DEPARTMENT OF TRANSPORTATION

Evaluation of Intersection Collision Warning Systems in Minnesota

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October 2017

Research Project
Final Report 2017-38

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Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC 2017-38		

4. Title and Subtitle	5. Report Date
Evaluation of Intersection Collision Warning Systems in Minnesota	October 2017
	6.
7. Author(s) Shauna L. Hallmark, Neal Hawkins, Raju Thapa, Skylar Knickerbocker, and John Gaspar	8. Performing Organization Report No.
9. Performing Organization Name and Address Center for Transportation Research and Education Iowa State University 2711 S. Loop Drive, Suite 4700 Ames, IA 50010	10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (C) 99004 (WO) 16
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

http:// mndot.gov/research/reports/2017/201738.pdf

16. Abstract (Limit: 250 words)

The Minnesota Department of Transportation (MnDOT) is investing significant resources in intersection collision warning systems (ICWS) based on early indications of effectiveness. However, the effectiveness is not well documented, and negative changes in driver behavior at treatment intersections may affect drivers overall, resulting in a spillover effect. Moreover, the effectiveness of ICWS may decrease if drivers do not perceive a change in the dynamic messages. Therefore, the objectives of this research were to (1) evaluate driver behavior at mainline and stop-controlled approaches for intersections with and without ICWS and (2) assess the traffic volume range and limits where the system is nearly continuously activated and is likely to lose its effectiveness. Video data were collected at five treatment and corresponding control intersections, and various metrics were used to compare changes in driver behavior. In general, no negative behaviors were noted for either treatment or control intersections.

17. Document Analysis/Descriptors	18. Availability Statement
warning signs, advanced traffic management systems, crash avoidance systems, traffic safety, unsignalized intersections, traffic conflicts, rural highways	No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	57	

Evaluation of Intersection Collision Warning Systems in Minnesota

FINAL REPORT

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October 2017

Published by:

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGMENTS

The team wishes to thank the Minnesota Department of Transportation (MnDOT) for its assistance in collecting data used in this work and for funding the project. We would also like to thank the members of the Technical Advisory Panel for helping guide this project.

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EXECUTIVE SUMMARY

The Minnesota Department of Transportation (MnDOT) is investing significant resources in intersection collision warning systems (ICWS) based on early indications of system effectiveness. However, the effectiveness is not well documented. Additionally, concerns have been noted that negative changes in driver behavior at treatment intersections may affect drivers overall, resulting in a spillover effect.

Spillover occurs when drivers change their behavior due to an intervention at one location and maintain the same behavior at other locations where the intervention is not present. Additionally, MnDOT expressed interest in assessing where ICWS may be continuously activated due to concerns that ICWS may be less effective if drivers do not perceive a change in the dynamic messages. As a result, the objectives of this research were as follows:

- Evaluate driver behavior at mainline and stop-controlled approaches for intersections with and without ICWS
- Develop an assessment of the traffic volume range and limits where the system is nearly continuously activated and is likely to lose its effectiveness

Video data were collected at five treatment and corresponding control intersections. Control sites were selected close to treatment intersections and were expected to have similar drivers. It should be noted that control sites were not true control sites in the traditional sense for safety studies. The purpose of the control sites was to assess whether a spillover effect had occurred at adjacent intersections.

Various metrics, including the following, were used to compare changes in driver behavior:

- Stopping
- Gap size
- Glances
- Continuous activation using simulation
- Conflicts

Stopping behavior, overall, was assessed and also compared by type of turn. Stopping behavior by ICWS activation was also evaluated. The results suggest that the system encouraged appropriate stopping behavior when active. However, drivers may become conditioned not to stop when the system suggests there is no need.

No change in stopping behavior was noted at control sites. This indicates that only drivers at the actual ICWS were changing their stopping behavior. In essence, no spillover effect was noted.

Gap size was another metric that was evaluated. The analysis of gap size indicates that, in general, drivers selected larger gaps after the ICWS was installed. This occurred at both the treatment and control sites. One limitation of the analysis is that higher volumes of vehicles in a given time period would result in different size gaps and consequently different gap selection.

Critical gaps were also calculated. The length of the critical gaps appeared to increase overall, which suggests that the ICWS improved drivers' gap selection at both the treatment and control intersections.

The number of times drivers looked left or right (glances) was evaluated at different time periods to determine whether drivers improved intersection scanning. On the one hand, there was a concern that drivers may scan less if they overly rely on the ICWS. On the other hand, drivers may pay more attention if the warning system is active.

The average number of left and right glances was estimated by type of stop and the number of glances increased at treatment intersections with drivers who made a complete stop. Similarly, the number of glances increased for drivers who made a rolling stop.

The change in the number of glances by turning movement was also evaluated. The number of glances increased at both the treatment and control sites for all turning maneuvers. The average number of glances to the right increased most significantly for right-turn maneuvers at both the treatment and control sites. Left glances increased the most for through movements at the treatment sites and for left turns at the control sites.

All conflicts were recorded for each intersection. Conflicts included near-crashes, evasive maneuvers, application of brakes or slowing, or changing lanes. Application of brakes or changing lanes was typically observed for mainline drivers, but any situation where evasive maneuvers were noted was coded as a near-crash.

Overall, near-crashes and other conflicts decreased at the treatment sites while they increased at the control sites. It is unknown why this was the case, but the team felt that these trends were not related to a spillover effect from the treatment sites.

Another objective of this research was to determine the threshold combinations of mainline/minor approach volumes for which the ICWS is likely to be continuously activated. At these thresholds, the system would nearly continuously display driver messages, and the system would no longer be dynamic for the duration of the time that these volumes are maintained. The hypothesis is that drivers may pay less attention to the signs when they are continuously activated, leading to a loss of effectiveness. Microsimulation modeling was used to assess the mainline/minor approach volumes for which the system would be continuously activated.

A graph was developed that can be used to help determine the volume at which the sign is active for a certain percentage of the time. For instance, when the mainstream volume reaches 1,600 vehicles per hour, the system is nearly continuously activated. This relationship would differ based on different geometric characteristics. However, the relationship provides a good indication of when the system would be continuously activated and therefore less effective.

While it was not possible to assess driver behavior in situations with continuous ICWS activation, the system is likely to lose its effectiveness when drivers are presented with what appears to be a static system. Although actual system performance is dependent on a number of factors, the use of ICWS may not be advisable when mainline volumes are greater than 1,400 to 1,600 vehicles per hour.

RECAP

In general, no negative behaviors were noted for either the treatment or control intersections. Stopping behavior appeared to improve marginally overall. The most significant impact was the improvement in stopping behavior when the system was active. Drivers were nearly one and half times more likely to come to a complete stop when the system was active compared to when the system was not active.

Gap size increased after installation of the ICWS, suggesting that drivers were more likely to select more appropriate gaps. Finally, the number of times drivers scanned the intersection generally increased.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Rural intersections account for about 30% of crashes in rural areas and 6% of all fatal crashes. One unique and promising solution has been the use of intersection conflict warning systems (ICWS).

Early studies have indicated lower intersection approach speeds, reduced conflicts, improved compliance with traffic control, and improved gap selection (FHWA 1999, Weidemann et al. 2011, Rakauskas et al. 2009, Kwon and Ismail 2014). Simple before-and-after crash analyses have indicated reductions in total crashes up to 46% and reductions in severe crashes up to 72% (MoDOT 2011, NCDOT 2011). However, there has been some evidence that when the ICWS was not activated, drivers were less likely to comply with the stop sign, and some sites experienced minor crash increases (Weidemann et al. 2011, NCDOT 2011).

The Minnesota Department of Transportation (MnDOT) is investing significant resources in ICWS based on early indications of system effectiveness. The main benefit of the research described in this report is better information in the short term on the effectiveness of these systems, which can guide future investments. If the systems appear to be more effective than expected, the results of this project can guide the next stage of investments. If issues are noted, future deployments can be guided using this information. Additionally, if the research finds that a significant positive spillover effect results from the ICWS, it could help agencies better determine placement, which can save resources.

1.2 OBJECTIVE

Although ICWS show promise, their effectiveness has not been well established. Because robust crash analyses are not yet available, it is desirable to evaluate the systems using crash surrogates so that further investments can be considered. Additionally, the influence of ICWS on adjacent untreated intersections has not been considered. As a result, the objectives of this research were as follows:

- Evaluate driver behavior at intersections with and without ICWS
- Develop an assessment of the traffic volume range and limits in which the system is nearly continuously activated and is likely to lose its effectiveness

CHAPTER 2: SITE SELECTION

This chapter summarizes the selection of treatment and control sites. Treatment sites were those intersections where an ICWS was installed. Control sites were intersections near the treatment sites that were expected to have similar drivers but had not received an ICWS. It should be noted that the control sites were not true control sites in the traditional sense for safety studies. Typically, control sites are selected to represent base conditions and reflect changes in crash or speed patterns related to characteristics other than an installed countermeasure. In this study, however, control intersections were selected to assess the spillover effect. The intent was to determine whether drivers in a particular area acclimated to the ICWS technology with a corresponding change in behavior overall. The term is used to differentiate treatment from non-treatment sites consistently within the study.

2.1 IDENTIFICATION OF TREATMENT SITES

A list of all known sites where ICWS was planned for installation during 2014 was provided by MnDOT. Test sites were examined to determine their suitability for data collection. For the most part, this entailed ensuring that trees/shrubs, steep ditches, or other objects along the roadway that would make setting up the video camera equipment difficult were not present.

