrows on the approaches to the roundabout and inside the roundabout were changed from "fish-hook" style to the standard (referred to as normal in the MUTCD) style, including a dot to represent the roundabout island.
- Additional turn arrows and lane designation signs have been placed at approximately 450 feet upstream of the yield line on all legs of the roundabout.

Lane Markings

- The solid lane line was extended from the original 50 feet upstream of the yield line to a current 250 feet. This particular element is in contrast to the examples provided in the 2009 MUTCD.
- Eliminate solids then skips in circulatory roadway and change to consistent line gap sequence of 6' line segment and a 3' gap 8"wide.

Signing

- Changes in signage include improving line-of-sight visibility (lowering) for one-way signs, median signs, and large street signs by lowering them by 3 feet, 2 feet, and 3 feet, respectively. All signs were mounted on street poles and "Roundabout Ahead" warning signs were moved to 500 feet from the roundabout.
- Turn arrows on lane designation signs were also changed from "fish-hook" style to the standard style.
- To address the high occurrence of drivers failing to yield to pedestrians, traditional crosswalk signs (W11-2) were replaced with R6-1 paddle signs.

For a visual aid, Figure 12 presents the proposed modification to pavement and lane markings while Figure 13 shows aerial views of (a) before and (b) after the changes.

At the time of the opening of the roundabout in 2008, the City of Richfield took steps to increase the public's understanding of proper roundabout driving procedures. Motorists were educated through various media in order to provide the knowledge required to properly traverse the roundabout. The local media, including local cable television programming, newspapers, informational online resources, pamphlets, open houses, city-wide mailings, and city council meetings, were used as means to spread roundabout awareness. The information these resources provided include general guidelines on how to traverse the roundabout for drivers, bikers, and pedestrians. Driver specific guidelines include the following: yield to all traffic already in the roundabout; lane changes are discouraged - chose the proper lane before entering; obey one-way signs at all times. Also provided were the correct lane choices for all possible maneuvers (i.e. straight through, left turn, right turn, U-turn) a commuter may make inside the roundabout.

In 2011, as part of this project, after the changes were implemented the city used Changeable Message Signs (CMS) to educate drivers. In addition, during the same period, there was an increase in traffic enforcement at the intersection by the Richfield Police Department. Officers aggressively enforced traffic violations in the roundabout between August 11th and September 12th, 2011, including 25 hours spent watching for violations. This increased enforcement resulted in 66 vehicle stops, 53 traffic related citations, and 15 traffic related warnings. Among the citations and warnings pertinent to our study, there were 37 yielding violations, 23 turn violations, 2 stopping violations, 2 lane changes, and 2 wrong way violations. In addition to issuing citations and/or warnings, officers verbally explained proper roundabout procedures and provided stopped motorists with informative roundabout pamphlets.

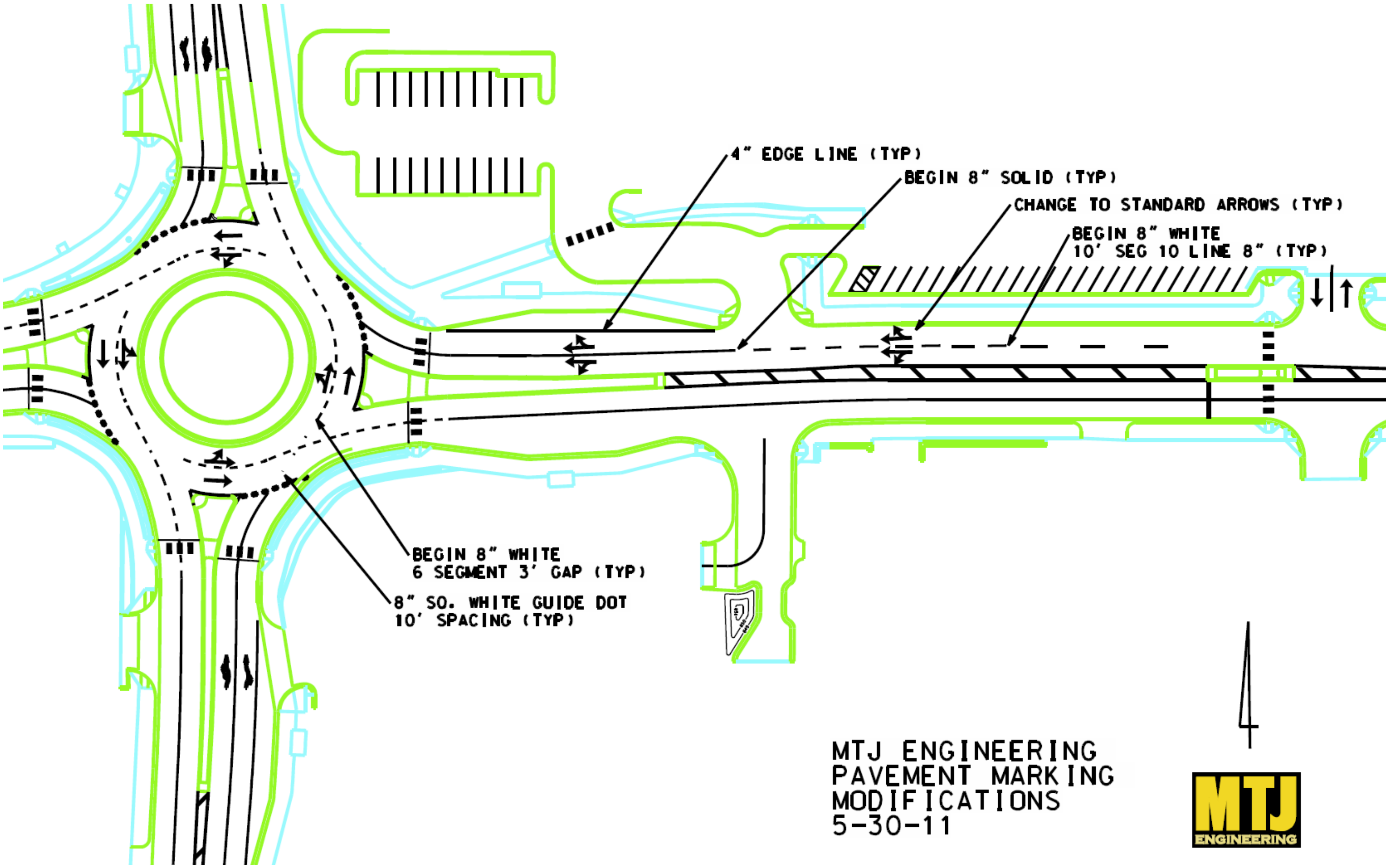


Figure 12 Pavement Marking Proposed Modifications. ©MTJ Engineering

© City of Richfield
(a) Before

© Google
(b) After

Figure 13 Aerial Photos of Roundabout Before and After Implemented Changes

5. Data Collection Methodology

In this project the scope was to identify and count all violations taking place anywhere in the roundabout. The resulting number and type of violations was developed from the aforementioned crash analysis, the literature, and from initial observations of the collected video. The observations were collected through the reduction of video recorded in the roundabout. To reduce project cost, the research team capitalized on the fact that video was collected the year before as part of the "*Observational Study of Pedestrian and Bicycle Crossing Experience in Two Modern Urban Roundabouts"* project.

5.1 Equipment Description

The Minnesota Traffic Observatory developed a set of custom digital recording devices allowing the recording of high resolution video from multiple cameras. The custom made surveillance hardware were mounted on an extendable mast trailer frequently utilized in highway work zones to carry and provide surveillance or illumination. The mast can reach a height of 38 feet. The power source of the deployed equipment consisted of rechargeable batteries that were built in the trailer's structure. Even though the power consumption of the recording equipment was not high, the batteries were recharged at certain points so that the process was not interrupted. The recharge process was made with the help of a portable generator. Figure 14 shows a photo of the trailer as deployed in the roundabout. The main body of the trailer (bright orange) was covered with a dark green tarp to make it less visible.

Figure 14 Instrumented Extendable Mast Trailer in the Roundabout

For the "before" video, four cameras comprised the view of the entire intersection, with each camera pointed at the splitter island of an approach (Figure 15). The format of the "after" video instead was changed to better facilitate the needs of this study, and differs from the "before" video by transitioning from four separate cameras to a single panoramic lens camera (Figure 16). Due to budget limitations it was not possible to concurrently collect data at a control site. While the addition of a control site would make the study more robust, we are confident from the data collected that the results are reliable.

Figure 15 Screenshots of “Before” Roundabout Video

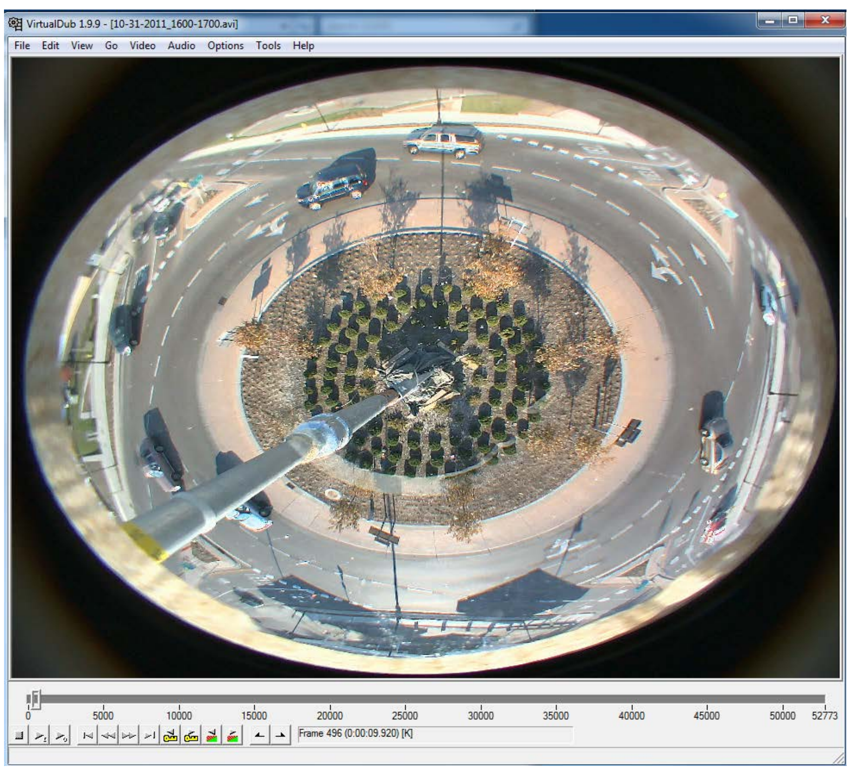


Figure 16 Screenshot of “After” Roundabout Video

5.2 Video Reduction Methodology and Training

Reducing the video collected during this project and extracting all the crash-prone trajectories performed involved a lot of effort. One way the research team resolved this issue is with the development of specialized tools and methodologies that assist/accelerate the video reduction process. The people tasked with processing the collected video are primarily undergraduate students in Civil Engineering primarily focusing on transportation engineering. Regardless, given the particular needs of the project, there are no experienced people available therefore a basic need was to explain the purpose of the project, instill on them the importance of the observation, and train them to identify the crash-prone vehicle maneuvers in as much uniform way as possible. The training regime and material developed for this project are extensive and were continuously refined while data reduction performance was closely monitored. Although the video format between the "before" and "after" periods was different, the video reduction process is similar. The "before" data required first to synchronize the video feeds so they are aligned spatially and temporally. The "after" video did not require this initial procedure.

Training and Performance Monitoring

Detailed training material were developed along with a regime for delivering the information, test the trainees to validate their ability to extract all the necessary data correctly, and periodic checks of performance. In addition to the training material, tools and procedures where created to accelerate the data reduction process. Examples of the training material as well as a description of the video observation acceleration tool developed are included in the appendix. All project materials were placed in shared Google documents and all members of the team were working under a common Google account. This way the data spreadsheets and other material are available from any computer of the MTO while all MTO computers have been upgraded to run the necessary software. This reduces the need for scheduling resources and allowed for constant remote supervision of the produced result.

Coding Procedure

A single video analysis assignment pertains to collecting data from all traffic entering from one direction of the roundabout, north, south, east, or west, for the length of the video (approximately one hour). By utilizing this method it becomes possible for each vehicle that enters the roundabout to be watched as it traverses through the roundabout and determine whether or not a violation is committed. When a violation committed by a vehicle entering from the assigned direction is detected, the associated data are recorded in a spreadsheet. The collected information pertains to the time, location, and description of each violation in addition to broad vehicle type classification.

As it is possible for a vehicle to commit multiple violations, each violation is designated its own record. Some information pertaining to the identity of the offending vehicle remains constant among all of its committed violations. This includes the Enter Frame, which correlates to the time at which the vehicle entered the roundabout; the Vehicle Type, with classifications including sedan, motorcycle, SUV/minivan, truck, bus, and semi-trailer; the Enter Lane, which in this study corresponds to the inner and outer traffic lanes; and the Incorrect Lane Choice, which when valid means that for the type of turning maneuver the vehicle makes, the vehicle chose the incorrect lane to enter the roundabout. For an Incorrect Lane Choice to have been made at least one Lane Change or Turn Violation must be committed and consequently; unlike the other violations, Incorrect Lane Choice is not designated as an independent violation. The following figure shows an example of the extracted data spreadsheet.

100808-ch02

File Edit View Insert Format Data Tools Help All changes saved

	A	B	C	D	E	F	G	H	I	J	K	
1	Enter Channel File	Enter Frame	Vehicle Type	Enter Lane	Violation Channel	Violation Frame	Yield Violation	Lane Change	Turn Violation	Wrong Way	Incorrect Lane Choice	
38	100808-ch02-130310-140310_xvid	1056	3	2	4	1099	0	0	2	0	1	
39		1913	1	1	1	1975	0	2	0	0	0	
40		2468	3	2	4	2504	0	0	2	0	1	
41		2626	1	1	4	2678	0	2	0	0	0	
42		6054	1	1	2	6054	1	0	0	0	0	
43		6146	1	2	4	6181	0	0	2	0	1	
44		6146	1	2	4	6185	0	2	0	0	1	
45		6146	1	2	2	6254	0	2	0	0	1	
46		16202	1	1	4	16243	0	2	0	0	0	
47		17233	3	2	4	17283	0	0	2	0	1	
48		19403	3	1	2	19403	2	0	0	0	0	
49	100808-ch02-140310-150310_xvid	255	1	1	4	305	0	2	0	0	0	
50		608	3	2	4	650	0	0	2	0	1	
51		2799	1	2	2	2799	1	0	0	0	1	
52		2799	1	2	4	2839	0	0	2	0	1	
53		5008	3	2	4	5051	0	0	2	0	1	
54		5189	1	1	4	5246	0	2	0	0	0	
55		6837	1	1	3	6853	0	1	0	0	1	
56		6837	1	1	4	6880	0	0	2	0	1	
57		9078	4	2	4	9137	0	0	2	0	1	
58		11047	3	1	2	11047	1	0	0	0	0	//instiga
59		14350	4	2	3	14360	0	1	0	0	0	
60		14350	4	2	4	14377	0	2	0	0	0	
61		16663	3	2	4	16713	0	0	2	0	1	
62		17020	4	2	4	17065	0	0	3	0	1	
63		17223	1	1	4	17262	0	2	0	0	0	
64	100808-ch02-150310-160310_xvid	246	1	2	4	295	0	0	2	0	1	
65		2762	1	1	2	2762	2	0	0	0	0	
66		3065	1	1	2	3065	1	0	0	0	0	
67		3065	1	1	3	3076	0	1	0	0	0	//lane c
68		3065	1	1	4	3112	0	0	2	0	0	//violati
69		3663	1	2	4	3707	0	0	2	0	1	
70		5926	1	2	4	5971	0	0	2	0	1	
71		6437	1	1	4	6490	0	2	0	0	0	
72		7987	1	1	2	7987	2	0	0	0	0	

Sheet1

Figure 17 Extracted Data Spreadsheet

The collected video records cover three periods of six days each; before, immediately after, and one year after the changes. Specifically the "before" observations were made on six days in August 2010 (8th, 11th, 24th, 25th, 26th, and 27th), the "after" observations were made in October (8th, 28th, and 31st) and November (1st, 2nd, and 3rd) of 2011, and the "one year after" observations were made in October (2nd, 6th, 11th, and 12th) and November (5th and 7th) of 2012. Alongside the violation data collection, in order to normalize the data with traffic volumes, a video analysis with a machine vision sensor provided 15 minute volumes. Care was given to minimize double counting vehicles during their trip through the roundabout. The device was used to collect traffic volume data for all observed roundabout video for both the before and after video. With the volume data available, normalized comparisons could be made.

