Before/After Study on the Effects of Signage and Striping on the Safety of a Modern Two-lane Roundabout

by

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ABSTRACT

This paper presents the study of the impact striping and signing have on driving behavior at a two-lane roundabout located in Richfield, Minnesota. After its completion, this roundabout exhibited a suspiciously high amount of crashes. In response, engineers experimented with changes in the roundabout’s signs and striping, as roundabout design regulations are relatively lax and non-specific in contrast to ones 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 reduction of 48% in normalized occurrences of improper turns, and a normalized 53% reduction of drivers choosing the incorrect lane a month after the changes while a year later these reductions were 44% and 50%, respectively.
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 striping 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 striping were implemented.

This study focuses on changes made to striping and signing at 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) experimented with changes in the roundabout’s signs and striping.

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 2009 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 include normal arrows like ones that would be located at a standard 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 (2009)), within the circulatory roadway continuous concentric lane lines may not be used (3C.02-4 (2009)), and exits cannot contain edge lines from the circulatory roadway (3C.03-3 (2009)), among other added recommendations and options for roundabout design. Differences between the Minnesota and federal MUTCDs are negligible pertaining to roundabout design regulations.
Figure 1: MUTCD Example Signs & Markings for a Two Lane Roundabout
ROUNDABOUT AND VIOLATIONS

The roundabout studied, 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 or turn left, 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 between a yield violation to the inner and to the outer circulatory lanes. The classifications of yielding violations specify whether the offending vehicle failed to yield to traffic in the inner lane (Figure 2.a), outer lane (Figure 2.b), or both lanes (Figure 2.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 2.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 2.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 2.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 2.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 2.h), turning left from the outer lane (Figure 2.i), and turning more than 270 degrees from the outer lane (Figure 2.j).

Figure 2: 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 2.k), and utilizing the entrance lanes to exit the roundabout (Figure 2.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 on trends from previous observation: stopping to yield to vehicles entering the roundabout unnecessarily (Figure 2.m), and stopping for other general and unjustified purposes (Figure 2.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 2.h, 2.i, and 2.d are common examples of incorrect lane choices.

ROUNDABOUT SIGNS AND STRIPING CHANGES
Due to a high count of avoidable crashes, the City of Richfield and Hennepin County took steps to improve the roundabout’s safety. With the help of MTJ Engineering, during early August 2011, various changes were made to the signing and striping of the roundabout.

- Turn arrows on the approaches to the roundabout, in the roundabout, and on lane designation signs, were changed from “fish-hook” style to the standard 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.
- The solid lane line was extended from the original 50 feet from the yield line to a current 250 feet. This particular element is in contrast to the examples provided in the MUTCD.

Pavement marking changes were also made within the roundabout:

- Striping width increased from 4 inches to 6 inches, stripes through the middle of the roundabout are now 3 feet long with a 1 foot gap, while within the circulatory roadway, 4 inch by 4 inch “cat track” concentric-spiral striping replaced all previously solid striping.
- Changes in signage include improving line-of-sight visibility 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.
Figure 3: Aerial Photos of Roundabout Before and After Implemented Changes
To address the high occurrence of drivers committing yielding violations, the size of yield signs increased from 30 inches to 36 inches.

For a visual aid, refer to Figure 3 for aerial views (a) before and (b) after the changes.

In addition to the engineering changes to the roundabout, the city of Richfield took steps to increase the public’s understanding of proper roundabout driving procedures. This is the first 2x2 roundabout in the area. 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, 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 prohibited - 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 addition to the increased education efforts, 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 24.25 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.

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

- **Turn violations:** 2
  - Left turn from the outer lane (Figure 1.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 1.a): 11
  - Failing to yield to the outer lane (Figure 1.b): 2

- **Lane changes:** 1
  - Lane change at exit (Figure 1.e): 1

- **Turn violations:** 12
  - Right turn from the inner lane (Figure 1.h): 1
  - Left turn from the outer lane (Figure 1.i): 11

Below, Figure 4 presents the preceding crash breakdown in terms of crash rates. 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. 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.

**RESEARCH METHODOLOGY**

To collect observation data, video was first recorded by deploying to the roundabout a trailer with an extendable mast, equipped with cameras pointed at the intersection (Figure 5). For the “before” video, four cameras comprised the view of the entire intersection, with each camera pointed at the splitter island of an approach. The “before” video was originally recorded for a different study, focusing on the yielding behavior of drivers at roundabout pedestrian crossings (Hourdos et al, 2012). The format of the “after” video instead was changed to better facilitate the needs of this study, and differs from the “before” video (not shown here) by transitioning from four separate cameras to a single panoramic lens camera (Figure 6). 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.
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. Once the video was obtained, a preliminary analysis was performed that helped create the violation categorizations outlined in the previous section. Observers were trained to properly watch the video and record all observed violations. Detailed training materials were developed along with a regime to test the trainees in order to validate their ability to extract all the necessary data correctly. The goal was to maximize the uniformity of the observations specifically on the more subjective violations like failure-to-yield. In addition to the training material, utilities and enhancements to open-source software were developed to accelerate the video reduction process.