Treatment sites were also examined for atypical characteristics that would make it difficult to select a control site with similar characteristics. These characteristics included the presence of a railroad or significant vertical or horizontal curve along one approach near the intersection, sight distance issues, etc.

All of the sites that were deemed feasible based on the above description are summarized Table 2-1.

Table 2-1. Initial treatment and control intersections

Intersection	Configuration	Highway type	Major volume	Minor volume	Type
MNTH 60 & CSAH 1	**Two way**	**divided**	**5400**	**1550**	**T**
MNTH 60 & 570th Ave	Two way	divided	5400	2000	C
MNTH 23 & CSAH 7	**Two way**	**divided**	**6700**	**2150**	**T**
W College Dr & CSAH 7	One way T	undivided	3000	2650	C
MNTH 7 & CSAH 15	**Two way**	**undivided**	**1800**	**2950**	**T**
1st St W & CSAH 15	Two way yield	undivided	-	-	C
MNTH 7 & CSAH 1	**Two way**	**undivided**	**7100**	**4400**	**T**
MNTH 7 & Falcon Ave N	Two way	undivided	6400	720	C
MNTH 7 & MNTH 9	Two way	undivided	7100	1600	C
MNTH 15 & CSAH 27	**Two way**	**undivided**	**3850**	**880**	**T**
MNTH 15 & 21	Two way	undivided	3850	620	C
US 75 & CSAH 18	**Two way**	**undivided**	**3900**	**1300**	**T**
MNTH 9 & CSAH 18	Two way	undivided	700	70	C
US 10 & CSAH 75	**Two way**	**undivided**	**6900**	**1050**	**T**
MNTH 29 & CSAH 75	Two way	undivided	3300	1050	C
MNTH 43 & CSAH 21	**Two way**	**undivided**	**7200**	**1450**	**T**
US 14 & CSAH 21	Two way	undivided	8800	2750	C
US 14 & CSAH 25	**Two way**	**undivided**	**3850**	**-**	**T**
US 14 & CSAH 20	T-Intersection	undivided	3850	280	C
MNTH 56 & 380TH ST	**Two way**	**undivided**	**1500**	**2300**	**T**
246th & 380th	Two way	undivided	1200	3300	C
MNTH 19 & CSAH 7	**Two way**	**undivided**	**2050**	**340**	**T**
Cnty Blvd 1 & CSAH 7	Two way	undivided	820	210	C
MNTH 19 & Cnty51 Blvd	Two way	undivided	2050	370	C
MNTH 47 & CSAH 8	**Two way**	**undivided**	**7400**	**2300**	**T**
MNTH 47 & CSAH 5	Two way	undivided	3750	1350	C
US 169 & CSAH 11	**Two way**	**divided**	**9400**	**1250**	**T**
US 169 & 160th	Two way	divided	9400	1400	C
USTH 169 & CSAH 28	**Two way**	**undivided**	**3750**	**780**	**T**
US 169 & 270th st	Two way	undivided	3750	640	C
MNTH 6 & CSAH 30	**Two way**	**undivided**	**3600**	**1100**	**T**
CSAH 30 & CSAH 31	T-intersection	undivided	1350	1100	C
MNTH 6 & CSAH 11	Two way	undivided	3600	1350	C

As the table shows, 15 viable treatment sites were identified, indicated in bold and with a "T" in the Type column. Due to a delay on the part of the contractor that installed the ICWS, sites were further reduced, as described in Section 2.3, to those that were likely to be installed by late summer/fall 2014.

2.2 IDENTIFICATION OF CONTROL SITES

At least one control site was selected for each of the 15 potential treatment intersections. Control sites were selected to be as close as possible to the treatment intersection in terms of geometry and traffic characteristics. Control sites are also provided in Table 2-1 and are indicated by a "C" in the Type column. The treatment site is shown first in bold, followed by one or more potential control sites for that intersection.

Control sites that have similar roadway geometry and traffic control to the corresponding treatment sites were selected. Because all of the test intersections have two-way stop control, only intersections with a two-way stop were considered for the control intersections. Other characteristics, such as mainline roadway characteristics, were matched as much as possible. For instance, a control site on a divided highway was selected if the treatment site was on a divided highway. Other characteristics for selection included turning lane configuration and intersection angle.

When possible, the control intersection was selected along the same minor roadway as the treatment site. As a result, data on similar or even the same drivers would be collected at both intersections. The distance between the test intersection and control intersection was also an important consideration. Control intersections that were between one and five miles away from the treatment intersections were given the highest priority. The traffic volumes on the major and minor roadways were also a significant deciding factor.

An effort was made to have major and minor roadway volumes that were similar between the treatment and control intersections. It was also necessary to have a large enough volume so that the system would be activated for a reasonable amount of time. Finally, the ability to situate data collection equipment along the control intersection was considered.

In most cases, several control intersections were initially identified for each treatment intersection. Only one control location per treatment location was ultimately utilized.

2.3 FINAL SITE SELECTION

Based on the scope of study, five intersection pairs were selected as study locations. Sites were selected in conjunction with the project's technical advisory panel (TAP). Figure 2-1 shows a map of each treatment and control intersection.

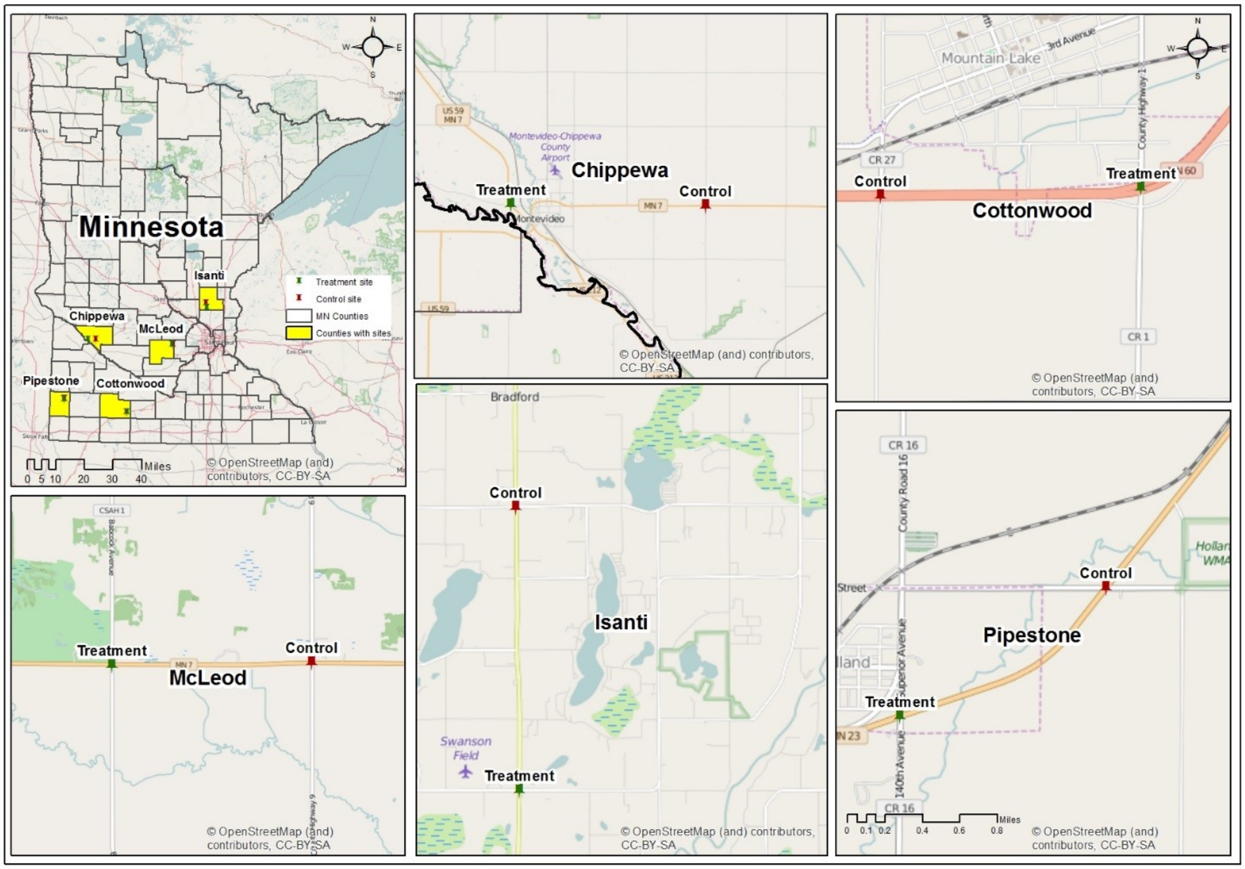


Figure 2-1. Control and treatment sites across different counties in Minnesota.

2.3.1 Chippewa County Treatment and Control Sites

Figure 2-2 shows images of the treatment and control sites in Chippewa County.

Treatment

Control

Figure 2-2: Sites in Chippewa County.

As noted, both sites have similar geometric configurations. The treatment site is at the intersection of MN 7 and MN 15. The control site is at the intersection of MN 7 and 1st Avenue S. Both intersections are located on MN 7 and are about 7.5 miles apart. The image of the treatment site was taken after installation of the ICWS.