6. Results

This section presents the results from the comparison of violation counts for the three periods of Before, After, and One Year After. Variable environmental conditions among these days have negligible differences, although construction several blocks away from the north approach to the roundabout accounts for the difference in traffic volumes. Table 2 presents two sets of data: observed violation counts and the corresponding traffic volume during the observation periods. The normalized violation occurrence rate is the observed count divided by the traffic volume. Table 3 offers a comparison among the three periods.

Notable differences between the "before" and "after" data include the reduction in yielding and turning violations, although all types of violations exhibited decreases in their normalized frequencies. These two types of violations account for the majority and most severe of crashes. The relationship between the "before" and "after" normalized rates of yielding violations is not necessarily a straightforward statistic. Due to the increased traffic counts in "after", a vehicle that would have failed to yield regardless of the situation is more likely to encounter a vehicle and commit a yielding violation than "before". The same argument is extended in the "one year after" period. Nonetheless, 1.04% of vehicles entering the roundabout in "before" committed a yielding violation, whereas "after" only 0.85% did, resulting in a 18% reduction, with a more notable drop in failing to yield to the outer lane than the inner lane. Turning violations were committed by 1.16% of vehicles "before" and 0.60% "after", boasting an occurrence reduction of 48%. The most common turning violation, making a left turn from the outer lane, was the primary contribution to the overall reduction and exhibits the most significant reduction in both count and rate of occurrence of all the violation types. This observation can be coupled with the decrease of the "Incorrect Lane Choice" for the intended destination, which decreased by 53%.

The "one year after" data suggests some behavior has stabilized while other behavior has regressed since the initial changes. Specifically, Table 2 demonstrates that a 60% increase in instances of yielding violations has taken place between "after" and "one year after". An overall 31% increase in normalized occurrences of yielding failures were observed between the "before" and the "one year after" periods. As can be seen from table 2, the volume of vehicles using the roundabout increased by 28% between "before" and "after" and by an additional 1% the year after that. To reinforce the argument of the connection between volume and yielding violations, Figures 18 -20 present the number of violations by time of day. One can observe that the "Failure to Yield" line tracks well the trends of the volume while the other types of violations do not show such a strong relationship. Similar graphs for all of the observed days can be found in the appendix.

Turning violations were committed by 1.16% of vehicles in 2010, 0.6% in 2011, and 0.65% in 2012. The comparison between "before" and "after", which includes the influence from the enforcement campaign, boasts an occurrence reduction of 48% while a "year after" this improvement seems to have retained its level at 44%. Focusing on the most common turning violation, making a left turn from the outer lane, we see that it is the primary contribution to the overall reduction of turning violations and exhibits the most significant reduction in both count and per capita occurrence of all the violation types. Specifically, instances of left turn from the outer lane were reduced by 49% two months after the changes and retained this improvement level a year after at 46%. In difference to the yielding violations, the turn violations show a lasting improvement over time suggesting that the changes permanently affected driver behavior.

Although the followed experimental setup renders impossible the quantification of effect each individual traffic control change had on driver behavior, it is interesting to combine the aforementioned turn violation changes with the changes in drivers' tendency to select the incorrect entrance lane for their intended destination. This particular bad behavior was reduced by 53% shortly after the changes and retained this level a year after at 50%. From all the changes implemented only three could have affected this behavior:

- The extension of the solid white line from 50 feet to 250 feet upstream of the yield line,
- The addition of turn arrows and lane designation signs further upstream of the roundabout entrance, and
- The change of these signs from "fish-hook" to standard style.

The assumption behind the first implementation of the "fish-hook" sign was that it will help prevent wrong-way left turns. Therefore, it is important to note that, following the change to standard style, there were no evidence of increased violations of this type.

From the results of the analysis we can observe an approximately 20% reduction in lane changes at the entrances and exits of the roundabout. This reduction was also sustained a year after the traffic control improvements. One design element this improvement can be attributed at are the changes in the lane marking in the circulatory way. Specifically, the original solid lines were replaces with consistent 6 feet line + 3 feet gap dashed ones.

From Table 3 one can also note that no significant regression was observed among instances of lane changes. In Figures 18-20 the trends in the "Lane Change" violations suggest that commuters, which are the predominant users during peak periods, are less susceptible to such mistakes as midday drivers. The "Improper Turn" violations show a weaker but observable correlation to volume.

Table 2 Summary Data

	Count	Normalized Occurrence	Count	Normalized Occurrence	Count	Normalized Occurrence
	Before - 2010 (72 hours)		**After - 2011** (72 hours)		**One Year After -2012** (72 hours)	
Traffic Volume	98015		125078		126044	
Total Violations	5205	5.31%	4918	3.93%	5607	4.45%
Yielding	1021	1.04%	1065	0.85%	1713	1.36%
Inner	666	0.68%	771	0.62%	1140	0.90%
Outer	300	0.31%	218	0.17%	457	0.36%
Both	55	0.06%	76	0.06%	116	0.09%
Lane Change	3037	3.10%	3095	2.47%	3073	2.44%
Entrance	1301	1.33%	1407	1.12%	1325	1.05%
Exit	1736	1.77%	1688	1.35%	1748	1.39%
Turn Violation	1135	1.16%	750	0.60%	818	0.65%
Right from inner	71	0.07%	77	0.06%	75	0.06%
Left from outer	1027	1.05%	665	0.53%	719	0.57%
More than 270 from outer	37	0.04%	8	0.01%	24	0.02%
Wrong Way	12	0.01%	8	0.01%	3	0.00%
Enter	10	0.01%	8	0.01%	3	0.00%
Exit	2	0.00%	0	0.00%	0	0.00%
Incorrect Lane Choice	1920	1.96%	1152	0.92%	1243	0.99%

Table 3 Comparison among "Before", "After", and "One Year After" Data

	Before - After			After - One Year After			Before - One Year After		
	Percent Change	**p-value**	**Z-statistic**	**Percent Change**	**p-value**	**Z-statistic**	**Percent Change**	**p-value**	**Z-statistic**
Total Violations	-26.0%	<0.01	15.526	13.1%	<0.01	-6.458	-16.23%	<0.01	9.445
Yielding	-18.3%	<0.01	4.633	59.6%	<0.01	-12.159	30.5%	<0.01	-6.788
Inner	**-9.3%**	**0.0646**	**1.848**	**46.7%**	**<0.01**	**-8.305**	**33.1%**	**<0.01**	**-5.908**
Outer	-43.1%	<0.01	6.419	108.0%	<0.01	-9.111	18.5%	0.022	-2.286
Both	8.3%	0.653	-0.450	51.5%	<0.01	-2.835	64.0%	<0.01	-3.054
Lane Change	-20.1%	<0.01	8.948	-1.5%	0.555	0.590	-21.3%	<0.01	9.522
Entrance	-15.3%	<0.01	4.334	-6.5%	0.075	1.780	-20.8%	<0.01	6.025
Exit	-23.8%	<0.01	8.039	2.8%	0.421	-0.804	-21.7%	<0.01	7.294
Turn Violation	-48.2%	<0.01	14.30	8.2%	0.116	-1.570	-44.0%	<0.01	12.858
Right from inner	-15.0%	0.322	0.990	-3.3%	0.834	0.210	-17.9%	0.234	1.1900
Left from outer	**-49.3%**	**<0.01**	**13.946**	7.3%	0.190	-1.312	**-45.6%**	**<0.01**	**12.748**
More than 270 from outer	-83.1%	<0.01	5.176	197.7%	<0.01	-2.807	-49.6%	<0.01	2.663
Wrong Way	-47.8%	0.148	1.448	-62.8%	-	-	-80.6%	-	-
Enter	-37.3%	0.321	0.993	-62.8%	-	-	-76.7%	-	-
Exit	-	-	-	-	-	-	-	-	-
Incorrect Lane Choice	**-53.0%**	**<0.01**	**20.877**	7.1%	0.093	-1.679	**-49.7%**	**<0.01**	**19.361**