Each hour of video was analyzed once for each approach of entering traffic, resulting in four viewings per hour of video. This allowed for every vehicle to be watched from the time it entered until the time it exit to detect the occurrence of a driving violation. Once a violation is committed, it was then classified and recorded in a database. The collected information pertains to the time, vehicle entrance lane, vehicle type, and violation categorization.

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.

Figure 5: Instrumented extendable mast trailer in the roundabout

Figure 6: Screenshot of roundabout video
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 1 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 2 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 1, 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, Figure 7 presents 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.

From Table 2 one can also note that no significant regression was observed among instances of lane changes, improper turns, or incorrect entrance lane choice which suggest that the changes in striping and signs produced a positive and lasting effect on those types of violations. In Figure 7 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 1: Summary Data

<table>
<thead>
<tr>
<th></th>
<th>Count</th>
<th>Normalized Occurrence</th>
<th>Count</th>
<th>Normalized Occurrence</th>
<th>Count</th>
<th>Normalized Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Traffic Volume</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before - 2010 (72 hours)</td>
<td>98015</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Violations</td>
<td>5205</td>
<td>5.31%</td>
<td>4918</td>
<td>3.93%</td>
<td>5607</td>
<td>4.45%</td>
</tr>
<tr>
<td>Yielding</td>
<td>1021</td>
<td>1.04%</td>
<td>1065</td>
<td>0.85%</td>
<td>1713</td>
<td>1.36%</td>
</tr>
<tr>
<td>Inner</td>
<td>666</td>
<td>0.68%</td>
<td>771</td>
<td>0.62%</td>
<td>1140</td>
<td>0.90%</td>
</tr>
<tr>
<td>Outer</td>
<td>300</td>
<td>0.31%</td>
<td>218</td>
<td>0.17%</td>
<td>457</td>
<td>0.36%</td>
</tr>
<tr>
<td>Both</td>
<td>55</td>
<td>0.06%</td>
<td>76</td>
<td>0.06%</td>
<td>116</td>
<td>0.09%</td>
</tr>
<tr>
<td>Lane Change</td>
<td>3037</td>
<td>3.10%</td>
<td>3095</td>
<td>2.47%</td>
<td>3073</td>
<td>2.44%</td>
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<tr>
<td>Entrance</td>
<td>1301</td>
<td>1.33%</td>
<td>1407</td>
<td>1.12%</td>
<td>1325</td>
<td>1.05%</td>
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<tr>
<td>Exit</td>
<td>1736</td>
<td>1.77%</td>
<td>1688</td>
<td>1.35%</td>
<td>1748</td>
<td>1.39%</td>
</tr>
<tr>
<td>Turn Violation</td>
<td>1135</td>
<td>1.16%</td>
<td>750</td>
<td>0.60%</td>
<td>818</td>
<td>0.65%</td>
</tr>
<tr>
<td>Right from inner</td>
<td>71</td>
<td>0.07%</td>
<td>77</td>
<td>0.06%</td>
<td>75</td>
<td>0.06%</td>
</tr>
<tr>
<td>Left from outer</td>
<td>1027</td>
<td>1.05%</td>
<td>665</td>
<td>0.53%</td>
<td>719</td>
<td>0.57%</td>
</tr>
<tr>
<td>More than 270 from outer</td>
<td>37</td>
<td>0.04%</td>
<td>8</td>
<td>0.01%</td>
<td>24</td>
<td>0.02%</td>
</tr>
<tr>
<td>Wrong Way</td>
<td>12</td>
<td>0.01%</td>
<td>8</td>
<td>0.01%</td>
<td>3</td>
<td>0.00%</td>
</tr>
<tr>
<td>Enter</td>
<td>10</td>
<td>0.01%</td>
<td>8</td>
<td>0.01%</td>
<td>3</td>
<td>0.00%</td>
</tr>
<tr>
<td>Exit</td>
<td>2</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>Incorrect Lane Choice</td>
<td>1920</td>
<td>1.96%</td>
<td>1152</td>
<td>0.92%</td>
<td>1243</td>
<td>0.99%</td>
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Table 2: Comparison among "before", "after", and "one year after" data