2.3.2 Cottonwood County Treatment and Control Sites

Figure 2-3 shows images of the treatment and control sites in Cottonwood County.

Treatment

Control

Figure 2-3. Sites in Cottonwood County.

The treatment site is located at the intersection of MN 60 and County Highway 1. The control site is located at the intersection of MN 60 and 570th Ave. Both intersections are located on MN 60 and are a mile apart. The treatment intersection image was taken after installation of the ICWS.

2.3.3 Isanti County Treatment and Control Sites

Figure 2-4 shows the treatment and control sites in Isanti County.

Treatment

Control

Figure 2-4. Sites in Isanti County.

The treatment site is located at the intersection of MN 47 and County Road 8. The control site is located at the intersection of MN 47 and County Road 5. Both intersections are along MN 47 and are a couple of miles apart. The image at the treatment intersection was taken after installation of the ICWS.

2.3.4 McLeod County Treatment and Control Sites

Figure 2-5 shows the treatment and control sites in McLeod County.

Treatment

Control

Figure 2-5. Sites in McLeod County.

The treatment intersection is located at the intersection of MN 7 and County Road 1. The control site is located at the intersection of MN 7 and County Road 9. Both intersections are located on MN 7 and are about a mile apart. Both intersections are adjacent intersections with similar geometric configurations. The image at the treatment intersection was taken after the ICWS was installed.

2.3.5 Pipestone County Treatment and Control Sites

Figure 2-6 shows the treatment and control sites in Pipestone County.

Treatment

Control

Figure 2-6. Sites in Pipestone County.

The treatment intersection is located at the intersection of MN 23 and County Road 16, and the control intersection is located at MN 23 and County Road 8. Both intersections are located on MN 23 and are less than a mile apart.

CHAPTER 3: DATA COLLECTION

Data were collected using a set of trailers and an array of video cameras. Data elements, such as stopping behavior, were identified, and the data collection was set up to optimize coverage of the appropriate areas where data needed to be collected using the fewest cameras.

The data collection methodology was first evaluated at one study intersection as a beta test to ensure that the methodology was feasible. Data were collected for one day and then reviewed for data quality and reduced to the format needed for use in analyses. The team identified several adjustments that needed to be made and, after discussion with the TAP, updated the data collection methodology.

Data collection equipment, shown in Figure 3-1, was rented from Live Technologies and consisted of trailers with a telescoping mast and an array of cameras.

Figure 3-1. Trailer with mast arm and camera array to collect aerial view of intersection.

The trailers were placed as shown in Figure 3-2 and used to record an aerial view of vehicles approaching the intersection. The cameras were placed about 100 meters upstream and downstream of the intersection with a focus on the intersection (labeled T-63 and T-64).

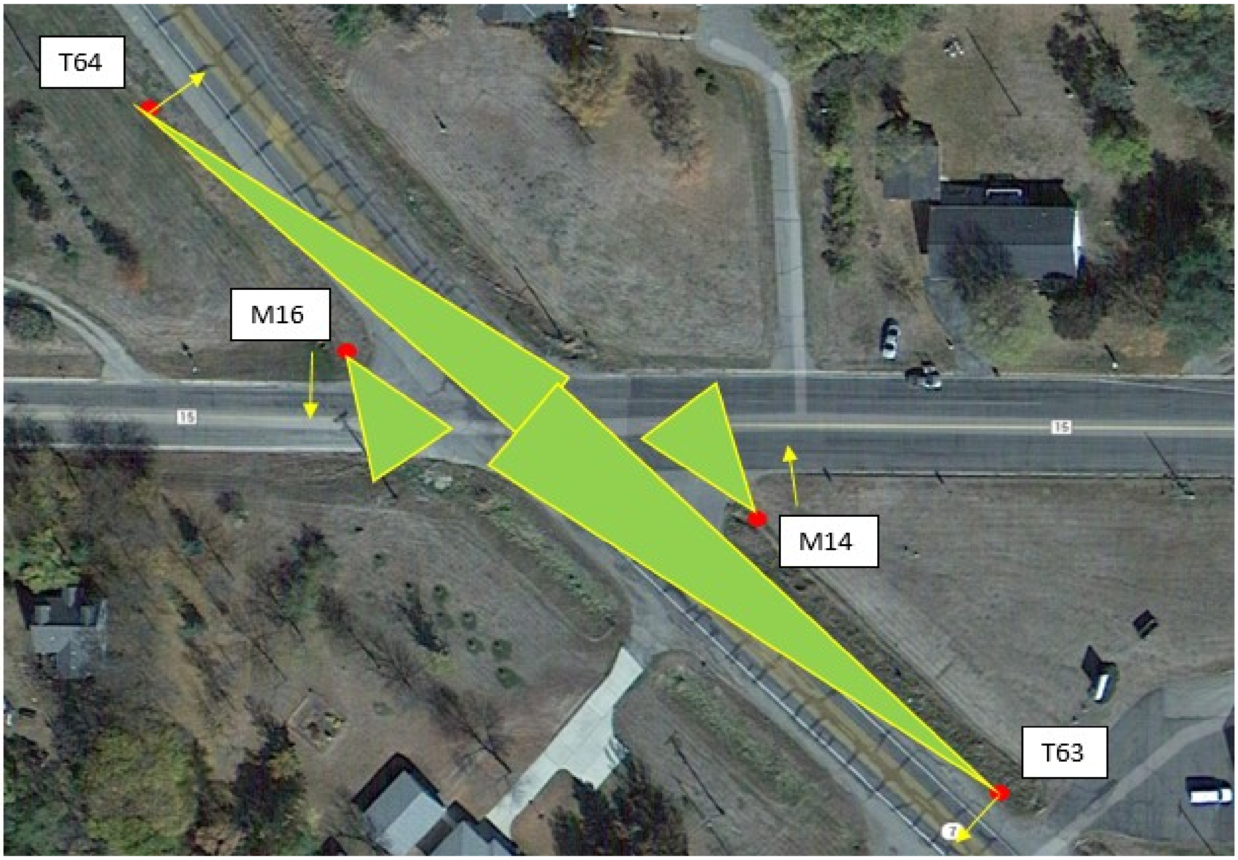


Figure 3-2. Location of camera at major and minor streets for data collection.

A post-mounted camera was placed on a Telspar pole and mounted across from the stop sign on the minor approach, as shown in Figure 3-3.

Figure 3-3. Camera mounted at vehicle level to record driver behavior.

The camera recorded video at approximately face level for approaching vehicles and was used to record driver behavior as drivers approached the intersection. Figure 3-2 also shows the placement of the vehicle-level mounted cameras (labeled as M-14 and M-16). All required tools and instruments were checked for their reliability before collecting the actual data.

Data were collected for over a week during each specified time period (i.e., before the ICWS was installed, 1 month after installation, and 12 months after installation). For each pair of intersections (control and treatment), data were collected in the same period to make the data from the two intersections comparable.

Once the equipment was placed in the field, data were collected continuously. The equipment was placed and the cameras were adjusted to the appropriate intersection area during the data collection setup. Project members had remote control over the cameras so that the cameras could be repositioned from the office as needed to ensure that data from the appropriate locations were collected and to troubleshoot when necessary. For instance, the camera positions occasionally became disoriented due to bad weather and were reoriented.

Data were collected over three different time periods: before the installation of the ICWS (identified as the "before" period), at one to three months after the installation of system (identified as the "1-month" period), and about one year after the installation of the ICWS at the treatment intersections (identified as the "12-month" period). During data collection, team members coordinated with the corresponding jurisdiction (e.g., MnDOT or the county) to ensure that proper permissions were obtained and procedures were followed. Table 3-1 shows different timeframes of data collection for each of 10 intersections.

Table 3-1. Data collection timeline for ICWS treatment and control sites

Intersections	Installation date for treatment	Date of Data Collection			Type
		Before	**Immediately after**	**12-months after**	
Chippewa	–	8/19/2014 to 8/25/2014	4/28/2015 to 5/5/2015	9/15/2015 to 9/21/2015	Control
	11/13/12014				Treatment
Cottonwood	–	8/29/2014 to to 9/2/2014	4/18/2015 to 4/23/2015	9/8/2015 to 9/14/2015	Control
	11/19/2014				Treatment
Isanti	–	9/5/2014 to 9/11/2014	5/6/2015 to 5/13/2015	10/13/2015 to 10/19/2015	Control
	12/4/2014				Treatment
McLeod	–	5/15/2015 to 5/21/2015	10/20/2015 to 10/26/2015	7/21/2016 to 7/26/2016	Control
	9/23/2015				Treatment
Pipestone	–	5/28/2015 to 6/3/2015	10/28/2015 to 11/3/2015	7/28/2016 to 8/2/2016	Control
	9/30/2015				Treatment

Videos from the camera located over the major street were used to code the gap-related information, stopping behavior, weather, and arrival time. Other features of the minor and major street vehicles, except the driver details, were collected from the cameras located on the minor streets. Driver details, including gender, distraction features (if any), and number of glances, were coded using the cameras on the minor street.