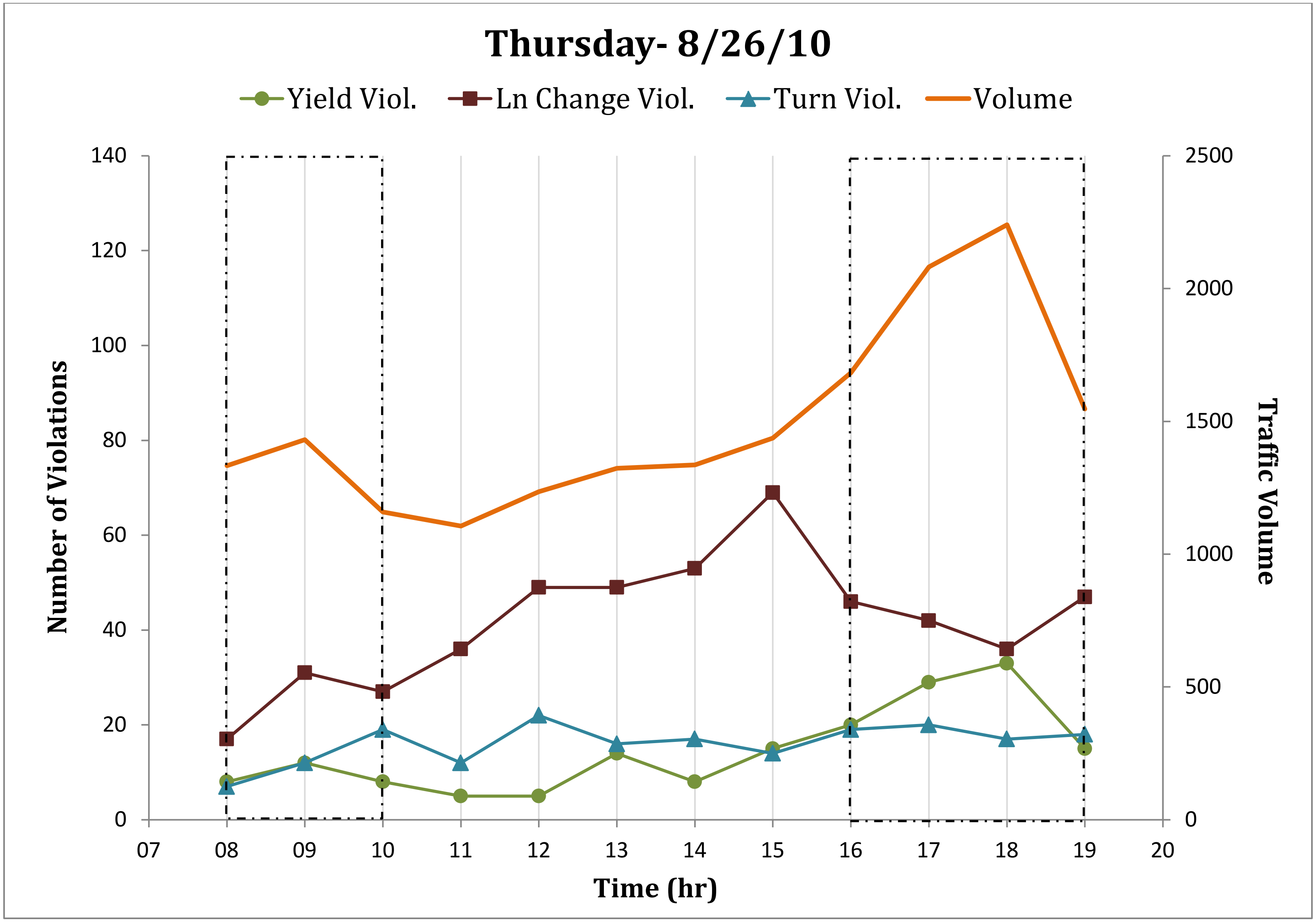


Figure 18 Violation Breakdown for Thursday, August 26th, 2010

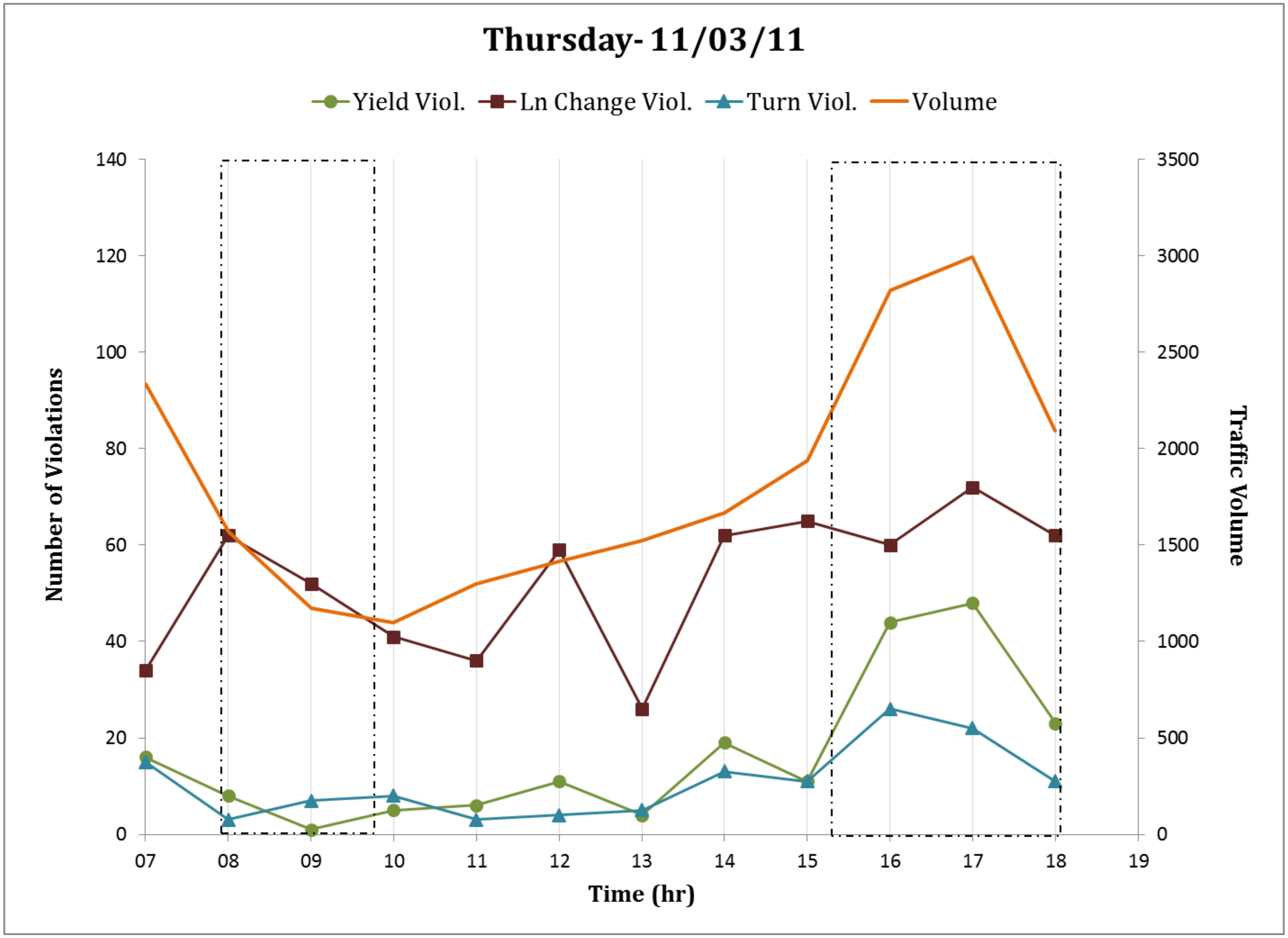


Figure 19 Violation Breakdown for Thursday, November 3rd, 2011

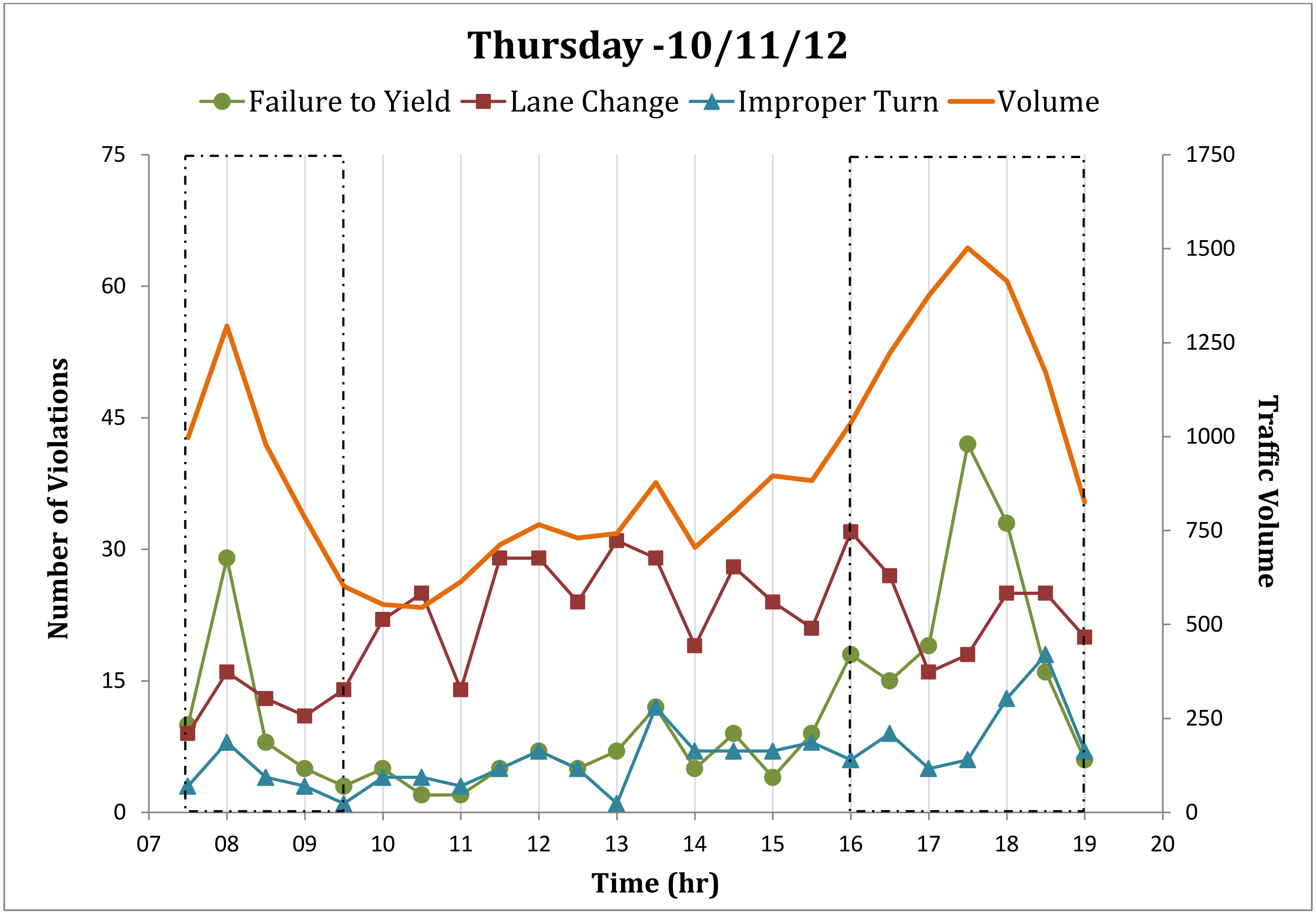


Figure 20 Violation Breakdown for Thursday, October 11th, 2012

7. Conclusions

This report describes the results from a straightforward before and after study of the effect of changes in signs and lane markings on a two–lane roundabout in Richfield, Minnesota. The subject roundabout was designed with the best standards and guidelines available in 2005. For the 35 months following its construction it exhibited a sustained suspiciously high crash rate for its type and demand. City, county and state engineers, having observed driving behavior in this and other roundabouts as well as having available the more detailed guidelines in the 2009 MUTCD, Decided to experiment with changes in the roundabout signs and lane markings. With the assistance of Mark T. Johnson, a consultant and roundabout expert, a set of proposed changes on the roundabout signs and lane markings was produced in an attempt to improve roundabout safety.

This study aimed to produce a more expedient evaluation of the effects of the planned changes. Instead of performing a traditional before/after study based on crash records, the research team capitalized on prior, unrelated, research pertaining to roundabouts conducted by the Minnesota Traffic Observatory to perform an observational study on the effect of the changes in driving violations performed within the roundabout. The earlier research had produced several hundred hours of video records of all the activity around the roundabout. Repeating the same data collection exercise after the changes were implemented allowed the research team to identify and count all violations performed by vehicles using the roundabout before and after the changes. Although the value of the exercise would have been greatly increased if data collection had been performed on a control site also, the project budget and timeline made this impossible. Regardless, the produced results display such large differences in the rates of certain violations before and after the changes that the positive effect of the changes can be safely illustrated.

In discussions prior to the design of the changes in signs and lane markings, it became evident that one major factor contributing to the high crash rate was the difficulty exhibited by the drivers in selecting the correct entrance lane for their intended destination. This inability resulted in confusion while entering, producing lane changes within the circulatory roadway and more significantly a large number of left turns from the outer lane. As noted in the report, crashes resulting from left turns from the outer lane accounted for 45% of the recorded crashes. The changes implemented in the approaches to the roundabout, such as the extension of the solid line from the original 50 feet from the yield line to 250 feet, the added signing and standard lane designation signs, reinforced the message to the drivers that they must select the correct lane before approaching the roundabout entrance. Although other changes focused on yielding violations and correct lane keeping inside the roundabout, the violation type exhibiting the most notable and lasting reduction was the improper left turn from the outer lane. It is important to note that although numerous details have been added and clarified on the MUTCD guidelines for roundabout markings, there is no specific guideline on the length of the solid line between lanes at the entrances while most of the figures show the line turn to dashed shortly upstream of the pedestrian crossing. Although further research is needed, we believe this is an area where improvements in the guidelines are possible. The research team has continued observations at the subject roundabout looking for the stability of the reported changes over time.

The findings from this study has shown that signs and lane markings are critical in the understanding of roundabout driving rules. Due to the nature of this study, implementing many changes at once, it is difficult to draw direct connections between individual sign and lane marking changes and the observed reductions in traffic violations. In addition, at the moment this represents a solidary experiment in one roundabout. In order to generalize the findings as well as clarify the contribution of each of the proposed changes on safety similar studies are needed in other 2-by-2 roundabouts in Minnesota and other states. Given a larger sample, the findings can be reinforced as well as perform more in depth analysis by separately staging the implementation of the different traffic control features.

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Appendix A: Example of Data Reduction Training Material

<u>Roundabout Violations Project Training Material</u>
<u>(Developed by Veronica Richfield and Gina Beers)</u>

This project pertains only to the Portland roundabout. We are interested in recording occurrences of vehicle violations within the roundabout. Each person is assigned one channel from channels 5-8 (which we will refer to as channels 1-4) for a particular day [*refer to the document "Violations Project Assignments" under the Violations folder in Google Docs*]. Unlike Phase 2, the whole day will be analyzed, from 07:00 am to 21:00 pm. Considering the length of time it will take to analyze a single day, we are only interested in Tuesdays, Wednesdays, and Thursdays. We are to set up the videos like we did for Phase 2, but this time we will make use of a script Gordon wrote with a freeware program that allows manipulation of all four videos at once.

Using AutoHotkey Program

<u>Running script from "VirtualDubControls.exe"</u>

Refer to the file *VirtualDubControls Script Instructions.doc* in the Violations folder on Google Docs for more detailed information.

<u>Using the "VirtualDubControls" Script:</u>

Once the script is running, using it to control the videos is a simple matter of learning the hotkeys that send commands to the VirtualDub windows. A table listing the hotkeys and a simple description of their functions is on the next page. A more detailed description of each function is as follows:

> **Play videos:** Press CTRL + ALT + P to play all four videos from their current frame number.
>
> **Stop videos:** Press CTRL + ALT + S to stop all four videos at their current frame number.
>
> **Advance 50 frames:** Press CTRL + ALT + F to advance each video 50 frames from its current frame number.
>
> **Move backwards 50 frames**: Press CTRL + ALT + R to move each video 50 frames back from its current frame number.
>
> **Move to beginning of videos:** Press CTRL + ALT + B to move to the beginning of all four videos.
>
> **Move to end of videos:** Press CTRL + ALT + E to move to the end of all four videos.
>
> **Synchronize to frame number:** To synchronize videos to a certain time, press CTRL + ALT + Y. This brings up a dialogue box that asks the user for the channel number (1 - 4) being synchronized to. Once a viable channel number is entered, another dialogue box queries the user for a frame number. The video of the channel previously indicated by the user will be moved to this frame number, and the remaining videos will be synchronized to this frame based on the information in the file "input.txt."
>
> **Change video frame rate:** To change the frame rate at which all four videos play, press CTRL + ALT + T. This brings up a dialogue box that queries the user for a frame rate. Once the user enters a number for the frame rate, the script will change the frame rate for all four videos to this number.

Each time you would like to use one of these commands, you will have to press every key indicated. That is, you must press CTRL and ALT each time you would like any of these functions to happen, and cannot simply leave CTRL or ALT pressed. Also, it is advisable that while these commands are being carried out, you do not attempt to make any manual keystrokes or click the mouse until the function has finished manipulating all four windows. Since you can see the script working, it will be easy to tell when the command is finished, as all four VirtualDub windows will be on top and will reflect the changes you have directed the script to make.

Hotkey	**Function**
CTRL + ALT + P	Play
CTRL + ALT + S	Stop
CTRL + ALT + F	Advance 50 frames
CTRL + ALT + R	Move backwards 50 frames
CTRL + ALT + B	Move to beginning
CTRL + ALT + E	Move to end
CTRL + ALT + Y	Synchronize to frame number
CTRL + ALT + T	Change playback framerate

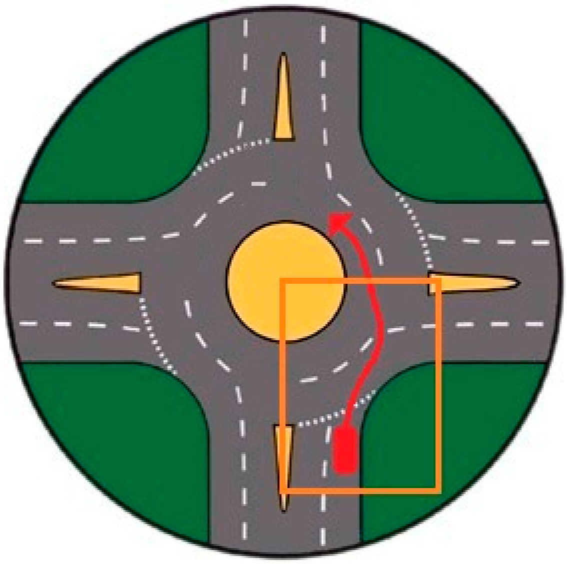
Types of Violations

We are concerned with seven types of violations. They are associated with yielding, lane changing, and turning. Recall that:

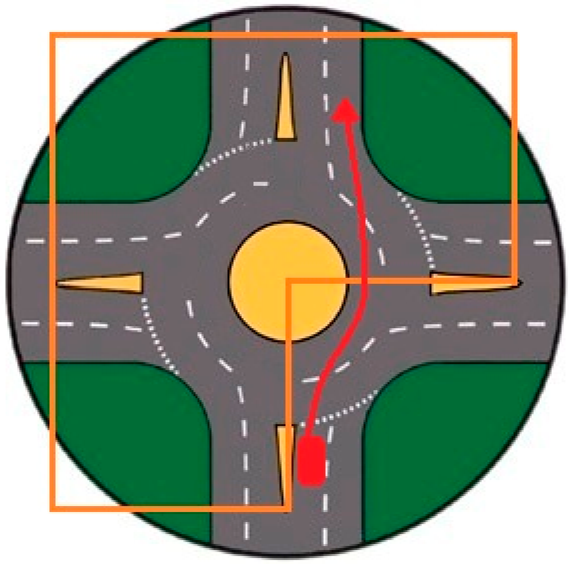
- Entering vehicles must yield to traffic in both lanes
- Vehicles may not make a lane change from the time they cross the yield line while entering to the end of the median while exiting
- It is not permitted to make a right turn from the inner lane
- It is not permitted to make a left turn or 360 from the outer lane

You may reference video examples in a folder titled “Violation Clips” under *T:\Roundabout Project\Violations* for further understanding and recognition of these violations.

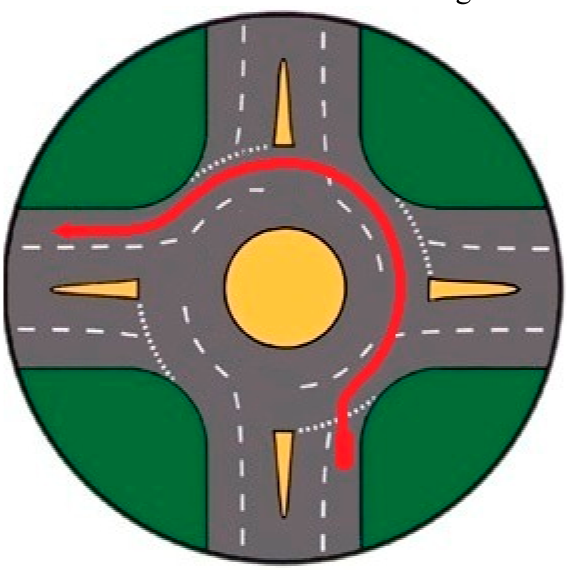
Picture Examples of Violations



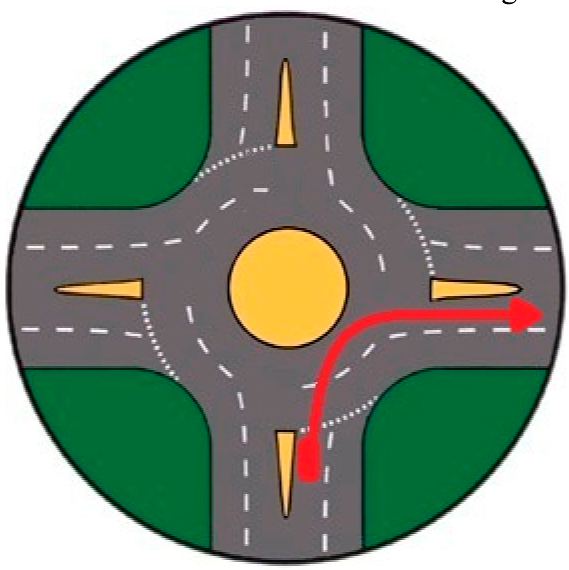
Entrance Lane Change



Exit Lane Change



Left Turn from Right Lane



Right Turn from Left Lane

Analyzing Process

Note: the Excel documents for each day are separated among channels, and the ready-to-begin documents for each channel are located in GoogleDocs under My Collections → Violations → Spreadsheets, and the folder for the respective day. Also, since multiple people will be using the same video files, the videos are available for shared use, located at T:\Roundabout Video Files\VIOLATIONS videos

1. Set the videos up as we did in Phase 2, with the videos rotated appropriately and at 75% zoom

2. Watch each vehicle that enters the roundabout from your assigned channel
3. When a violation occurs, enter the following data into Excel:

Under the "Enter Frame" column:

- Input the frame number at which the vehicle begins to cross the yield line to enter the roundabout

Under the "Vehicle Type" column: *[Note that these are the same as they were in Phase 2]*

- 1: Sedan
- 2: Motorcycle
- 3: SUV/Minivan
- 4: Truck
- 5: Bus
- 6: Semi-trailer

Under the "Enter Lane" column:

- "1" denotes the inner lane
- "2" denotes the outer lane

Under the "Violation Channel" and "Violation Frame" columns:

- Use the channel that has the clearest view of the violation
    - o While we are using channels 5-8, denote this in terms of channels 1-4
- Input a frame number near the beginning of the violation

Under the "Yield Violation" column:

- "0" indicates no yield violations occurred
- "1" indicates failing to yield to traffic in the inner lane
- "2" indicates failing to yield to traffic in the outer lane
- "3" indicates failing to yield to traffic in both lanes

Under the "Lane Change" column:

- "0" indicates no lane change violations occurred
- "1" indicates a lane change in the first 90 degrees upon entering
- "2" indicates a lane change after the vehicle's first 90 degrees

Under the "Turn Violation" column:

- "0" indicates that no turn violations occurred

- “1” indicates that a vehicle made a right turn from the inner lane
- “2” indicates that a vehicle made a left turn from the outer lane
- “3” indicates that a vehicle made a 360 degree or more turn from the outer lane

Note: For lane change violations, you may consider the violation to occur when the vehicle has begun the illegal maneuver, i.e. when the vehicle entering from the inner lane begins a right-turn exit, or when the vehicle entering from the outer lane begins a left-turn.

Under the “Incorrect Lane Choice” column:

- “0” denotes a correct lane choice
- “1” denotes an incorrect lane choice

Note: It is of particular importance to this project to note whether or not the car selected the appropriate entrance lane for its desired turn

Occurrences to watch for

<u>Buses</u>

Buses coming from the east on 66th Street and heading south onto Portland Avenue (therefore they are making a left turn) are special cases. The bus stops are on the outer/right lanes, while in order to make a left turn the bus must be in the inner lane. There is not enough space between the bus stops and the roundabout entrances and exits for the bus drivers to make legal lane changes. Consequently, such buses will routinely make one or two of three violations: an entrance lane change from the outer lane to the inner lane, a left turn from the outer lane, or an exit lane change. These events are recorded appropriately.