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<thead>
<tr>
<th>Category</th>
<th>Percent Change</th>
<th>p-value</th>
<th>Z-statistic</th>
<th>Percent Change</th>
<th>p-value</th>
<th>Z-statistic</th>
<th>Percent Change</th>
<th>p-value</th>
<th>Z-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Violations</td>
<td>-26.0%</td>
<td>&lt;0.01</td>
<td>15.526</td>
<td>13.1%</td>
<td>&lt;0.01</td>
<td>-6.458</td>
<td>16.23%</td>
<td>&lt;0.01</td>
<td>9.445</td>
</tr>
<tr>
<td>Yielding</td>
<td>-18.3%</td>
<td>&lt;0.01</td>
<td>4.633</td>
<td>59.6%</td>
<td>&lt;0.01</td>
<td>-12.159</td>
<td>30.5%</td>
<td>&lt;0.01</td>
<td>-6.788</td>
</tr>
<tr>
<td>Inner</td>
<td>-9.3%</td>
<td>0.0646</td>
<td>1.848</td>
<td>46.7%</td>
<td>&lt;0.01</td>
<td>-8.305</td>
<td>33.1%</td>
<td>&lt;0.01</td>
<td>-5.908</td>
</tr>
<tr>
<td>Outer</td>
<td>-43.1%</td>
<td>&lt;0.01</td>
<td>6.419</td>
<td>108.0%</td>
<td>&lt;0.01</td>
<td>-9.111</td>
<td>18.5%</td>
<td>0.022</td>
<td>-2.286</td>
</tr>
<tr>
<td>Both</td>
<td>8.3%</td>
<td>0.653</td>
<td>-0.450</td>
<td>51.5%</td>
<td>&lt;0.01</td>
<td>-2.835</td>
<td>64.0%</td>
<td>&lt;0.01</td>
<td>-3.054</td>
</tr>
<tr>
<td>Lane Change</td>
<td>-20.1%</td>
<td>&lt;0.01</td>
<td>8.948</td>
<td>-1.5%</td>
<td>0.555</td>
<td>0.590</td>
<td>-21.3%</td>
<td>&lt;0.01</td>
<td>9.522</td>
</tr>
<tr>
<td>Entrance</td>
<td>-15.3%</td>
<td>&lt;0.01</td>
<td>4.334</td>
<td>-6.5%</td>
<td>0.075</td>
<td>1.780</td>
<td>-20.8%</td>
<td>&lt;0.01</td>
<td>6.025</td>
</tr>
<tr>
<td>Exit</td>
<td>-23.8%</td>
<td>&lt;0.01</td>
<td>8.039</td>
<td>2.8%</td>
<td>0.421</td>
<td>-0.804</td>
<td>-21.7%</td>
<td>&lt;0.01</td>
<td>7.294</td>
</tr>
<tr>
<td>Turn Violation</td>
<td>-48.2%</td>
<td>&lt;0.01</td>
<td>14.30</td>
<td>8.2%</td>
<td>0.116</td>
<td>-1.570</td>
<td>-44.0%</td>
<td>&lt;0.01</td>
<td>12.858</td>
</tr>
<tr>
<td>Right from inner</td>
<td>-15.0%</td>
<td>0.322</td>
<td>0.990</td>
<td>-3.3%</td>
<td>0.834</td>
<td>0.210</td>
<td>-17.9%</td>
<td>0.234</td>
<td>1.1900</td>
</tr>
<tr>
<td>Left from outer</td>
<td>-49.3%</td>
<td>&lt;0.01</td>
<td>13.946</td>
<td>7.3%</td>
<td>0.190</td>
<td>-1.312</td>
<td>-45.6%</td>
<td>&lt;0.01</td>
<td>12.748</td>
</tr>
<tr>
<td>More than 270 from outer</td>
<td>-83.1%</td>
<td>&lt;0.01</td>
<td>5.176</td>
<td>197.7%</td>
<td>&lt;0.01</td>
<td>-2.807</td>
<td>-49.6%</td>
<td>&lt;0.01</td>
<td>2.663</td>
</tr>
<tr>
<td>Wrong Way</td>
<td>-47.8%</td>
<td>0.148</td>
<td>1.448</td>
<td>-62.8%</td>
<td>-</td>
<td>-</td>
<td>-80.6%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Enter</td>
<td>-37.3%</td>
<td>0.321</td>
<td>0.993</td>
<td>-62.8%</td>
<td>-</td>
<td>-</td>
<td>-76.7%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Exit</td>
<td>-53.0%</td>
<td>&lt;0.01</td>
<td>20.877</td>
<td>7.1%</td>
<td>0.093</td>
<td>-1.679</td>
<td>-49.7%</td>
<td>&lt;0.01</td>
<td>19.361</td>
</tr>
</tbody>
</table>
Figure 7: Violation Breakdown for Monday, November 5th, 2012
CONCLUSIONS

This paper describes the results from a straightforward before and after study of the effect of changes in signs and striping 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 MUTCD, produced a set of proposed changes on the roundabout signs and striping in an attempt to improve roundabout safety.

This study aimed in producing 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 conducted pertaining to roundabouts 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 was performed also on a control site, 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 striping, 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 paper, 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, 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.
REFERENCES

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5 <http://mutcd.fhwa.dot.gov/>.


9 <http://www.dot.state.mn.us/trafficeng/publ/mutcd/index.html>.