CHAPTER 4: DATA REDUCTION

The variables to be coded from the video data were determined before a data collection procedure was developed. Different measures of effectiveness, as defined in the research proposal, were considered in depth at the time of data reduction. Data were reduced only for the minor stream vehicles. The following variables were reduced:

- Arrival time
- Departure time
- Type of vehicle: Seven types
- Color of vehicle
- Type of turning movement: Left / Right / Through
- Type of stop: Complete stop / Slow rolling / Fast rolling / No slow
- Stop location: Before / After / At the stop bar
- Intersection leg
- ICWS status at arrival: Activated / Un-activated / Unknown
- ICWS status at departure: Activated / Un-activated / Unknown
- Conflict: Description / Time
- Weather: Sunny / Cloudy / Rain / Snow
- Pavement surface: Dry / Wet / Snow
- Lighting condition: Day / Dawn / Dusk
- Accepted gap
- Neighboring vehicle
- Vehicle platoon
- Number of rejected gaps
- Rejected gap length
- Gender
- Distraction details: Cell phone / Passengers
- Number of glances: between start and end point

Data were coded only for weekdays from 6:00 a.m. to 8:00 p.m. Nighttime video was too grainy to be consistently utilized. Due to the large amount of video data that resulted and the resources available to reduce the data, only a sample of vehicles was reduced. A random time generator was developed in an Excel spreadsheet and was used to randomly select the start time for each hour. Based on that start time, a 15-minute period was selected for each hour. During that 15-minute time interval, the first five vehicles in the free flow condition were reduced.

Because data collection for each intersection pair (i.e., treatment and control sites) was done at the same time, the same random timeframe was used for both intersections in the pair. As mentioned above, minor stream vehicles in the queue were excluded from the analysis because it was assumed that queueing altered their behavior and the team was most interested in seeing how drivers reacted to the ICWS. The following sections summarize in more detail how various variables were reduced.

4.1 TIME AT MINOR APPROACH

The time at the minor approach included the arrival time, departure time, merge time, and queuing or waiting time of the minor stream vehicles at the minor approach. Arrival time was defined as the time when the vehicle's front bumper just passed the stop bar. Departure time was defined as the time when the vehicle left the minor approach and started merging onto the major road. Merge time was defined as the instant when the vehicle completely merged onto the main road (i.e., the vehicle's traveling direction was aligned with the roadway direction). Waiting time was defined as the time that elapsed between the instant when the vehicle arrived at the stop bar and the instant when the driver just started moving (i.e., the difference between the departure and arrival times).

4.2 STOPPING

Vehicle movement included the stopping behavior and stopping location of the vehicles in the minor stream. Stopping behavior indicated the type of stop. Although actual speeds were not coded, an estimate of vehicle speeds was made and the type of stop was coded using the following definitions:

- Full stop: speed was reduced to approximately zero
- Rolling: clear braking was noted and vehicle speed was approximately greater than zero but less than ten miles per hour
- Non-stop: vehicle speed was approximately greater than ten miles per hour

An attempt was made to differentiate "rolling stop" into "slow rolling" and "fast rolling," but it was too difficult to distinguish between the two and they were ultimately combined into simply "rolling stop."

4.3 STOPPING LOCATION

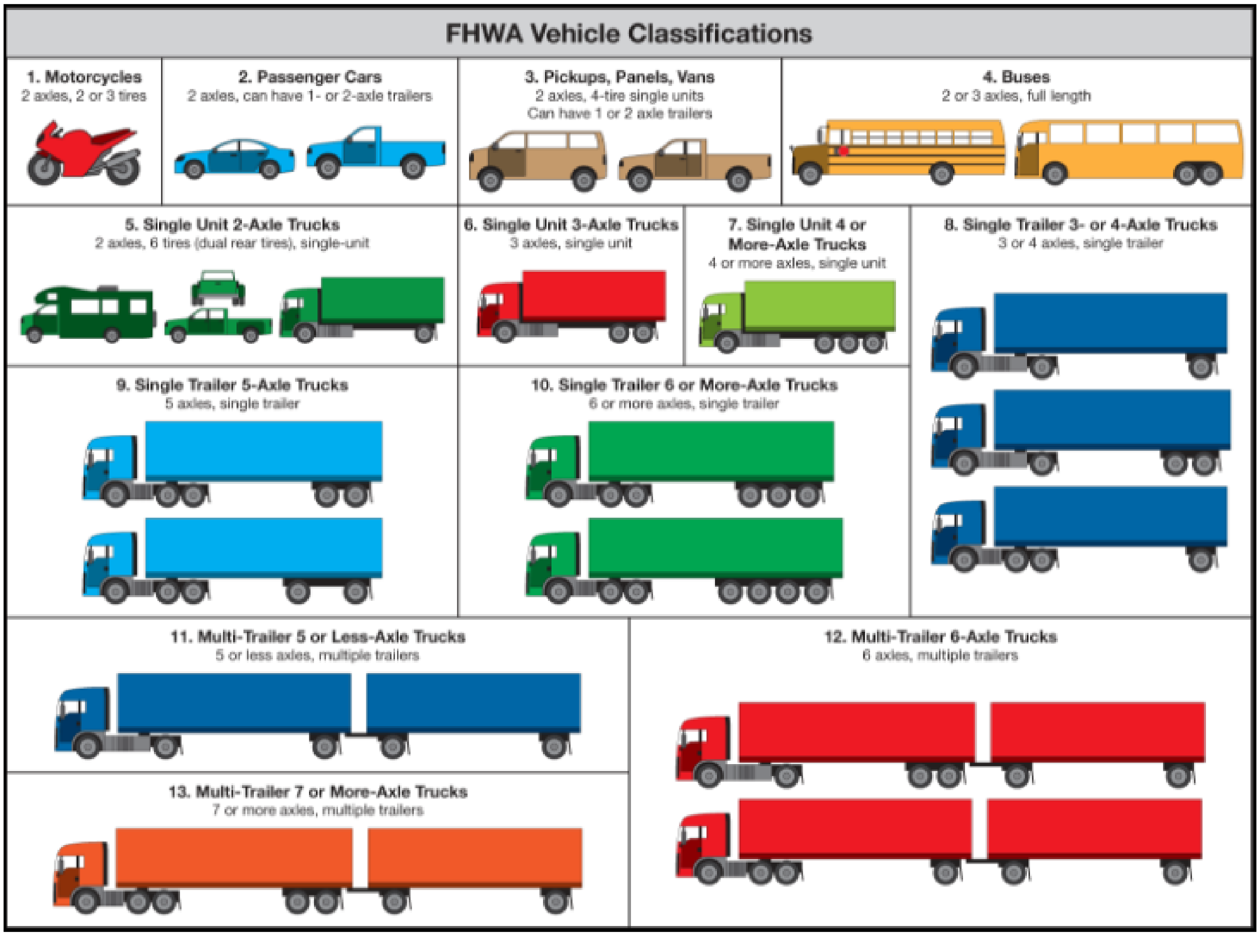
Stopping location was based on the location of the front bumper with respect to the stop bar, if present, or the approximate location of the stop bar, if not present, as follows:

- Stop before the stop bar: the vehicle stopped before the stop bar
- Stop at the stop bar: the vehicle stopped at the stop bar or the front bumper was still in the range of the stop bar
- Stop after the stop bar: the vehicle significantly crossed the stop bar

Sample videos were collected showing different stopping behaviors and stopping locations and were used to familiarize the data reducers with the different stopping behaviors and locations before the data reduction procedure began, which helped to keep uniformity in the coded information.

4.4 VEHICLE INFORMATION

Vehicles were initially classified into seven groups based on the Federal Highway Administration (FHWA) vehicle classification scheme (Figure 4-1).



Source: *http://onlinemanuals.txdot.gov/txdotmanuals/tri/images/FHWA_Classification_Chart_FINAL.png*

Figure 4-1. FHWA vehicle classification scheme.

The first group consisted of motorcycles, the second was small passenger cars, the third group was minivans and SUVs, the fourth group was pickup trucks, the fifth group was buses, the sixth group was single or multi-axle commercial trucks, and the seventh group consisted of farm vehicles. Group 3 was subdivided into vans and pickup trucks. Vehicle color was also coded so that it would be easy for the data coder to go back to the video if any error was noticed. Presence of a trailer was added if observed.

4.5 ICWS STATUS

After installation of the ICWS, the activation status of the system was coded throughout the data reduction period. If the system was activated the flashing beacon light, as shown in Figure 4-2, was coded as "ON," and if the system was deactivated the flashing beacon light was coded as "OFF." This information was only coded at the treatment site after the installation of the system because no system was present at the control sites. Figure 4-2 shows an example of an activated system.