<u>Swinging wide</u>

While a vehicle is turning within or into the roundabout, if the vehicle swings into another lane, but does not turn this into a definite lane change, do **not** count this as a lane change.

There is an exception to this rule. If the vehicle is physically unable to avoid encroaching on a lane it should not be in, no matter how slow or sharp the turn, take note by filling out only the “Enter Frame”, “Vehicle Type”, and “Enter Lane” columns, as well as making a note of the occurrence in a “Comments” column. It is generally believed that this will apply only to semi-trailers.

<u>Close Calls/Accidents</u>

When you witness a close call or accident pertaining to a vehicle that entered from your channel, be sure to enter the appropriate information, descriptively, in the “Roundabout Violations & Close Calls” document in the violations folder in Google Docs. Try to make sure that another person has not already entered information pertaining to the same incident, since close calls and accidents involve two or more parties, which likely come from different channels.

It may be difficult to determine whether or not the incident was an actual accident, but telltale signs include the vehicles pulling over at some point afterward to inspect their vehicles or talk to each other, and considering the high volume of police officers patrolling the area, it may be likely that an officer may approach the scene as well.

A close call will require some form of discretion, but should include when vehicles must slam on their brakes or swerving to avoid a collision.

AutoHotkey Scripts written for the Roundabout Violations Project
(Developed by Gordon Parikh)

One of the challenges for data collection in the Violations project came out of the way footage of the roundabout was recorded. The use of four separate cameras, each recording a separate channel of traffic, to collect footage meant that watching traffic move through the entire roundabout would require additional effort. For one, it was necessary to set up videos four at a time in order to see the entire roundabout at once. A protocol was developed for this that involved setting up four VirtualDub windows as shown in Figure 1.

Figure 1: Screenshot of Roundabout Video Setup

This allowed the roundabout to be viewed in its entirety, and permitted any orientation, that is any channel number in the top position, so long as the channel numbers increased in the clockwise direction.

This solved the problem of how to view the entire roundabout, however because of the volume of traffic moving through the roundabout it would not be possible to individually manipulate each of these windows without slowing down the rate of data collection to an unacceptable level. It was therefore necessary to either modify the videos, or to otherwise modify the playing of the videos to allow their simultaneous control. Attempts to combine the four videos into one proved unattractive, as this was a very computationally intensive process that would have taken far too much time given the amount of video to be processed. Beyond this, the scripting language native to VirtualDub, Sylia, was found to be inadequate for almost any purpose, lacking almost all useful commands. Any automated manipulation thus had to take place outside of VirtualDub.

The simplest solution to this problem seemed to involve the use of keyboard macros to automate a number of simple tasks. An early prototype of the program used for this project consisted only of scripted Windows and VirtualDub keyboard shortcuts (for example alt + tab to switch between windows and Enter to play videos), used in conjunction with considerable user interaction to ensure their proper function. To make the automation even more user-friendly, a more sophisticated macro and automation utility, AutoHotkey, was used. AutoHotkey is free and open-source, and runs on a fully developed scripting language capable of modifying any application user interface, which made it the ideal choice for this problem, as it would be capable of manipulating all of VirtualDub's features.

The first version of the script that was ultimately used for data collection was based on some of the same principles as the prototype macro that had been written, namely the use of keyboard shortcuts to manipulate the video windows. The primary change involved the use of the WinActivate command, which can be used to activate any window based on its window title (or other identifying characteristic). This command made the program considerably easier to use, as it could simply grab the correct window without user interaction. However it soon became obvious that the program would need to be able to distinguish video windows not just from other windows, but from each other, essentially requiring that the program understand what a "channel" was. This was accomplished by taking advantage of VirtualDub's window titling scheme in conjunction with the video file titling scheme that was used for this project. An example of a window title for a window containing one of these videos would look something like:

VirtualDub 1.9.9 – [100808-ch01-070310-080310_xvid.avi]

This offered a good solution to this problem, but getting it to work required a few things. First, the version number (1.9.9 in the example above) had to remain static, and second, the recording date code (100808 in the example above) had to be accessible to the program in some way. The first issue was resolved by ensuring that the version of VirtualDub running on the computers being used to analyze video was the version the script was written for, and the second issue was resolved by requiring the user to create a text file, named "input.txt," that would contain on the first line the date code of the videos being analyzed to be read into a variable by the program.

After these two issues were resolved, the majority of the script worked relatively simply. Each window would be activated individually and the Send command used to send the assigned keyboard shortcut to play, pause, advance, or reverse the video. Figures 2 and 3 show the code for the "Play" command, assigned the hotkey **ctrl + alt + p**, and the "Advance 50 Frames" command, assigned the hotkey **ctrl + alt + f**, respectively.

```
^!p::
    IfWinExist, VirtualDub 1.9.9 - [%date%-ch01
            WinActivate
            Send {enter}
    IfWinExist, VirtualDub 1.9.9 - [%date%-ch02
            WinActivate
            Send {enter}
    IfWinExist, VirtualDub 1.9.9 - [%date%-ch03
            WinActivate
            Send {enter}
    IfWinExist, VirtualDub 1.9.9 - [%date%-ch04
            WinActivate
            Send {enter}
return
```

Figure 2: Code for the Original Play Command

```
^!f::
    IfWinExist, VirtualDub 1.9.9 - [%date%-ch01
        WinActivate
        Send {lalt down}{right}{lalt up}
    IfWinExist, VirtualDub 1.9.9 - [%date%-ch02
        WinActivate
        Send {lalt down}{right}{lalt up}
    IfWinExist, VirtualDub 1.9.9 - [%date%-ch03
        WinActivate
        Send {lalt down}{right}{lalt up}
    IfWinExist, VirtualDub 1.9.9 - [%date%-ch04
        WinActivate
        Send {lalt down}{right}{lalt up}
return
```

Figure 3: Code for the Advance 50 Frames Command

This would have been enough for the project to run, however some additional functionality was sought out in order to make the data collection process easier for the workers. This came about primarily through the addition of a “Sync” command, which would automatically synchronize all four videos to a user-specified time to make up for uneven play rates or user manipulation of the videos. To write this command required a few things: the frame numbers used to synchronize the videos, determined by the workers as described in the “Process” section, had to be loaded into the program, and a means for the user to specify a time to which to move the videos.

The first requirement was met easily by expanding the “input.txt” file to include on separate lines the synchronizing frame numbers, starting with that corresponding to channel one with the remaining following respective to their numbering. The second requirement, however, was a little more complicated, as workers would need to use the command multiple times before changing videos. The solution was to write a user-friendly interface that would query a worker for a frame number, corresponding to a specific channel, to move the videos to. The code for this consisted of a series of loops that would display boxes into which the frame and channel numbers could be entered (see Figure 4)

```
Loop
    InputBox, channel, Channel Number, What is the channel you are syncing to?
        If ErrorLevel
            Exit
        If channel between 1 and 4
            break
        If channel not between 1 and 4
            MsgBox, That is not a valid channel number.
            continue
```

Figure 4: Example of Code for Input Box, from Sync Command

From here, a series of simple calculations would be carried out using the synchronization frame numbers and the frame and channel number specified by the user to determine which frame number to move each video to. The code ran by the program if channel one is selected is shown in Figure 5.

```
IfEqual, channel, 1
    ch01frame := frame
    ch02frame := frame - ch01sync + ch02sync
    ch03frame := frame - ch01sync + ch03sync
    ch04frame := frame - ch01sync + ch04sync
```

Figure 5: Example of Frame Number Calculations for Sync Command

Videos would then be moved to the frame numbers obtained by these calculations, using the Send command to, in each window, trigger keyboard shortcuts for the “Jump to frame” dialogue box and type into it the corresponding frame number. This caused each window to be moved to the correct frame number with minimal user effort, saving considerable time.

A similar command was also included to save the user the time it would take to individually change the playback frame rate of each window, in order to allow workers to go through the video at the rate they were most comfortable with. The execution of this function was very similar to the “Sync” command, querying the user for a frame rate and using keyboard shortcuts to bring up the dialogue in VirtualDub to enter in this value in order to change the frame rate.

Upon the introduction of new workers for this project, the script was updated to streamline its operation and remove some bugs that were the cause of frequent work-stopping issues. First, the requirement that the program be version-specific was eliminated. This was done by using AutoHotkey’s WinGetTitle command to query the full window title of VirtualDub windows and using a parsing loop to read through this string until the version number was found (see Figure 6).

```
WinGetTitle, wintitle, VirtualDub

Loop, Parse, wintitle, %A_Space%
    version = %A_LoopField%
    IfEqual, version, VirtualDub
        continue
    Else
        break
```

Figure 6: Code to Determine Version Number of VirtualDub

In addition to this, the method for referring to a window was changed from window title to its unique window handle. This value is obtained in AutoHotkey through use of the WinGet command, as seen in Figure 7 where the variable “ch01” is created and set equal to the unique identifier for the window containing the video for channel 1.

```
WinGet, ch01, ID, VirtualDub %version% - [%date%-ch01
```

Figure 7: Obtaining the Unique ID for the Channel 1 Video Window

The window IDs that were obtained by this method were then used to replace in the code for all commands the Send command with the ControlSend command. In AutoHotkey’s scripting language, a “control” is essentially any object that can be manipulated, so using this command allowed for the manipulation of a program's user interface with minimal interaction with a window, and therefore with little disturbance to the user.

This command made the code for advancing and reversing video simultaneously less elaborate and more powerful. The code for this command is shown below. Using this scheme, the twelve lines of code that were required to move the four videos forward by 50 frames were replaced by four lines that allowed videos to be advanced one frame at a time, by keyframe, and by 50 frames. Besides this additional functionality, triggering this command was made simpler, changed from **ctrl + alt + f** to simply **F12** (see Figure 8), pressed alone or in conjunction with a modifier key depending on the desired movement (frame, keyframe, or 50 frames).

```
*F12::
    ControlSend,, {blind}{right}, ahk_id %ch01%
    ControlSend,, {blind}{right}, ahk_id %ch02%
    ControlSend,, {blind}{right}, ahk_id %ch03%
    ControlSend,, {blind}{right}, ahk_id %ch04%
return
```

Figure 8: Code for the F12 Hotkey

While this change made some commands simpler, it also necessitated the rewrite of several others. For instance, the "Play" command, which in the previous version of the script used VirtualDub's keyboard shortcut for previewing filtered video (the enter key), had to be rewritten due to some issues with using the enter key in conjunction with the ControlSend command. The fix for this involved directly modifying the play button (Figure 9) and was also employed for the updated Stop command.

```
^!p::
    Control, Check,, Button3, ahk_id %ch01%
    Control, Check,, Button3, ahk_id %ch02%
    Control, Check,, Button3, ahk_id %ch03%
    Control, Check,, Button3, ahk_id %ch04%
Return
```

Figure 9: Code for the Updated Play Command

Another issue again involved a compatibility issue between the ControlSend command and a certain key, in this case **ctrl**. This interfered with the sync and change frame rate commands, but was remedied by directly manipulating VirtualDub's menu bar to select the corresponding item from the Video menu, as shown in Figure 10.

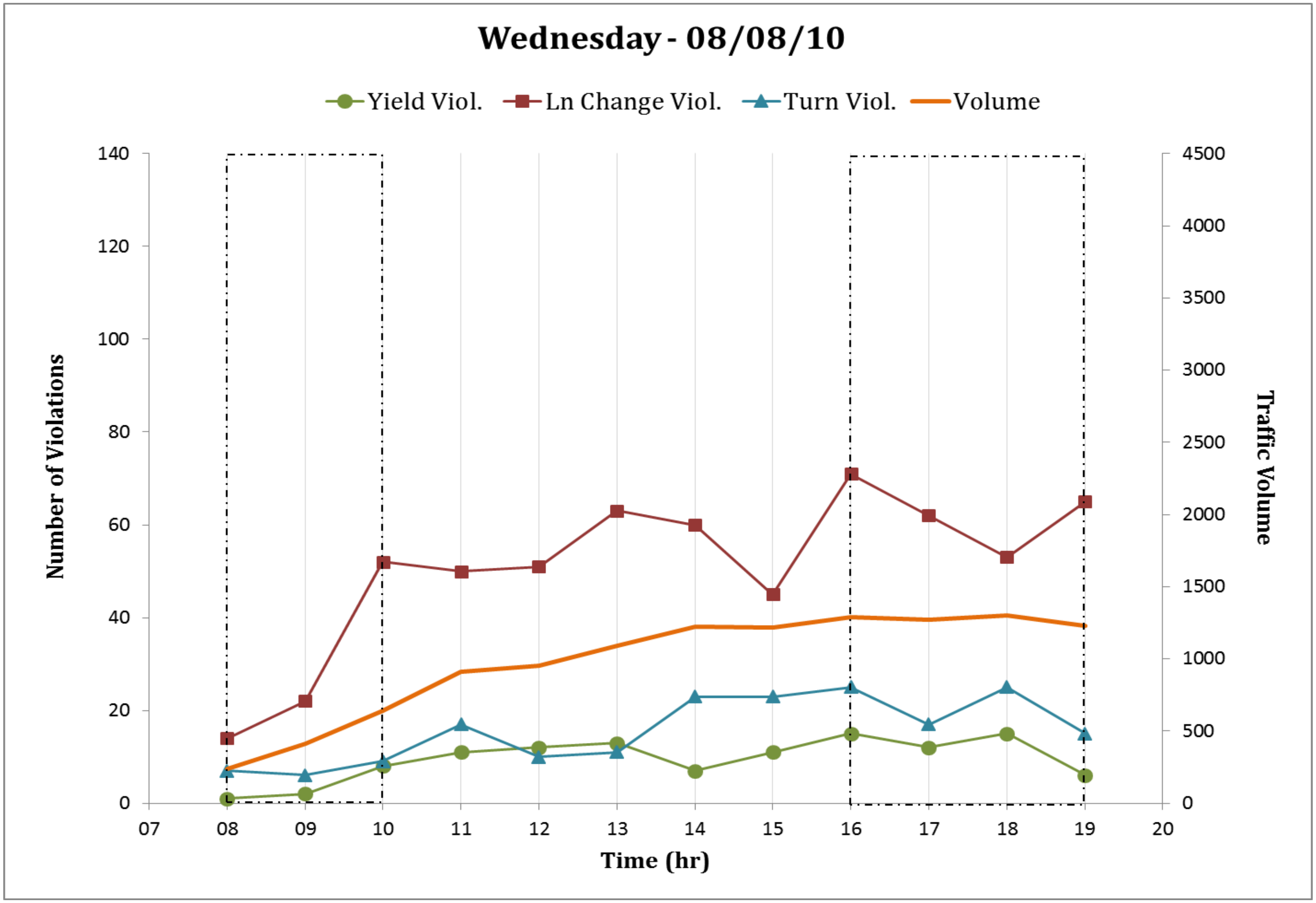
```
WinMenuSelectItem, ahk_id %ch01%,, Go, Go To Frame...
WinWait, Jump to frame
ControlSend, Edit1, %ch01frame%, Jump to frame
ControlSend,, {enter}, Jump to frame
```