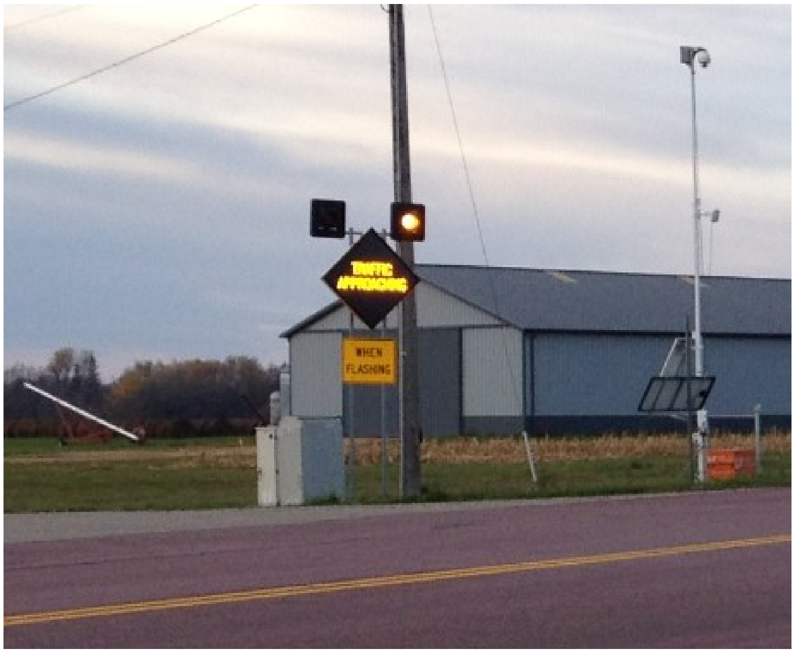
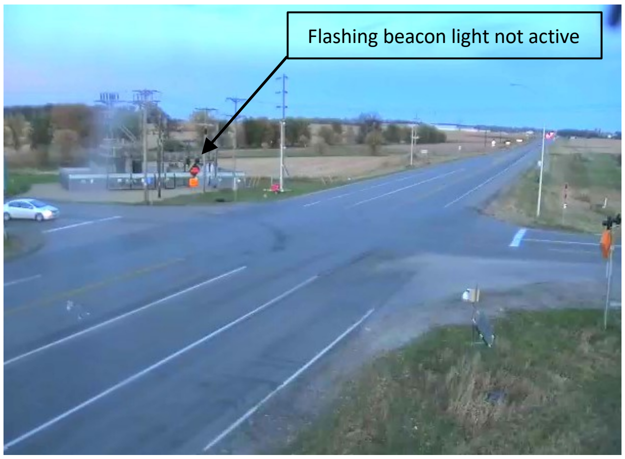


Figure 4-2. Activated system.

A gap threshold of 6.5 seconds was used at all treatment sites because the system becomes active only if a vehicle is within a gap threshold time from the intersection. Figure 4-3 shows a treatment site with an activated (top) and deactivated (bottom) system.

Activated



Deactivated

Figure 4-3. System activation and deactivation at the treatment site.

4.6 GAP

All gaps that could be viewed from the overhead camera for each vehicle were coded. The gaps that drivers used to complete their respective maneuvers were coded as accepted gaps. Rejected gaps were those where drivers remained on the minor approach and waited for another gap. The number of rejected gaps for each vehicle was coded. Additionally, the direction of oncoming vehicles for each gap and whether the oncoming vehicle was in a platoon were recorded.

A gap was defined as the time headway between the front bumpers of two successive major stream vehicles. However, coding a gap entailed the presence of vehicles in the major stream. In some cases, a vehicle in the minor stream approached the intersection and no vehicles were present on the major approach. In such cases, it was difficult to identify the actual gap size. However, the gap was at least 12 seconds, so the gap was coded as “12 seconds.”

Gap selection also depended on stopping behavior. Drivers may begin identifying gaps before they come to a stop. However, for consistency, a gap was measured from the instant the minor stream vehicle arrived at the stop bar.

A platoon was only coded if more than three successive vehicles on the major approach were travelling in the same direction with a gap of less than five seconds between successive vehicles. A sample video showing the details of the gap coding procedure was developed at the beginning of the project and was used frequently to familiarize the data coders with the gap coding procedure.

4.7 EVASIVE MANEUVERS

Evasive maneuvers were coded if there were crashes, near-crashes, or conflicts at the intersection involving at least one minor street vehicle. Conflicts included actions such as significant slowing, brake application, or lane changes of major stream vehicles due to the movement of minor stream vehicles. A near-crash was as an event where vehicles nearly collided or made significant evasive maneuvers to avoid a collision.

Unlike other metrics where a subset of vehicles was sampled, all video data were reviewed to identify conflicts. As a result, all evasive maneuvers that occurred during the daytime data collection period were recorded. Figure 4-4 shows examples of evasive maneuvers.

Applied brake

Slowed down

Near-crash

Figure 4-4. Examples of conflict scenarios.

4.8 ENVIRONMENT VARIABLES

Environment included the type of weather at the intersection, such as rainy, cloudy, or snowy conditions. Lighting indicated whether day, night, or dawn/dusk conditions were evident. The identification of dawn and dusk conditions was based on published sunrise and sunset times. Data were not collected during severe weather conditions, so the presence of snow, ice, and other adverse weather conditions was not included in the data. Pavements were coded as “dry” or “wet.”

4.9 DRIVER INFORMATION

Driver characteristics were coded using the cameras located at the minor approach. Driver information such as gender, number of left and right glances, and types of distraction within a subject vehicle were coded. Number of glances was coded by establishing two predefined points for each intersection and then measuring the number of glances in each direction that occurred during this interval. The start and end points at the minor stream were uniform throughout the study period.

Figure 4-5 shows an example of a start and end point for a control section in Chippewa County.

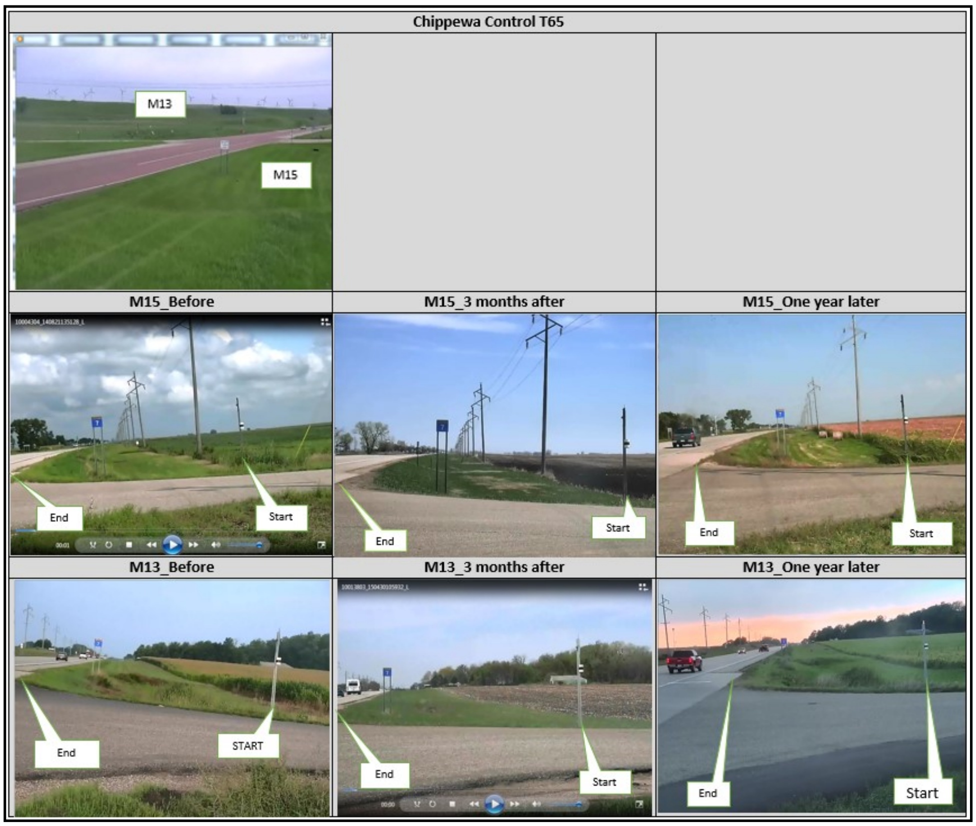


Figure 4-5. Start and end points for number of glances.

M13 and M15 in the figure are two cameras, each one covering one of the minor approaches. The start and end points for each camera were kept uniform through the three different data coding periods. Start and end points were fixed such that drivers’ glances were recorded as soon as their vehicles approached the stop bar until the vehicles departed to the major stream. If the vehicles stopped before the stop bar or start point, the number of glances was not coded for that specific vehicle because the side of the vehicle could not be viewed. It was difficult to see individual drivers in some scenarios, such as during bad weather, when sunlight created glare, when the car had tinted windows, and during night time. As a result, driver information could not be collected for all vehicles selected for sampling. For each driver coded, the level of confidence in terms of the coder's ability to view the driver in the video was also coded because the view of the driver was not always clear.

CHAPTER 5: ANALYSIS

Several different analyses were conducted using the reduced data, as described in this chapter. When intersections showed similar trends, their data were combined for simplicity in presenting results. When relevant differences were noted among intersections, the data were presented by individual intersection. Data were also reviewed by type of vehicle. However, samples for some of the vehicle categories were so small that data could not be compared. As a result, all vehicle types were combined.

Data were collected over three different time periods referenced to the installation of the ICWS at the treatment intersection. These periods included before the installation of the ICWS (referred to as "before"), one to three months after the installation of the ICWS (referred to as "1-month"), and about one year after the installation (referred to as "12-month"). Data were collected at each pair of intersections (treatment and control) during the same time period. For instance, data collected at the Chippewa control and treatment sites were collected on the same dates.

5.1 STOPPING BEHAVIOR

Stopping behavior for all vehicles was compared among the three periods. As noted in Tables 5-1 to 5-5, the percent of vehicles coming to a complete stop increased at the Chippewa, Cottonwood, and Isanti treatment sites during the 1- and 12-month after periods as compared to the before period. The percentage of vehicles completing a rolling stop decreased accordingly.