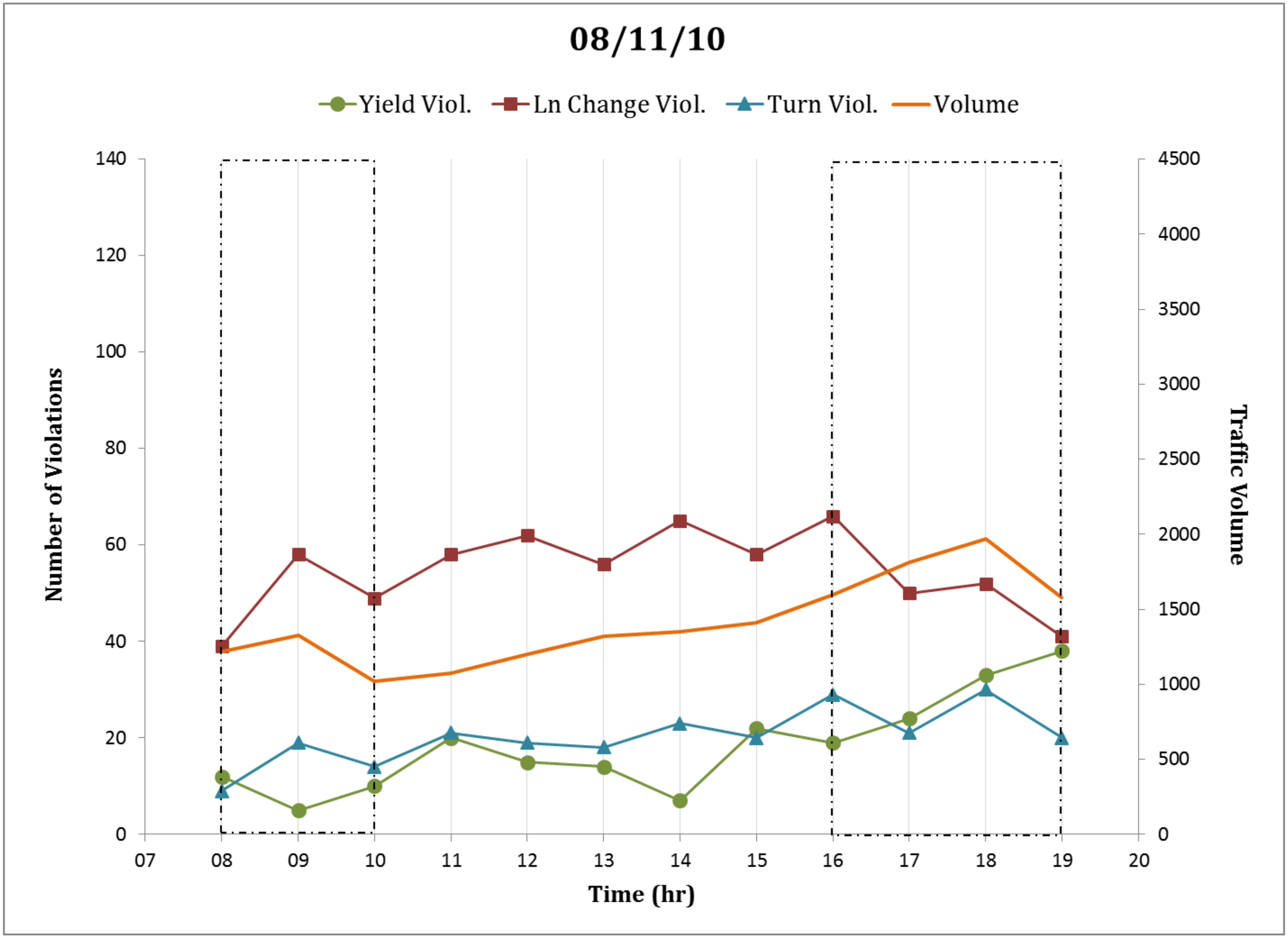
Figure 10: Code from the Sync Command, Sending the Necessary Commands to VirtualDub

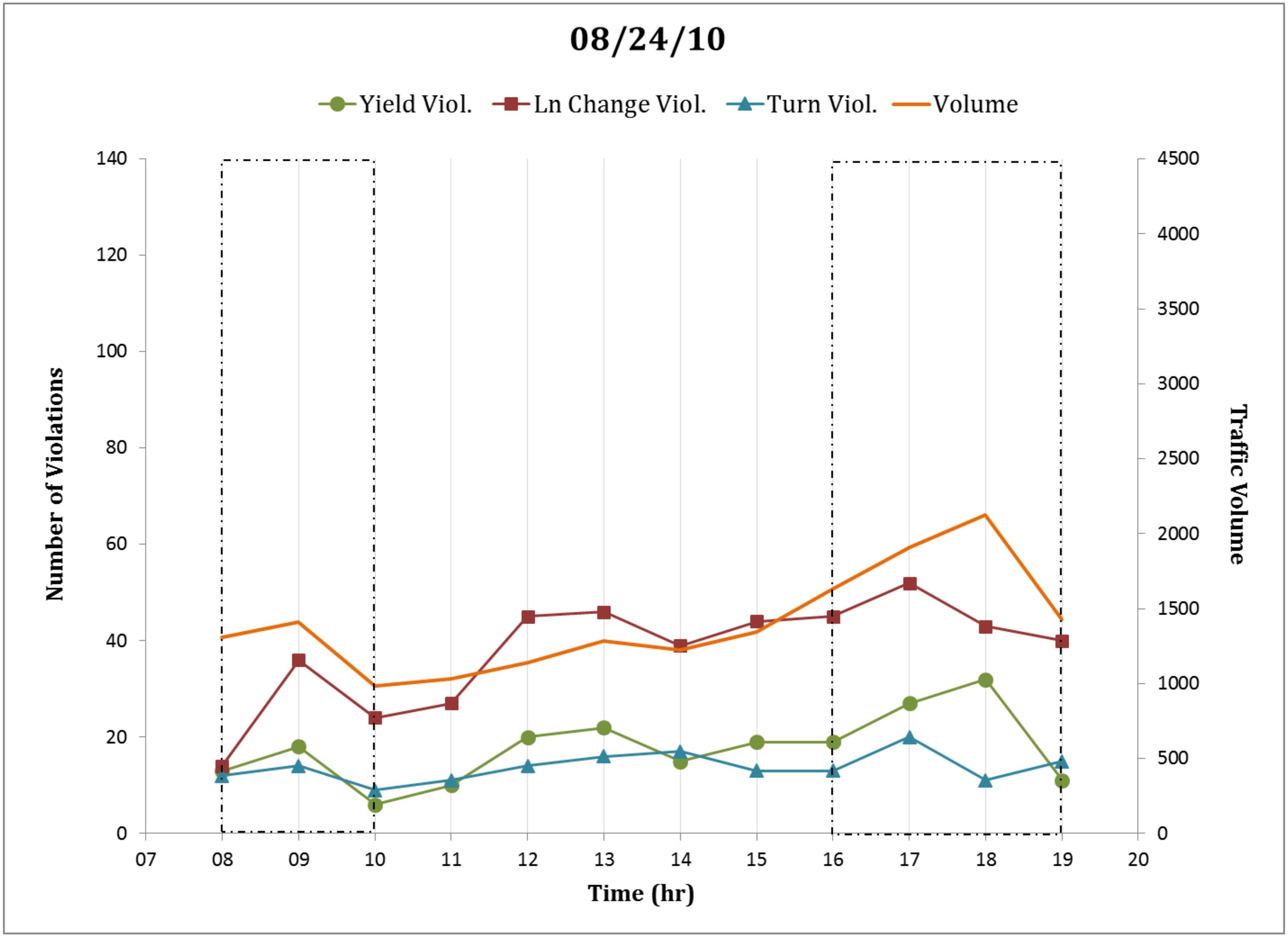
Following these updates, the script ran considerably more quickly and with less worker interruption, allowing for a higher rate of video analysis and less troubleshooting.

Appendix B: Hourly Counts of Violations

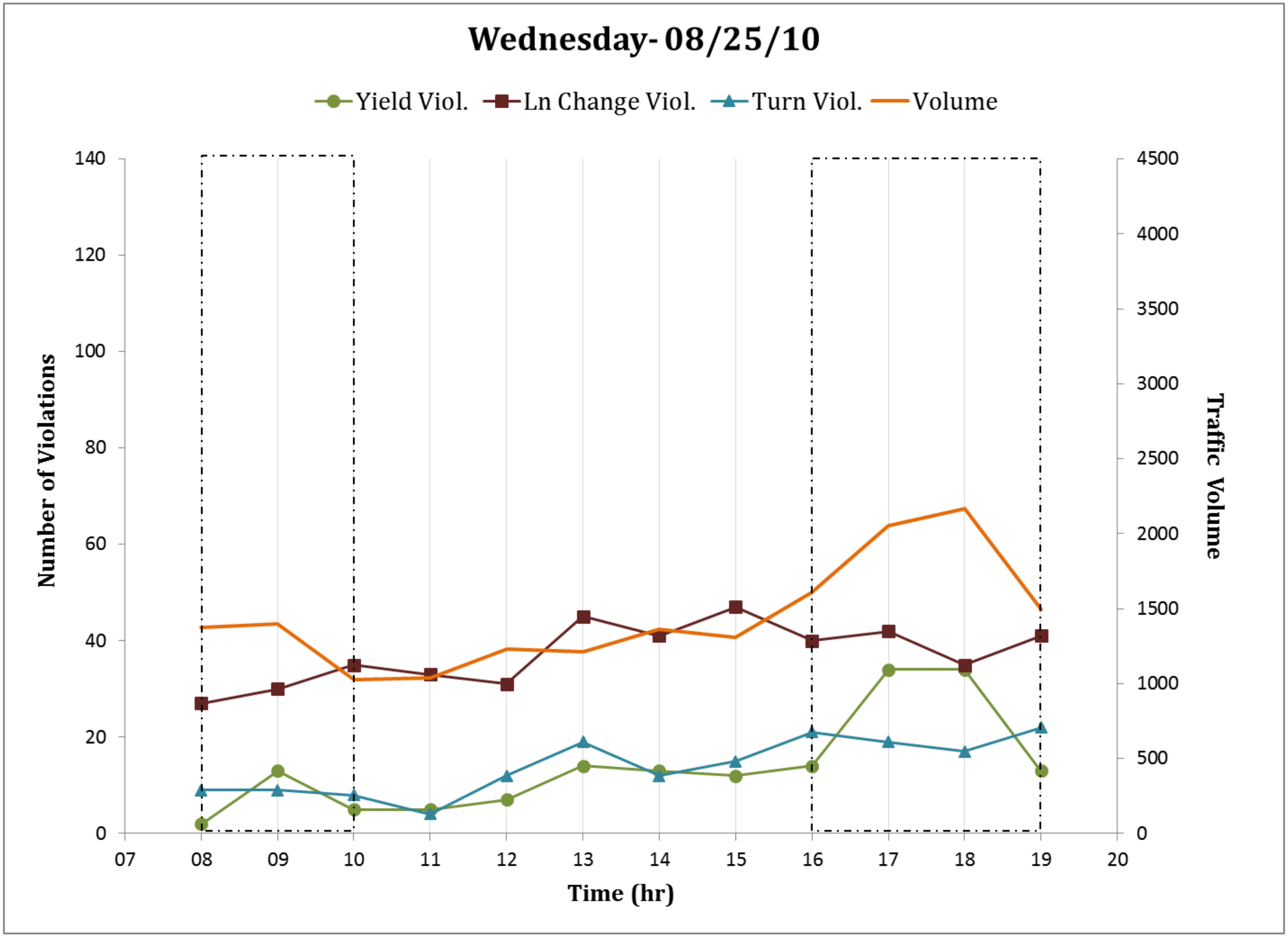
The following figures present the hourly counts of violation on each of the days of the study along with the estimated hourly volume entering the roundabout



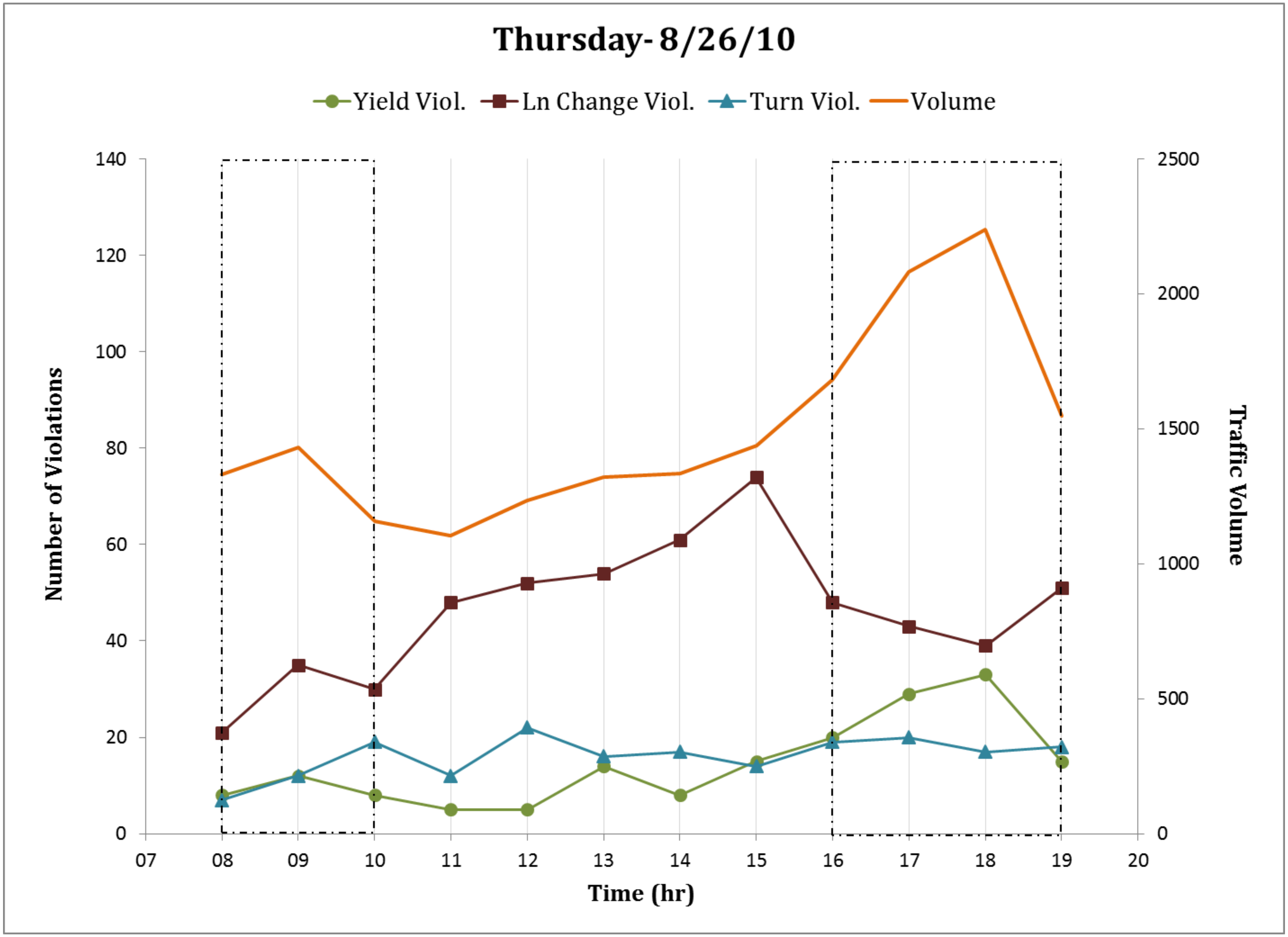

08/11/10
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
3500
4000
4500
07
08
09
10
11
12
13
14
15
16
17
18
19
20