Table 5-1. Change in stopping behavior for Chippewa

	Treatment					Control				
	before	**1-mon**	**change**	**12-mon**	**change**	**before**	**1-mon**	**change**	**12-mon**	**change**
complete stop	27.6%	34.6%	7.0%	33.3%	2.2%	50.3%	49.3%	-1.0%	51.5%	2.2%
rolling stop	72.4%	65.1%	-7.3%	66.3%	-1.5%	49.7%	50.0%	0.3%	48.5%	-1.5%
non-stop	0.0%	0.3%	0.3%	0.3%	-0.7%	0.0%	0.7%	0.7%	0.0%	-0.7%
sample	275	344		300		181	272		264	

Table 5-2. Change in stopping behavior for Cottonwood

	Treatment					Control				
	before	**1-mon**	**change**	**12-mon**	**change**	**before**	**1-mon**	**change**	**12-mon**	**change**
complete stop	43.1%	49.5%	6.4%	43.5%	0.4%	49.8%	50.2%	0.4%	45.1%	-5.1%
rolling stop	56.3%	49.1%	-7.2%	56.5%	0.2%	50.2%	49.3%	-0.9%	54.9%	5.6%
non-stop	0.7%	1.4%	0.7%	0%	-0.7%	0%	0.4%	0.4%	0%	-0.4%
sample	295	212		285		305	223		266	

Table 5-3. Change in stopping behavior for Isanti

	Treatment					Control				
	before	1-mon	change	12-mon	change	before	1-mon	change	12-mon	change
complete stop	46.0%	47.7%	1.7%	48.3%	2.3%	40.4%	43.7%	3.3%	42.7%	-1.0%
rolling stop	53.2%	52.0%	-1.2%	51.7%	-1.5%	58.1%	55.4%	-2.7%	57.3%	1.9%
non-stop	0.8%	0.3%	-0.5%	0.0%	-0.8%	1.5%	0.9%	-0.6%	0.0%	-0.9%
sample	265	354		300		270	341		234	

Table 5-4. Change in stopping behavior for McLeod

	Treatment					Control				
	before	1-mon	change	12-mon	change	before	1-mon	change	12-mon	change
complete stop	67.5%	53.5%	-14.0%	63.5%	-4.0%	55.5%	57.5%	2.0%	63.6%	6.1%
rolling stop	32.2%	46.5%	14.3%	36.5%	4.3%	43.6%	42.0%	-1.6%	36.4%	-5.6%
non-stop	0.3%	0.0%	-0.3%	0.0%	-0.3%	0.8%	0.4%	-0.4%	0.0%	-0.4%
sample	295	310		211		236	226		272	

Table 5-5. Change in stopping behavior for Pipestone

	Treatment					Control				
	before	1-mon	change	12-mon	change	before	1-mon	change	12-mon	change
complete stop	55.1%	43.3%	-11.8%	18.6%	-36.5%	55.6%	51.7%	-3.9%	32.2%	-19.5%
rolling stop	44.9%	56.7%	11.8%	80.9%	36.0%	44.4%	48.3%	3.9%	67.8%	19.5%
non-stop	0.0%	0.0%	0.0%	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%
sample	267	201		220		144	60		152	

The percentage of vehicles coming to a complete stop did not change significantly at the control sites for those three counties (Chippewa, Cottonwood, and Isanti). For instance, the percentage of vehicles coming to a full stop at the Chippewa treatment site increased 7%, with a corresponding decrease in rolling stops, 1 month after installation of the ICWS. At the Chippewa control site, complete stops decreased by 1% at 1 month and increased by 2% at 12 months.

Alternatively, the number of vehicles coming to a complete stop at the McLeod and Pipestone treatment intersections decreased while the percentage of vehicles coming to a rolling stop increased. The number of vehicles coming to a complete stop also decreased at the Pipestone control site, with an accompanying increase in rolling stops. However, the percentage of vehicles coming to a complete stop increased at the McLeod control intersection.

5.2 STOPPING BEHAVIOR BY TURNING MOVEMENT

Stopping behavior by turning movement was also assessed. Because no consistent pattern was noted across the intersections, results are provided by intersection. Change in stopping behavior for the treatment intersections is shown in Tables 5-6 to 5-10.

Table 5-6. Change in stopping behavior for Chippewa treatment

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	complete	rolling	complete	rolling		complete	rolling	
Left	45.5%	54.5%	70.0%	30.0%	24.5%	42.9%	57.1%	-2.6%
Through	37.9%	62.1%	45.1%	54.9%	7.2%	46.3%	53.7%	8.4%
Right	21.5%	78.5%	28.4%	71.1%	7.0%	27.5%	72.1%	6.0%

Table 5-7. Change in stopping behavior for Cottonwood treatment

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	complete	rolling	complete	rolling		complete	rolling	
Left	44.1%	55.9%	35.9%	64.1%	-8.2%	43.9%	56.1%	-0.2%
Through	45.3%	54.2%	52.0%	45.7%	6.7%	45.7%	54.3%	0.4%
Right	35.0%	63.3%	54.3%	45.7%	19.3%	38.0%	62.0%	3.0%

Table 5-8. Change in stopping behavior for Isanti treatment

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	complete	rolling	complete	rolling		complete	rolling	
Left	54.7%	45.3%	53.6%	46.4%	-1.1%	51.4%	48.6%	-3.3%
Through	50.6%	47.0%	52.3%	47.7%	1.7%	48.3%	51.7%	-2.3%
Right	28.9%	71.1%	32.6%	66.3%	3.6%	18.2%	81.8%	-10.8%

Table 5-9. Change in stopping behavior for McLeod treatment

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	Complete	rolling	complete	rolling		complete	rolling	
Left	73.9%	26.1%	66.3%	33.7%	-7.6%	73.3%	26.7%	-0.5%
Through	69.5%	30.5%	51.2%	48.8%	-18.3%	70.6%	29.4%	1.1%
Right	51.8%	46.4%	42.6%	57.4%	-9.2%	50.6%	49.4%	-1.2%

Table 5-10. Change in stopping behavior for Pipestone treatment

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	Complete	rolling	complete	rolling		complete	rolling	
Left	50.0%	50.0%	53.3%	46.7%	3.3%	37.5%	62.5%	-12.5%
Through	64.8%	35.2%	49.6%	50.4%	-15.3%	28.6%	69.4%	-36.3%
Right	45.4%	54.6%	29.2%	70.8%	-16.1%	14.7%	85.3%	-30.7%

Very little change in non-stops occurred. As a result, for brevity, the change in non-stops is not presented. Additionally, because change in rolling stops is the inverse of change in stopping behavior, that metric can be inferred and is not presented. For example, a 24.5% increase in complete stops was noted for left turning vehicles at the Chippewa treatment intersection. Alternatively, rolling stops decreased by about 24.5%.

As noted, in general the percentage of complete stops for left turn maneuvers decreased, with a corresponding increase in rolling stops. The percentage of complete stops for through and right turn movements increased at Chippewa, Cottonwood, and Isanti. For instance, complete stops for through movements increased at the Chippewa treatment intersection by 7.2% at 1 month and 8.4% at 12 months. The percentage of complete stops decreased in general at the McLeod and Pipestone treatment intersections.

Change in stopping behavior by stopping maneuver for the control locations is shown in Tables 5-11 to 5-15.

Table 5-11. Change in stopping behavior for Chippewa control

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	complete	rolling	complete	rolling		complete	rolling	
Left	54.3%	45.7%	51.6%	48.4%	-2.7%	62.2%	37.8%	8.0%
Through	52.2%	47.8%	60.9%	37.7%	8.7%	38.2%	61.8%	-13.9%
Right	44.6%	55.4%	40.0%	59.1%	-4.6%	50.0%	50.0%	5.4%

Table 5-12. Change in stopping behavior for Cottonwood control

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	complete	rolling	complete	rolling		complete	rolling	
Left	61.9%	38.1%	64.5%	35.5%	2.6%	48.4%	0.0%	-13.5%
Through	62.8%	37.2%	66.7%	33.3%	3.9%	37.3%	0.0%	-25.5%
Right	45.0%	55.0%	44.0%	55.3%	-1.0%	60.9%	0.0%	15.9%

Table 5-13. Change in stopping behavior for Isanti control

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	complete	rolling	complete	rolling		complete	rolling	
Left	37.9%	62.1%	43.1%	56.9%	5.2%	53.1%	0.0%	15.2%
Through	41.5%	58.5%	49.2%	49.2%	7.7%	51.6%	0.0%	10.1%
Right	38.5%	55.4%	33.0%	67.0%	-5.5%	68.9%	0.0%	30.5%

Table 5-14. Change in stopping behavior for McLeod control

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	Complete	rolling	complete	rolling		complete	rolling	
Left	60.0%	40.0%	71.1%	28.9%	11.1%	30.9%	0.0%	-29.1%
Through	57.0%	43.0%	58.2%	40.5%	1.3%	32.5%	0.0%	-24.4%
Right	50.6%	47.1%	42.3%	57.7%	-8.3%	45.3%	0.0%	-5.3%

Table 5-15. Change in stopping behavior for Pipestone control

	Before		1-month		Change in complete stop	12-month		Change in complete stop
	Complete	rolling	complete	rolling		complete	rolling	
Left	63.6%	36.4%	73.7%	26.3%	10.0%	67.6%	0.0%	4.0%
Through	48.7%	51.3%	40.0%	60.0%	-8.7%	69.6%	0.0%	20.9%
Right	50.0%	50.0%	100.0%	0.0%	50.0%	0.0%	0.0%	-50.0%

As the tables show, at 1 month four intersections showed an increase in the percentage of vehicles coming to a complete stop (from 2.6% to 11.1%). At 12 months, three intersections showed an increase in complete stops at left turns. Four intersections experienced an increase in complete stops for through movements at 1 month (1.3% to 8.7%), while only two showed increases at 12 months. The results were inconclusive for right turns, with a similar number of intersections experiencing increases as decreases.