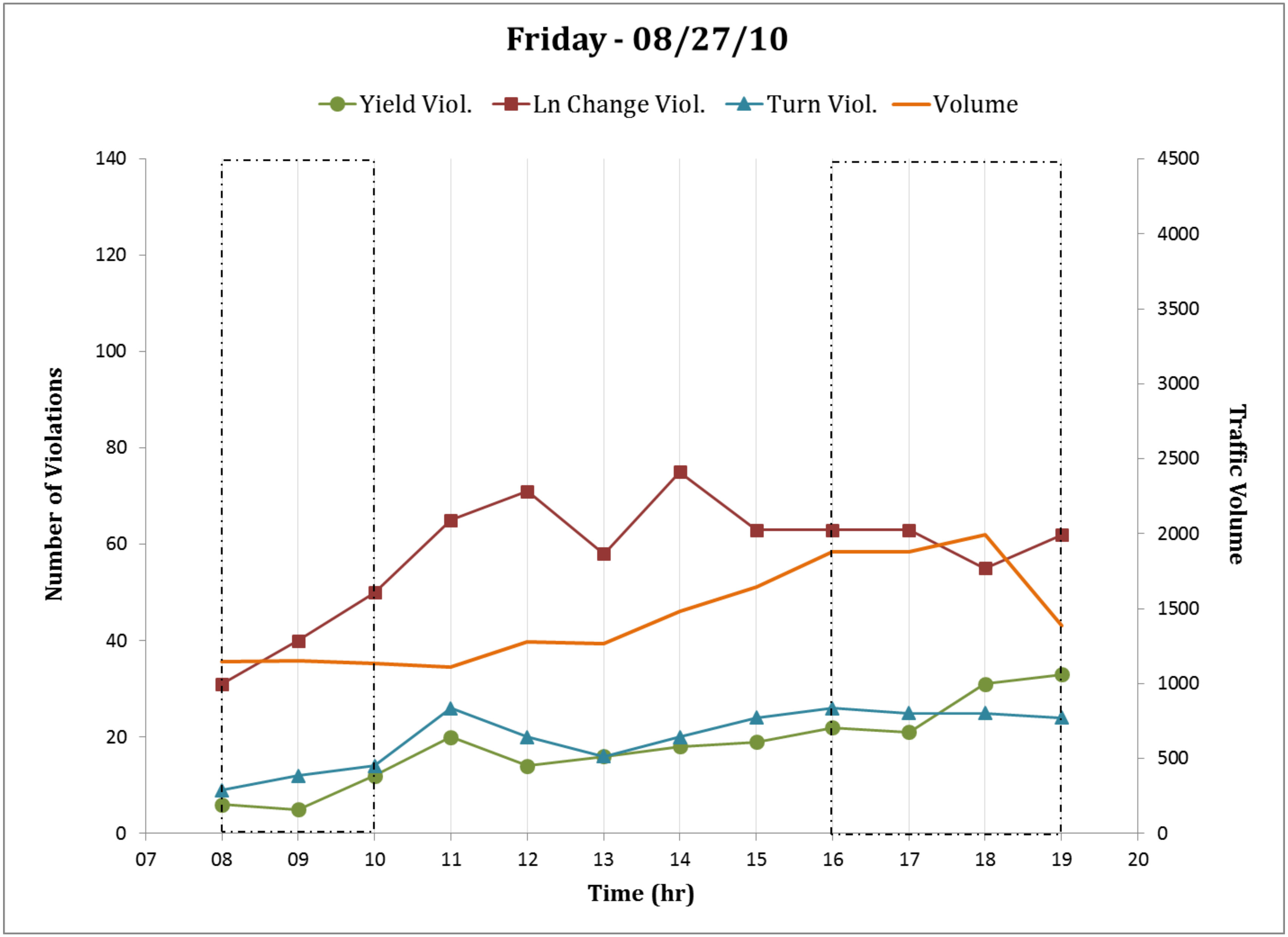


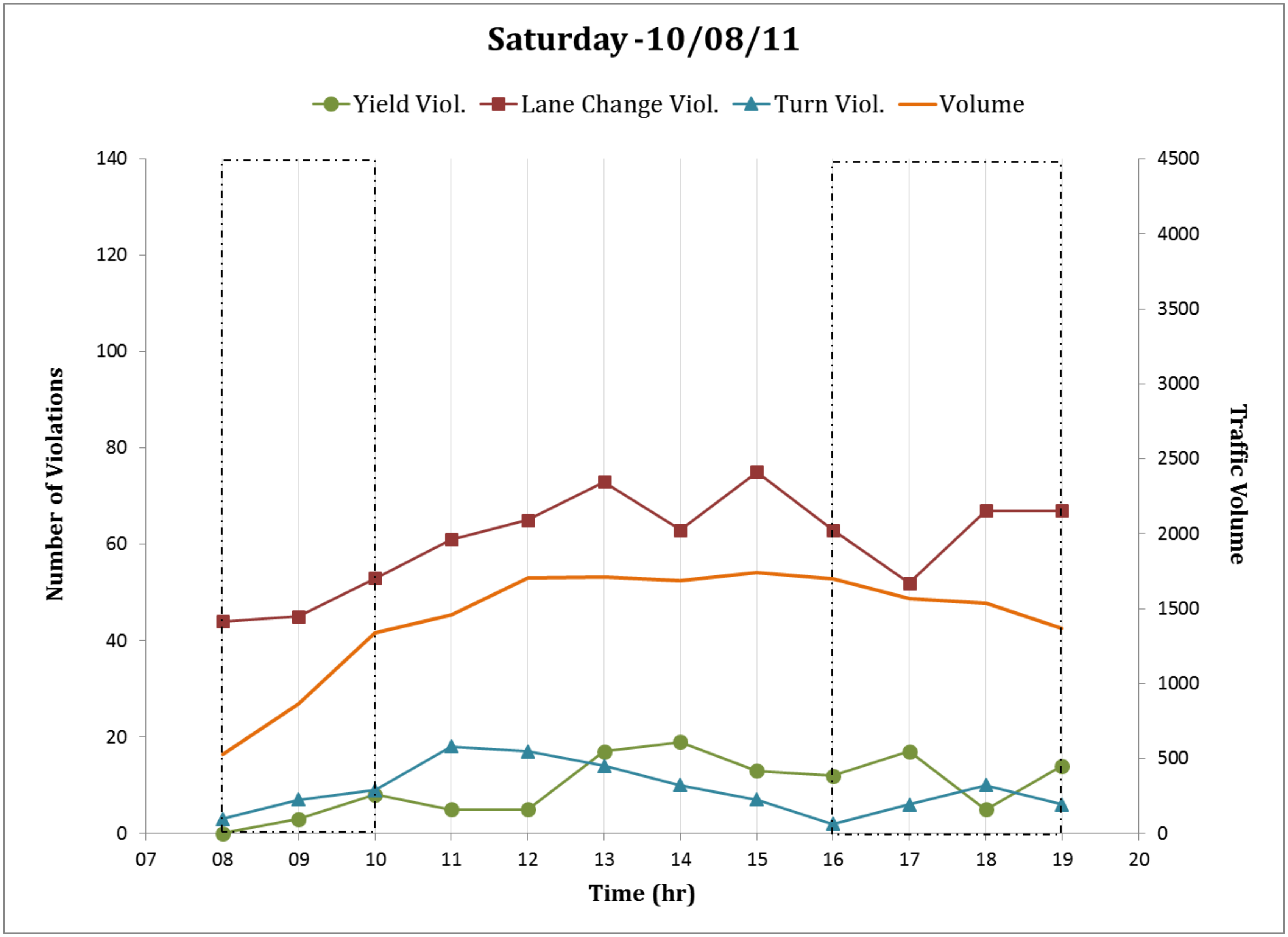
08/24/10
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
140
120
100
80
60
40
20
0
4500
4000
3500
3000
2500
2000
1500
1000
500
0
07
08
09
10
11
12
13
14
15
16
17
18
19
20

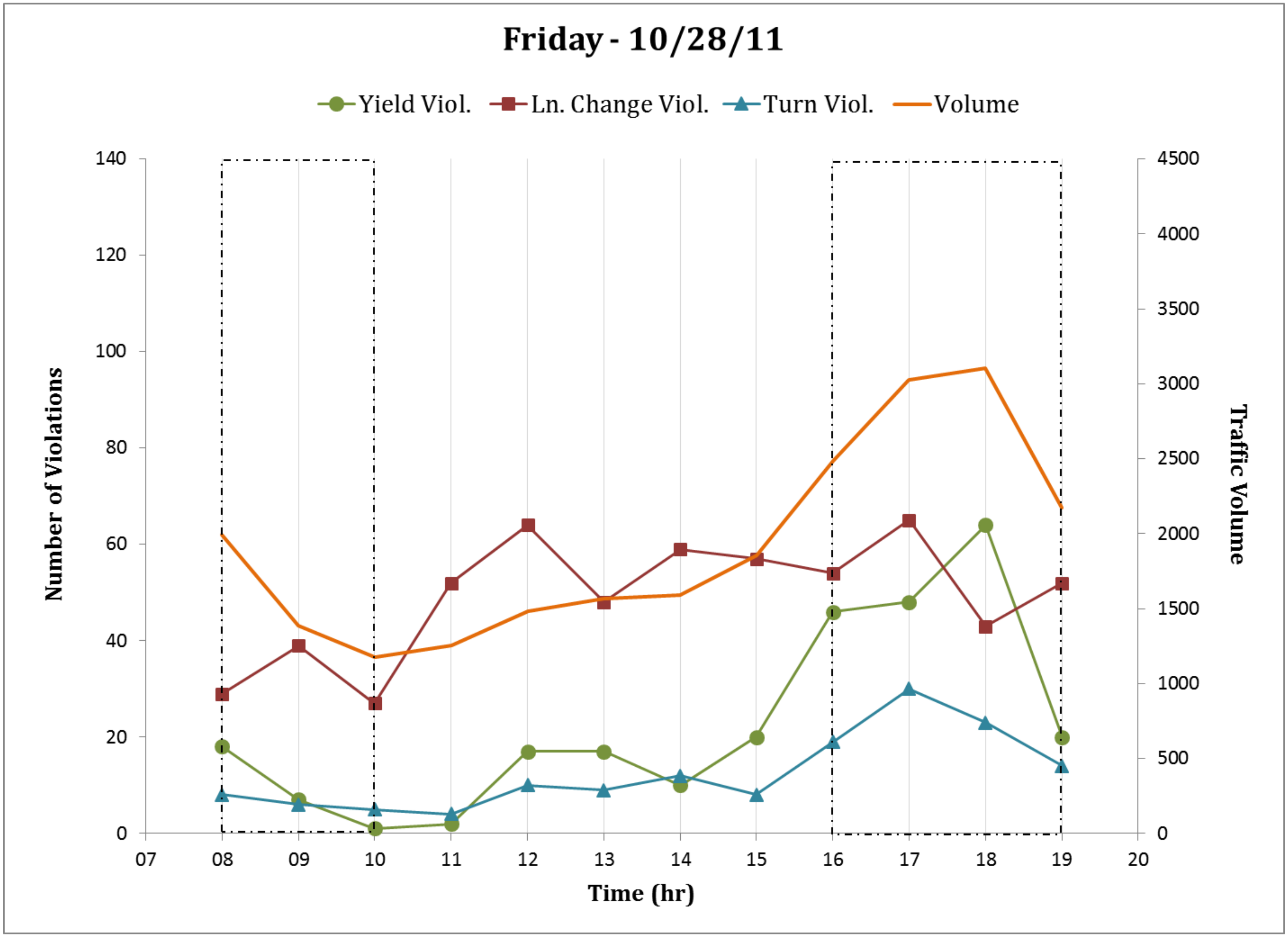


Wednesday- 08/25/10
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
3500
4000
4500
07
08
09
10
11
12
13
14
15
16
17
18
19
20


Thursday- 8/26/10
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
07
08
09
10
11
12
13
14
15
16
17
18
19
20


Friday - 08/27/10
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
3500
4000
4500
07
08
09
10
11
12
13
14
15
16
17
18
19
20


Saturday -10/08/11
Yield Viol.
Lane Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
3500
4000
4500
07
08
09
10
11
12
13
14
15
16
17
18
19
20



Friday - 10/28/11
Yield Viol.
Ln. Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
3500
4000
4500
07
08
09
10
11
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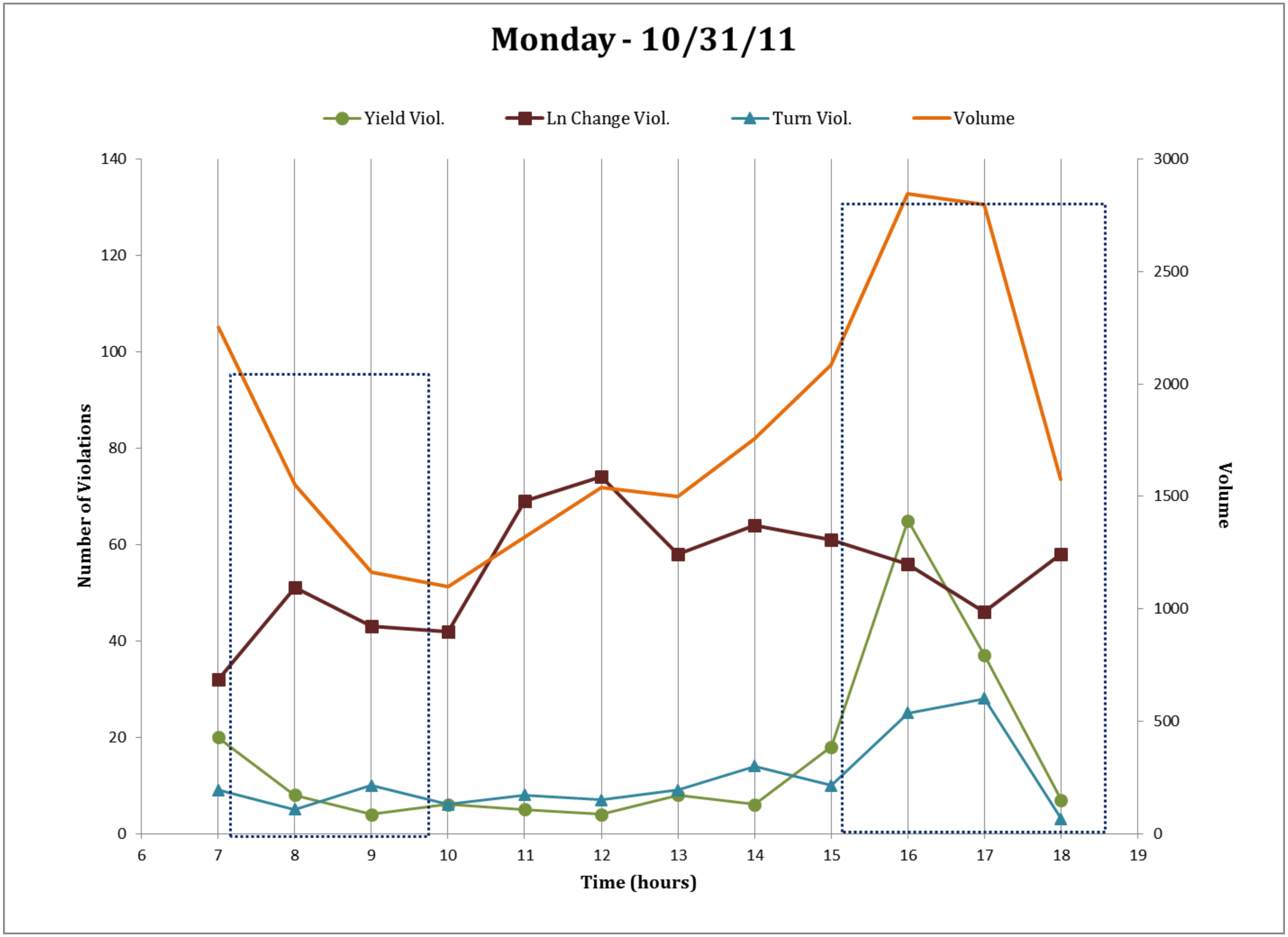
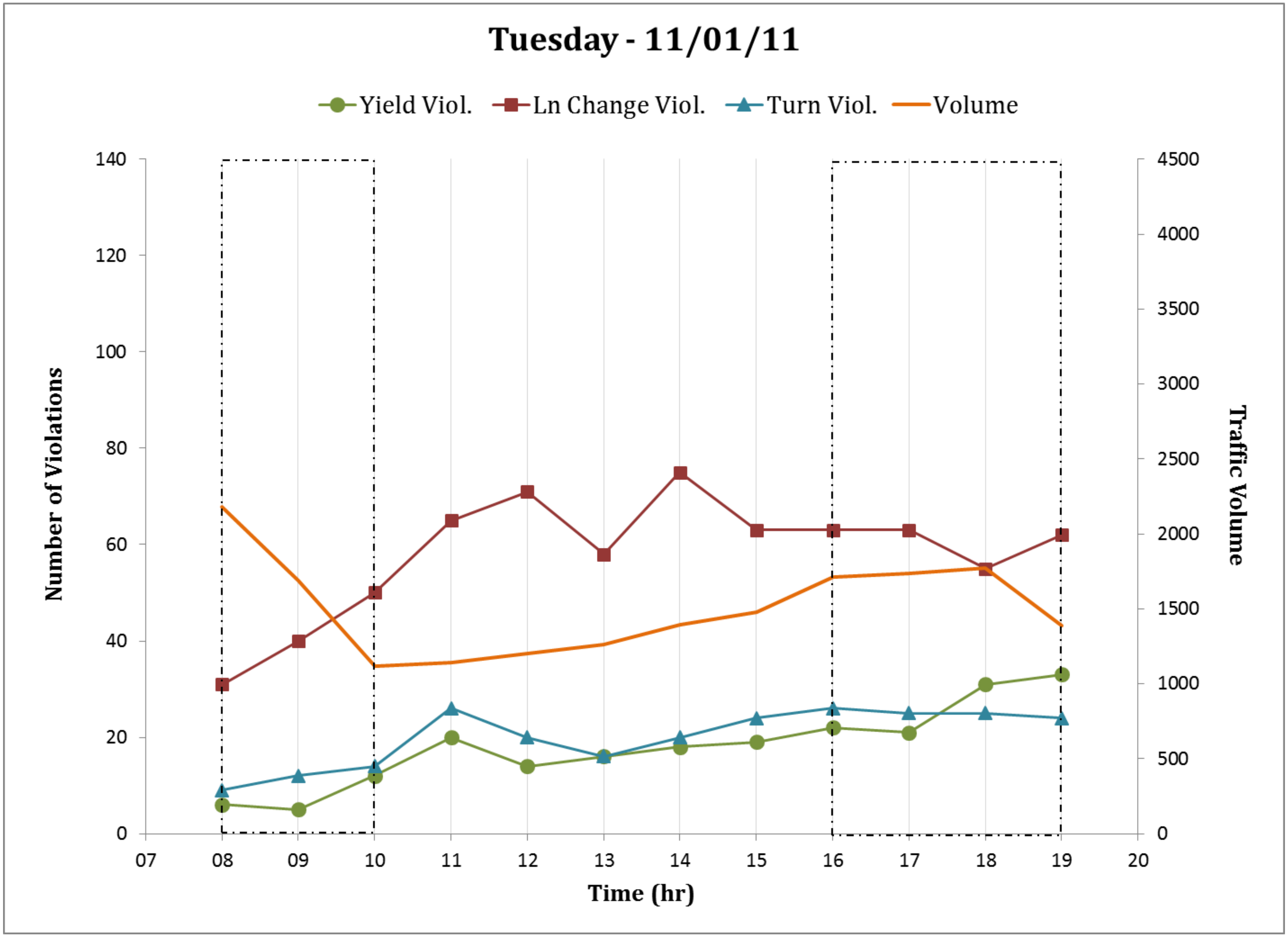
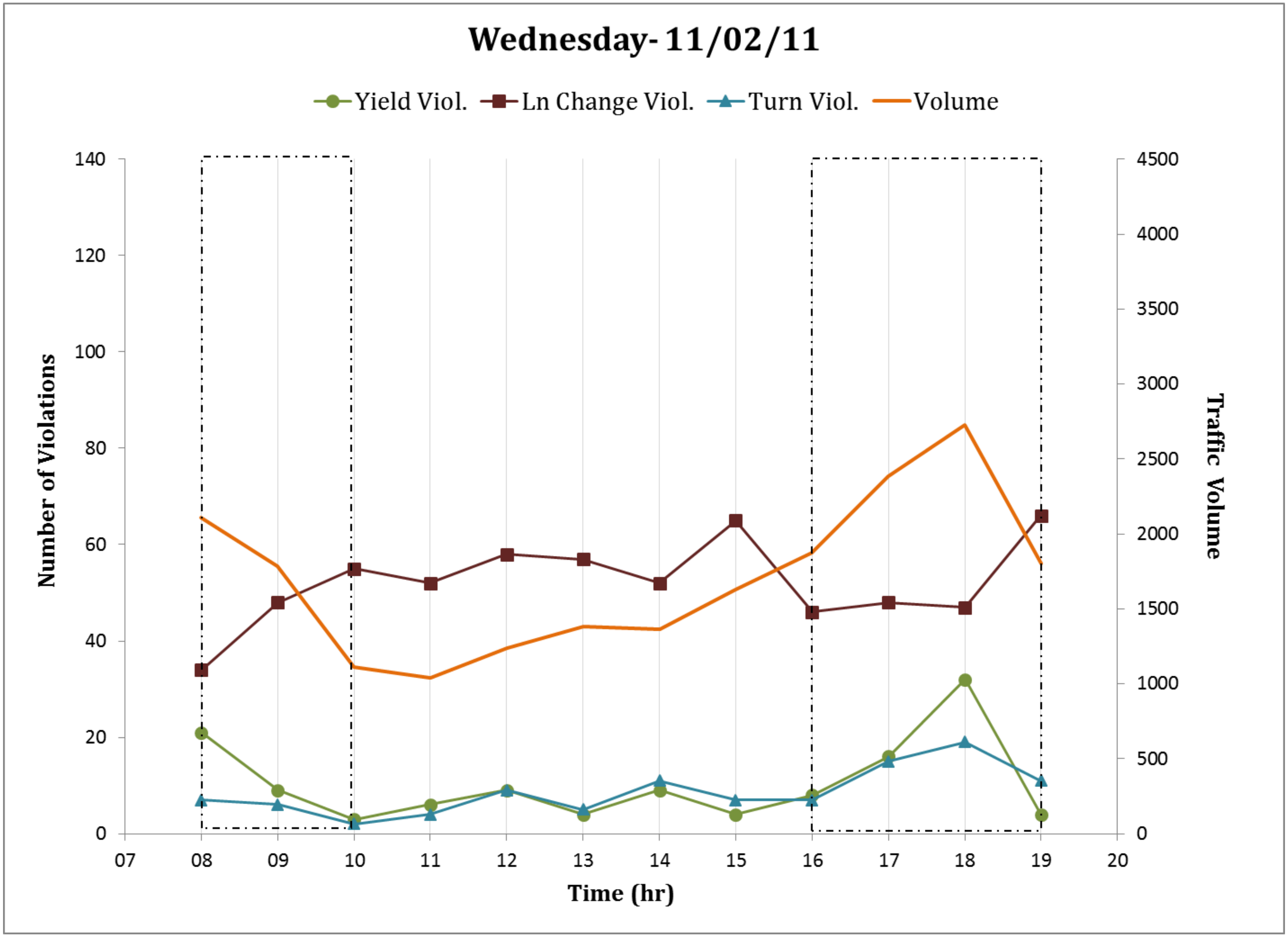
15
16
17
18
19
20



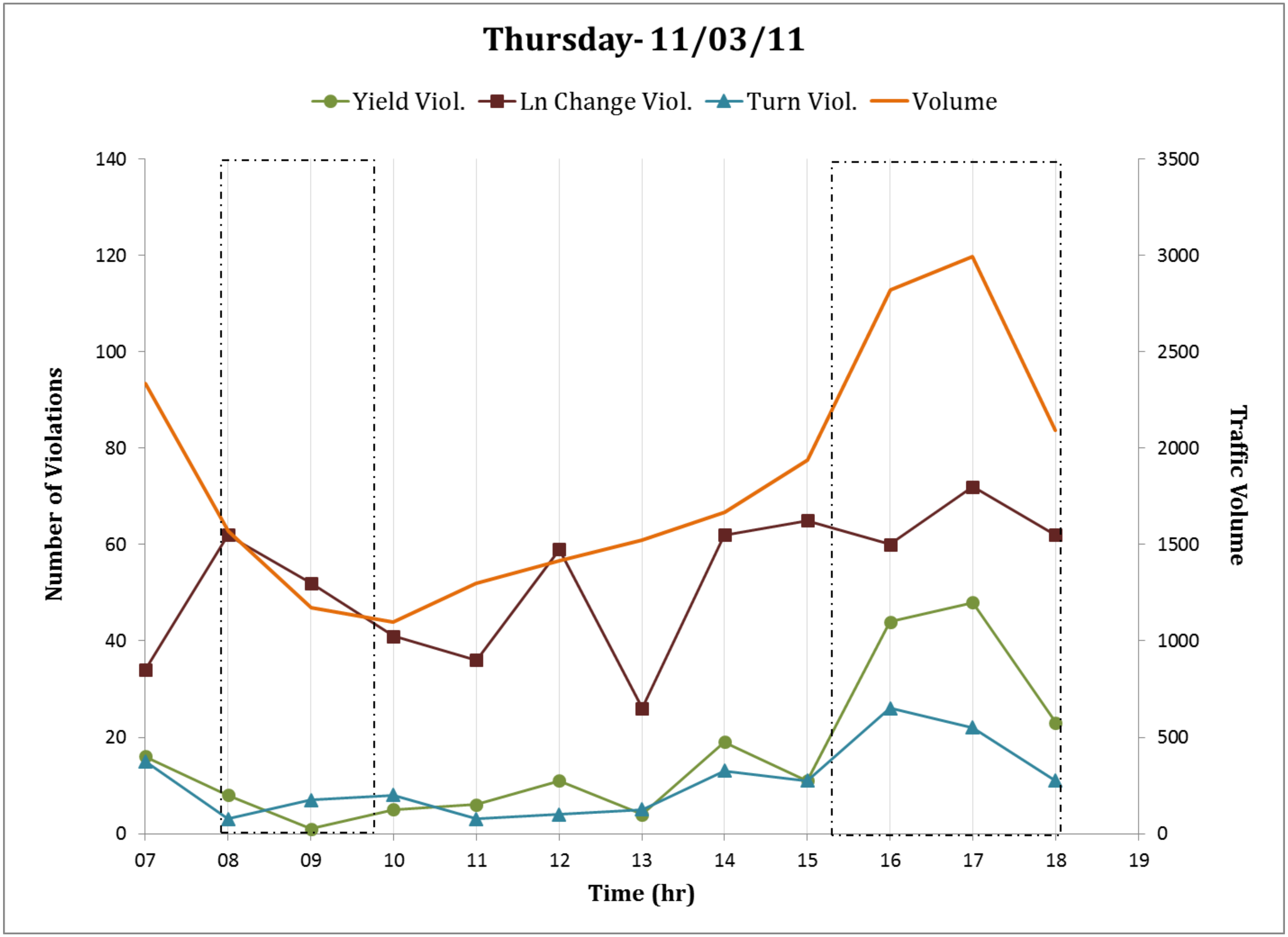
Monday - 10/31/11
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Volume
Time (hours)
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
6
7
8
9
10
11
12
13
14
15
16
17
18
19



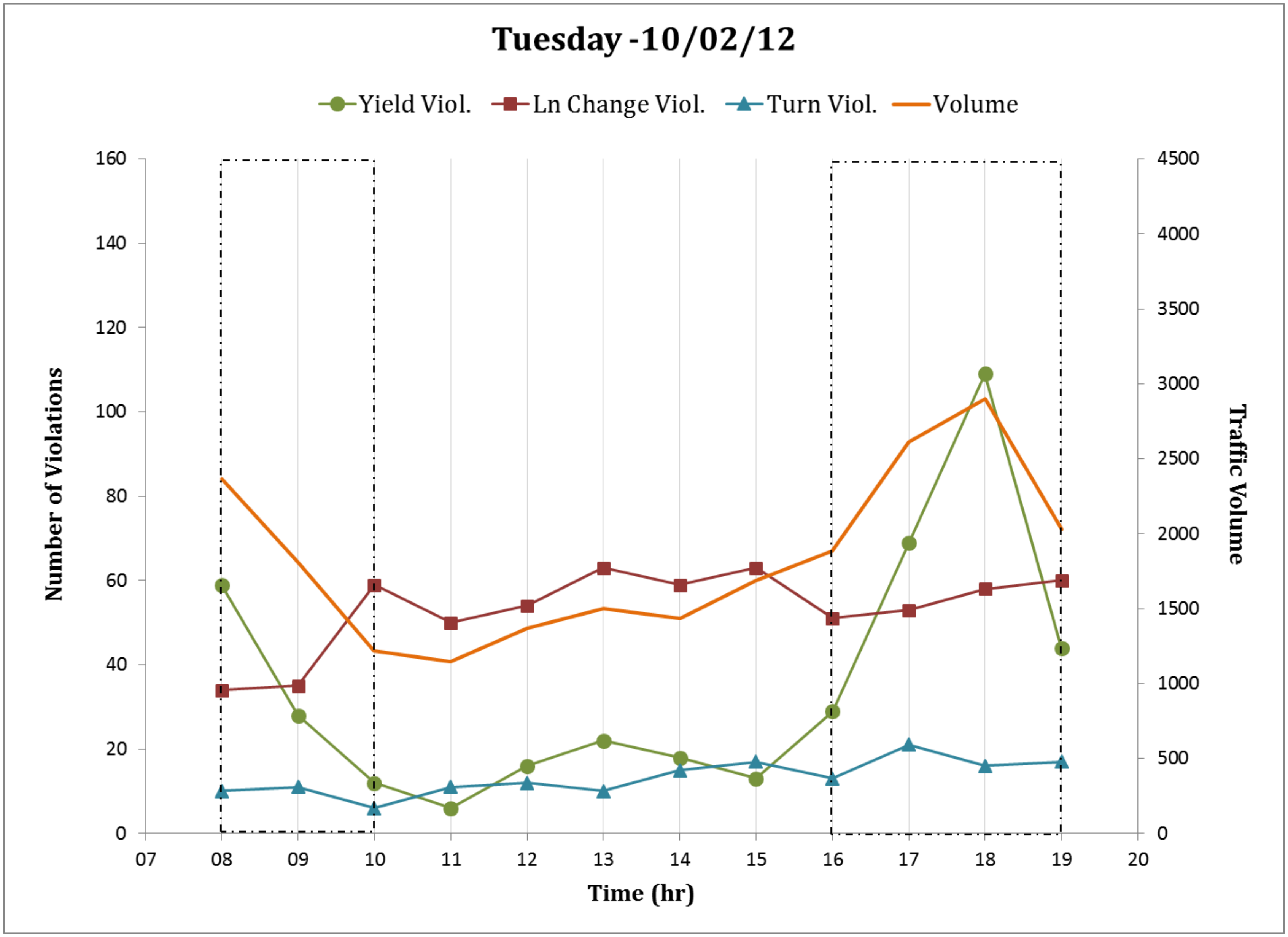
Tuesday - 11/01/11
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
3500
4000
4500
07
08
09
10
11
12
13
14
15
16
17
18
19
20



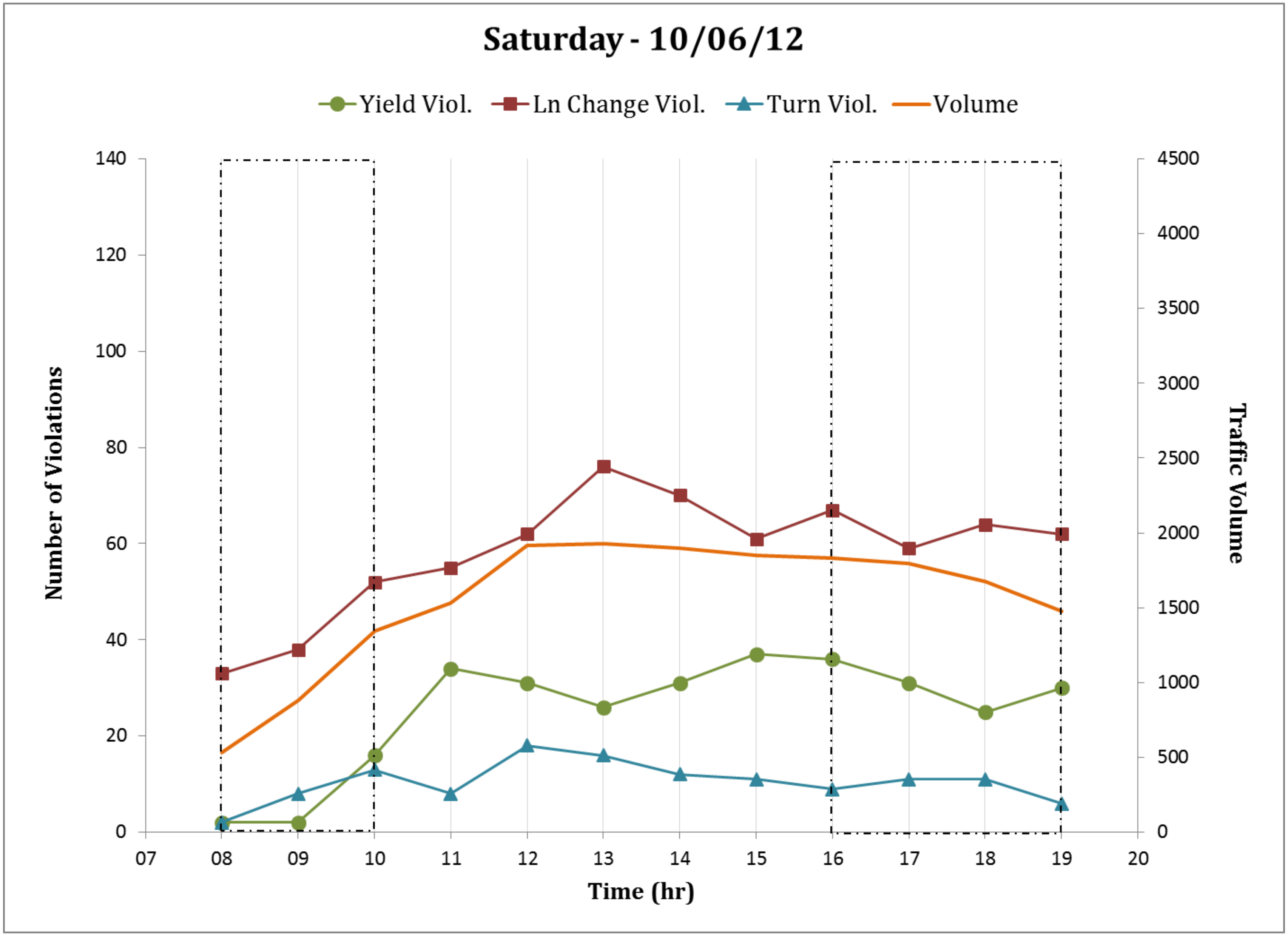
Wednesday- 11/02/11
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
140
120
100
80
60
40
20
0
Traffic Volume
4500
4000
3500
3000
2500
2000
1500
1000
500
0
07
08
09
10
11
12
13
14
15
16
17
18
19
20
Time (hr)