5.3 STOPPING BEHAVIOR BY SYSTEM ACTIVATION STATUS

Stopping behavior was analyzed based on the activation status of the ICWS to determine how drivers interact with the system. All treatment sites had similar patterns, so results were combined. Figure 5-1 shows stopping behavior by system status. Because only treatment sites have the ICWS, no corresponding results are presented for control sites.

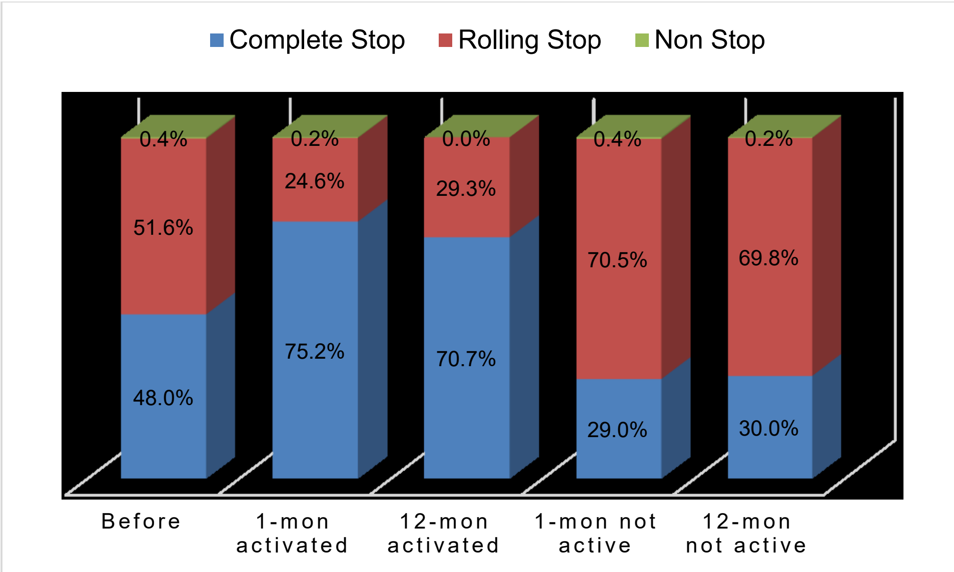


Figure 5-1. Stopping behavior by system activation status.

Figure 5-1 shows stops according to system activation at treatment sites. As the figure shows, when the system was activated 72% of vehicles came to a complete stop at 1 month and 71% came to a complete stop at 12 months. When the system was not activated, only 29% to 30% of vehicles came to a complete stop. A summary of stopping behavior before the ICWS was installed is also shown for reference. About 48% of drivers at all treatment intersections engaged in a complete stop before implementation of the ICWS. Therefore, the increase at sites with an activated system was significant.

The odds of a driver coming to a complete stop at 1 month and 12 months were 1.57 higher (CI = 1.33, 1.82) and 1.47 (CI = 1.22, 1.77), respectively, than before the ICWS was installed. The decrease in drivers coming to a complete stop when the system was not activated was also significant. The odds that a driver would stop when the ICWS was not activated was 0.60 (CI = 0.51, 0.71) times lower at 1 month and 0.62 times lower at 12 months (CI = 0.53, 0.73). When the confidence interval contains 1, the results are not statistically significant at the 95% level of confidence. Therefore, the changes observed in stopping behavior when the system was activated were statistically significant, while changes observed in stopping behavior when the system was not activated were not statistically significant.

The results suggest that the system encouraged appropriate stopping behavior when activated. However, drivers may become conditioned to not stop when they do not perceive a need to stop.

5.4 GAP SIZE BY TURNING MOVEMENT

The sizes of accepted and rejected gaps were coded as described in Section 4.6. The percentage of drivers who accepted a gap of less than or equal to 6 seconds, 7 to 9 seconds, 10 to 12 seconds, or more than 12 seconds is shown by turning maneuver in Table 5-16. Because similar patterns were present across sites, data were combined.

Table 5-16. Change in accepted gaps for 1-month after period for treatment sites

	Before			1-month			Change		
	Left	**Thru**	**Right**	**Left**	**Thru**	**Right**	**Left**	**Thru**	**Right**
≤ 6 sec	2.7%	2.5%	0.4%	2.3%	1.6%	0.4%	-0.4%	-0.8%	0.0%
7 to 9 sec	8.1%	10.9%	2.0%	7.0%	10.9%	3.9%	-1.1%	0.0%	1.8%
10 to 12 sec	13.5%	10.9%	3.3%	11.3%	11.5%	4.3%	-2.2%	0.6%	1.0%
> 12 sec	75.7%	75.7%	94.3%	79.4%	76.0%	91.5%	3.7%	0.3%	-2.8%

Table 5-16 shows the sizes of accepted gaps by type of turning movement at the treatment sites before installation of the ICWS and at 1 month after installation. As the table shows, 2.7% of left turning drivers took a gap of 6 seconds or less before installation of the ICWS, while 2.3% of left turning drivers took a gap of similar size 1 month after installation (decrease of 0.4%). Also for left turning drivers, the number of accepted gaps of 7 to 9 seconds and 10 to 12 seconds also decreased, while gaps greater than 12 seconds increased.

Acceptance of smaller gaps also decreased for through movements. For example, 2.5% of drivers accepted a gap of 6 seconds or less before installation, and only 1.6% of drivers making a through movement accepted a gap of that size 1 month after installation (decrease of 0.8%).

Right turns showed no change in very small gaps (6 seconds or less), while the number of gaps of 7 to 9 seconds and 10 to 12 seconds increased and the percentage of gaps of 12 or more seconds decreased.

Accepted gaps at treatments sites for the 12-month after period are provided in Table 5-17. The percentage of smaller accepted gaps decreased for all turning maneuvers during the 12-month after period compared to the before period.

Table 5-17. Change in accepted gaps for 12-month after period for treatment sites

	Before			1-month			Change		
	Left	**Thru**	**Right**	**Left**	**Thru**	**Right**	**Left**	**Thru**	**Right**
≤ 6 sec	2.7%	2.5%	0.4%	0.9%	1.3%	0.0%	-1.8%	-1.2%	-0.4%
7 to 9 sec	8.1%	10.9%	2.0%	6.5%	6.5%	1.9%	-1.6%	-4.4%	-0.2%
10 to 12 sec	13.5%	10.9%	3.3%	11.2%	8.5%	2.3%	-2.3%	-2.4%	-1.0%
> 12 sec	75.7%	75.7%	94.3%	81.5%	83.7%	95.9%	5.8%	8.0%	1.6%

Table 5-18 shows the change in gap size before installation of the ICWS and 1 month after installation at the control sites.

Table 5-18. Change in accepted gaps for 1-month after period for control sites

	Before			1-month			Change		
	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right
≤ 6 sec	1.4%	1.9%	0.7%	1.5%	2.4%	0.5%	0.1%	0.5%	-0.2%
7 to 9 sec	7.2%	10.2%	4.3%	7.0%	14.5%	3.7%	-0.2%	4.3%	-0.7%
10 to 12 sec	10.5%	9.0%	7.0%	8.1%	10.6%	6.2%	-2.4%	1.6%	-0.9%
> 12 sec	80.8%	78.8%	88.0%	83.3%	72.5%	89.7%	2.5%	-6.3%	1.8%

As the table shows, there was relatively little change in the acceptance of gaps of 6 seconds or less for left turns, while a minor increase in gaps of that size was observed for through vehicles. The percentage of vehicles accepting a gap of 7 to 9 seconds or 10 to 12 seconds decreased for left turns and right turns. In contrast, the fraction of accepted gaps of similar sizes increased for through maneuvers.

Similar results were found for the control sites during the 12-month after period, as shown in Table 5-19, which demonstrates the change in the gaps selected.

Table 5-19. Change in accepted gaps for 12-month after period for control sites

	Before			12-month			Change		
	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right
≤ 6 sec	1.4%	1.9%	0.7%	0.6%	1.3%	0.2%	-0.9%	-0.6%	-0.5%
7 to 9 sec	7.2%	10.2%	4.3%	3.1%	5.3%	4.2%	-4.2%	-4.9%	-0.1%
10 to 12 sec	10.5%	9.0%	7.0%	6.9%	10.1%	4.4%	-3.6%	1.1%	-2.6%
> 12 sec	80.8%	78.8%	88.0%	89.4%	83.2%	91.2%	8.6%	4.4%	3.2%

The percentage of smaller accepted gaps decreased for all turning maneuvers during the 12-month after period, except for 10 to 12 second gaps for through maneuvers. Similarly, the percentage of vehicles taking a gap of more than 12 seconds increased, with changes of 3.2% and 8.6% for left and right turning vehicles, respectively.