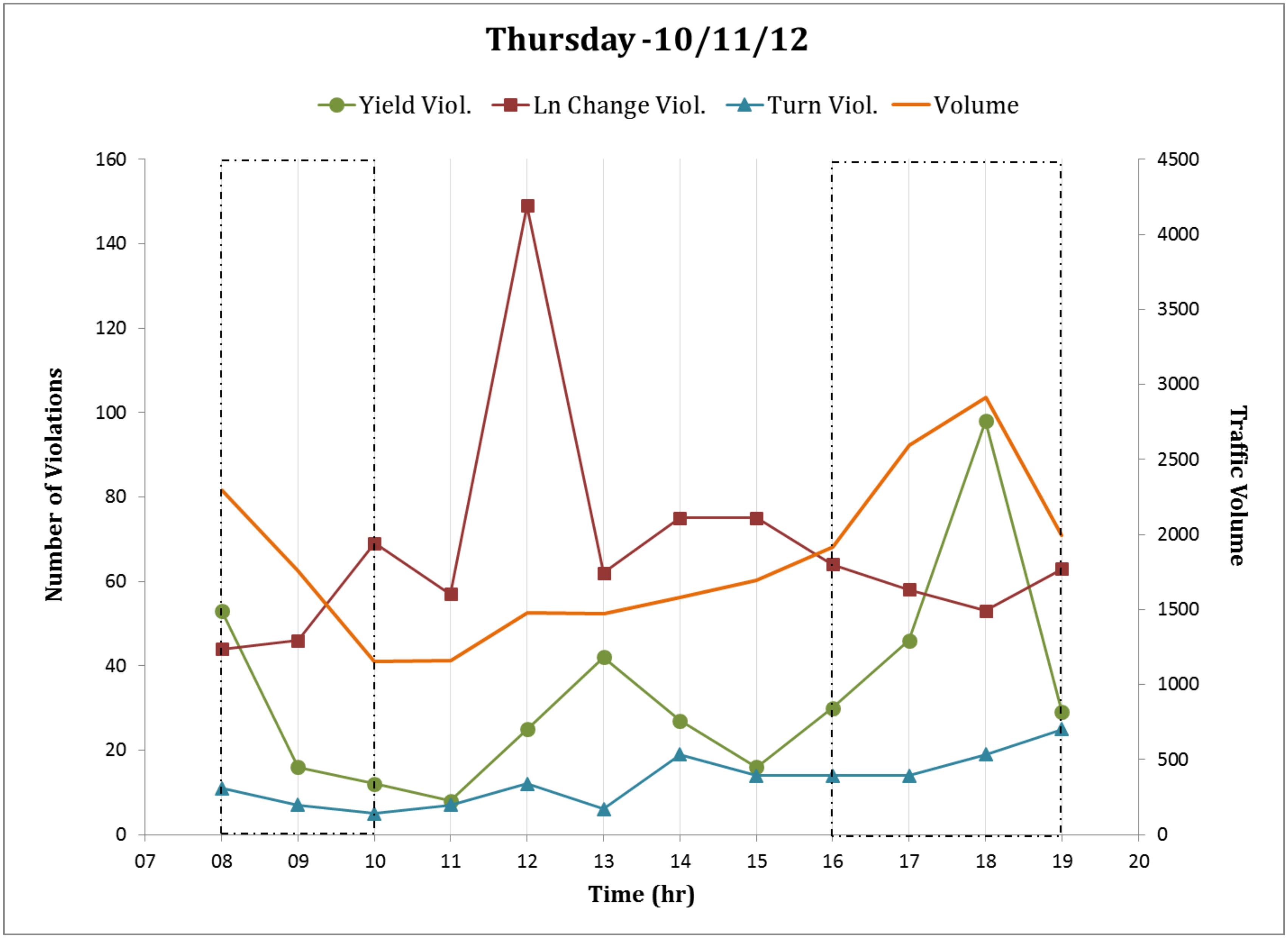
Thursday- 11/03/11
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
3500
07
08
09
10
11
12
13
14
15
16
17
18
19

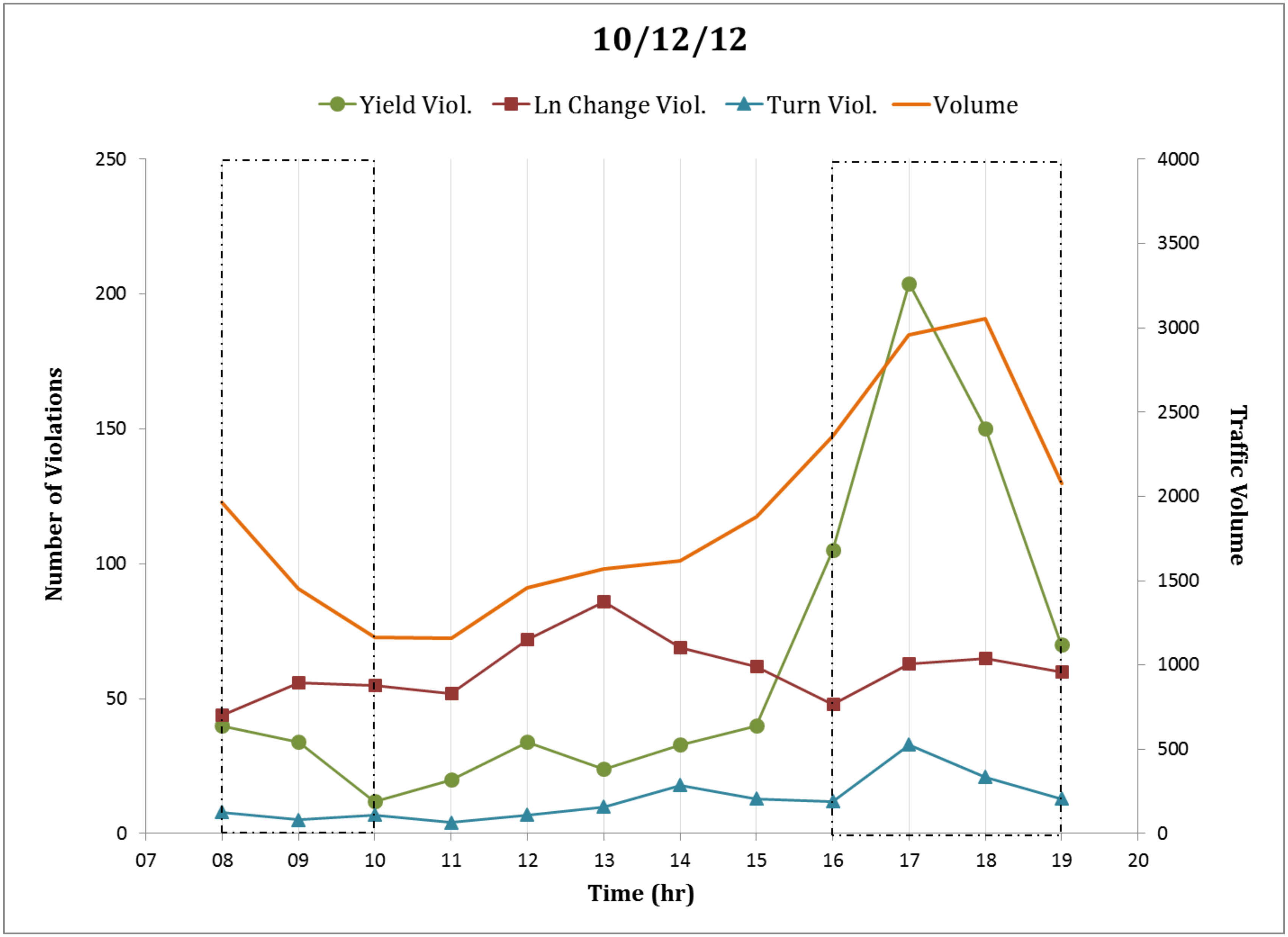


Tuesday -10/02/12
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
160
140
120
100
80
60
40
20
0
4500
4000
3500
3000
2500
2000
1500
1000
500
0
07
08
09
10
11
12
13
14
15
16
17
18
19
20

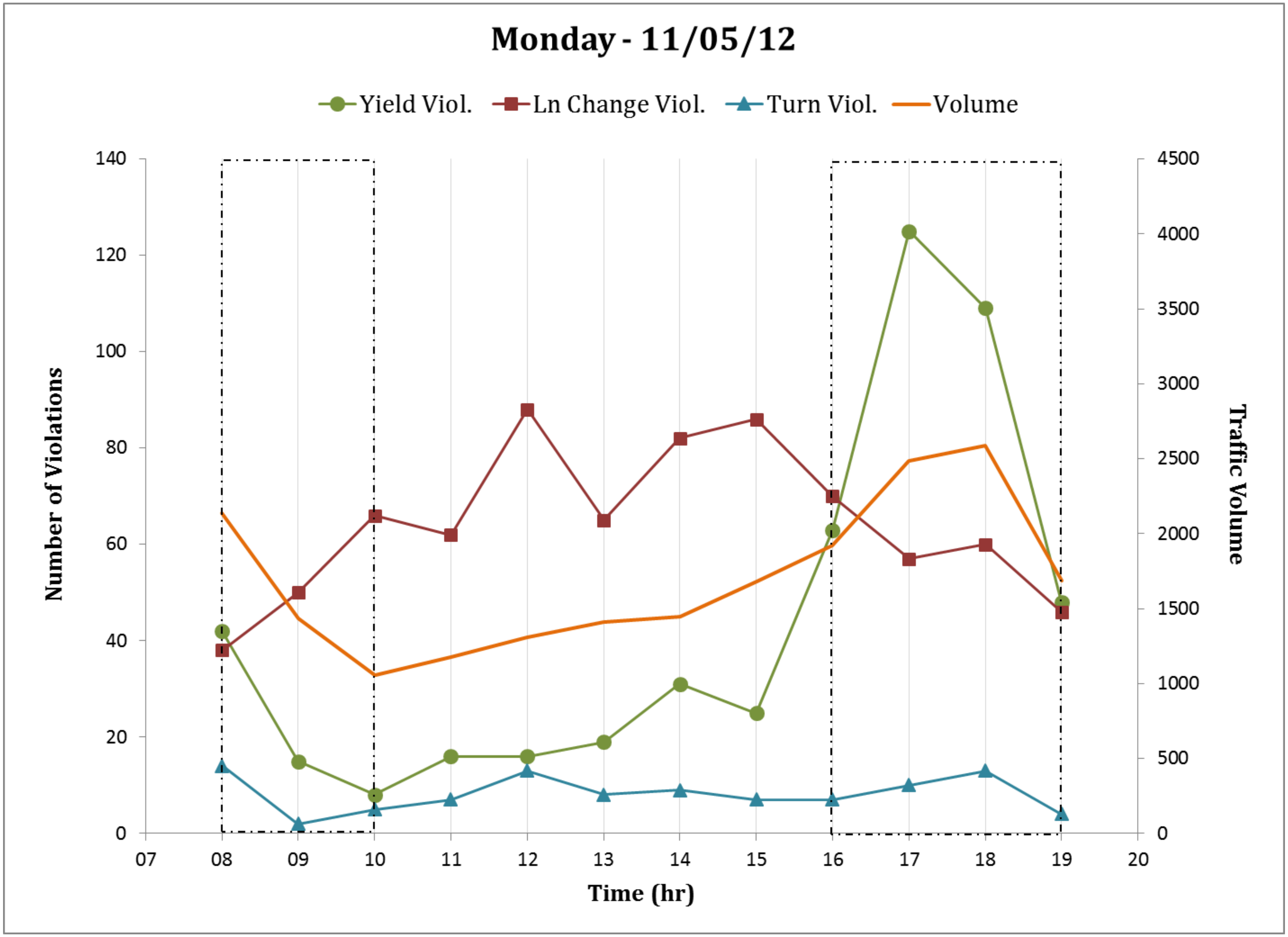


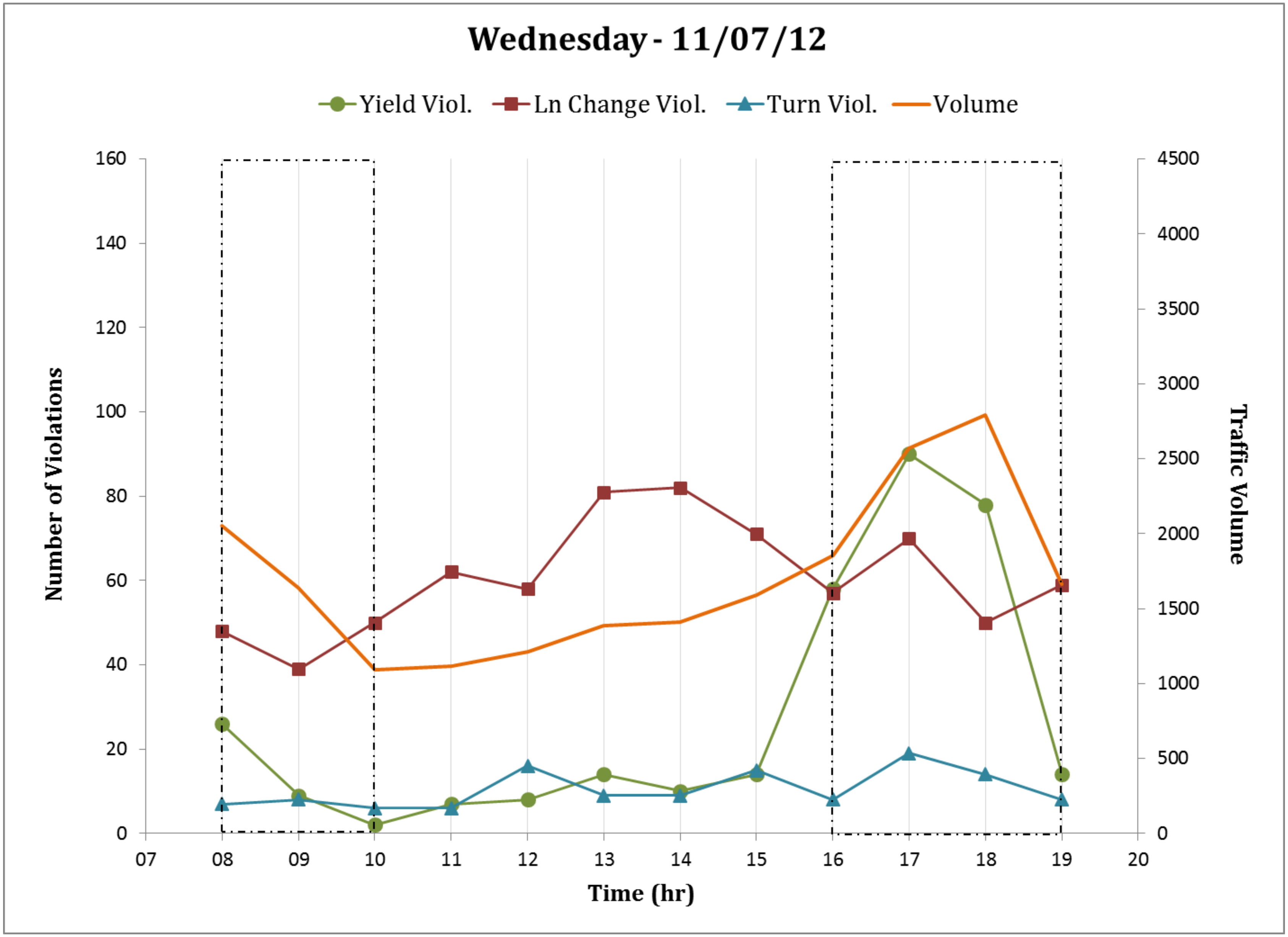
Saturday - 10/06/12
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
140
120
100
80
60
40
20
0
4500
4000
3500
3000
2500
2000
1500
1000
500
0
07
08
09
10
11
12
13
14
15
16
17
18
19
20


Thursday -10/11/12
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
0
20
40
60
80
100
120
140
160
Traffic Volume
0
500
1000
1500
2000
2500
3000
3500
4000
4500
07
08
09
10
11
12
13
14
15
16
17
18
19
20
Time (hr)



10/12/12
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
250
200
150
100
50
0
4000
3500
3000
2500
2000
1500
1000
500
0
Traffic Volume
07
08
09
10
11
12
13
14
15
16
17
18
19
20
Time (hr)


Monday - 11/05/12
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
140
120
100
80
60
40
20
0
4500
4000
3500
3000
2500
2000
1500
1000
500
0
07
08
09
10
11
12
13
14
15
16
17
18
19
20


Wednesday - 11/07/12
Yield Viol.
Ln Change Viol.
Turn Viol.
Volume
Number of Violations
Traffic Volume
Time (hr)
160
140
120
100
80
60
40
20
0
4500
4000
3500
3000
2500
2000
1500
1000
500
0
07
08
09
10
11
12
13
14
15
16
17
18
19
20