The analysis of gap size indicates that, in general, drivers selected larger gaps after the ICWS was installed. This occurred at both the treatment and control sites. One limitation of the analysis is that higher volumes of vehicles in a given time period would result in different size gaps and consequently different gap selection.

5.5 CRITICAL GAPS

Raff and Hart (1950) define a critical gap as the size of gap for which the number of accepted gaps is equal to the number of rejected gaps. In other words, the critical gap is the average gap that drivers are equally likely to accept or reject, and it represents average selected gap size. To obtain the critical gap, the cumulative frequencies of accepted and rejected gaps are plotted against gap size, and the intersection between two curves is defined as the critical gap. Initially, Raff and Hart (1950) used only lag data for the analysis of the critical gap. This approach is considered incorrect by some researchers due to the lack of accepted and rejected gap information (Miller 1971). This problem can be solved by either merging the lag and gap data, assuming no statistical difference between the lag and gap data (Fitzpatrick 1991), or analyzing the lag data only and gap data only. For this study, the critical gap was analyzed using Raff's method and assumed no significant difference between the lag and gap data.

Another method to calculate critical gap is the Greenshields method (Greenshields et al. 1947). According to this method, the critical gap can be defined as the gap that has equal numbers of rejected and accepted gaps. To obtain the critical gap using this method, a histogram is plotted with the numbers of accepted and rejected gaps on the y- axis and the gap size on the x-axis. The positive y-axis includes the number of accepted gaps of a certain size, while the negative y-axis includes the number of rejected gaps. Based on this approach, the gap size on the x-axis with equal numbers of accepted and rejected gaps is determined to be the critical gap (Greenshields et al. 1947). If none of the gap sizes have equal numbers of accepted and rejected gaps, the one whose accepted and rejected gaps are closest to equal is selected as the critical gap. The limitation of this method is that lower sample size may affect and distort the analysis (Mason et al. 1990).

Both Raff's method and the Greenshields model were used to calculate critical gaps for each of the time periods. In all cases, both methods gave similar results. Raff's method was used because it did not depend on having an equal number of accepted and rejected gaps. Figure 5-2 shows the critical gaps for the treatment sites.

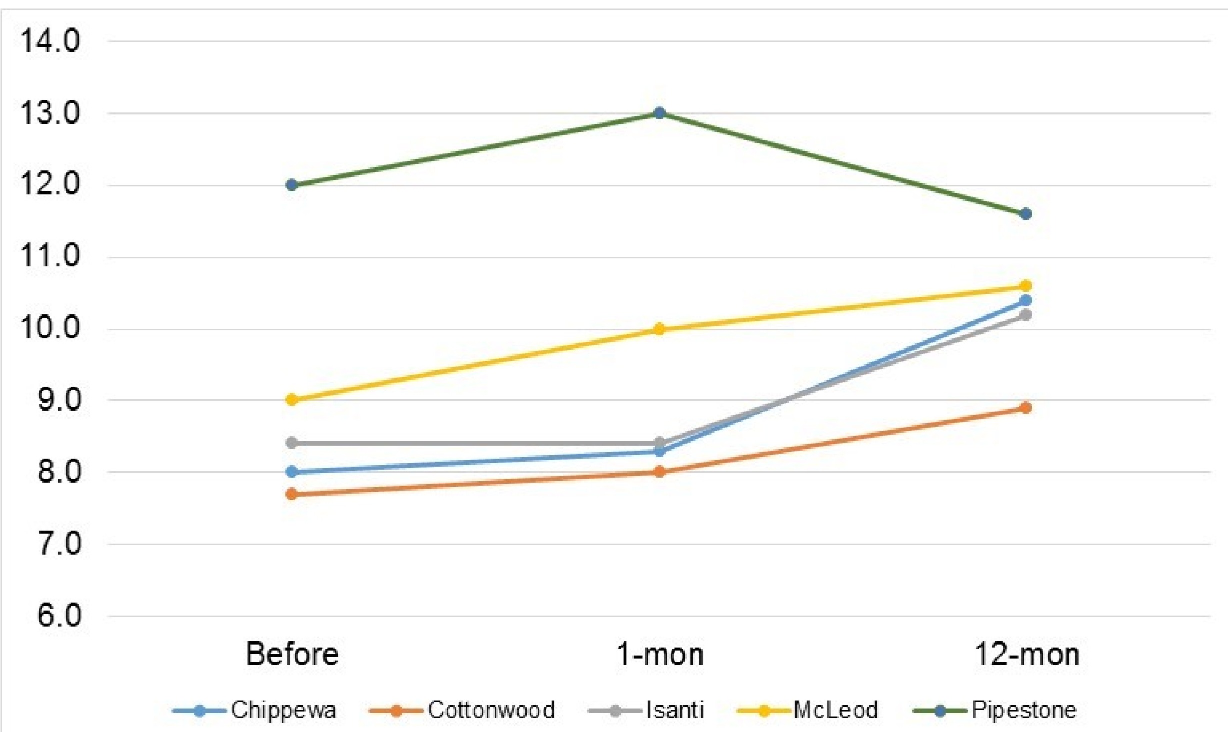


Figure 5-2. Raff's critical gaps for treatment intersections.

The critical gap was higher for the 1-month after period than for the before period for all intersections except for Isanti, which exhibited a similar critical gap in both the before and after periods. The critical gap increased for the 12-month after period for all intersections except for the Pipestone treatment intersection, where a small decrease occurred.

Figure 5-3 shows the critical gaps for control intersections.

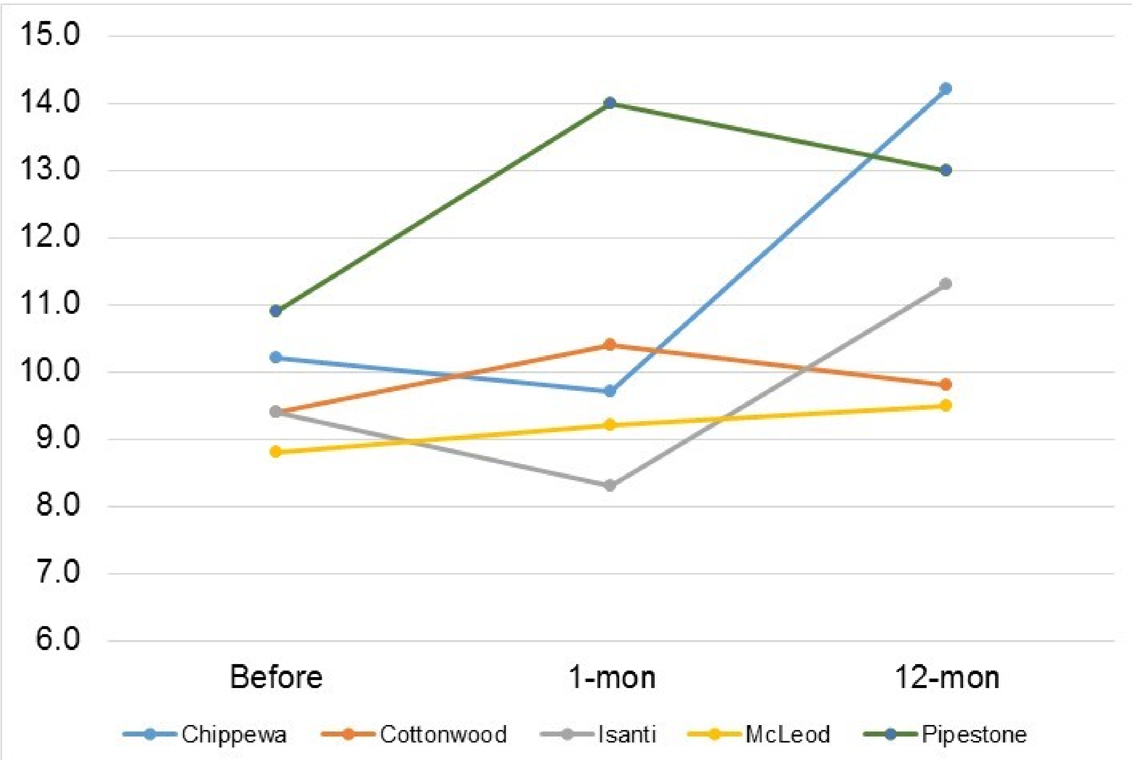


Figure 5-3. Raff's critical gaps for control intersections.

As the figure shows, the critical gap increased during the 1-month after period for the Cottonwood, McLeod, and Pipestone intersections by 0.4 to 3.1 seconds. The Chippewa and Isanti intersections experienced decreases of 0.5 and 1.1 seconds, respectively. During the 12-month after period, Chippewa, Isanti, and McLeod had increases in critical gaps of 0.3 to 4.5 seconds. Cottonwood and Pipestone had decreases of 0.6 and 1.0 seconds, respectively.

The length of the critical gaps appeared to increase overall, which suggests that the ICWS improved drivers' gap selection at both the treatment and control intersections.

5.6 GLANCES

The number of glances at different time periods was evaluated to determine whether drivers improved intersection scanning. Intersection scanning is the process of looking left and right to determine the presence and location of oncoming vehicles. There was no defined example of what good scanning behavior entails. As a result, it was assumed that an increase in glances to the left and right indicate better scanning behavior. On the one hand, there was a concern that drivers may scan less if they overly rely on the ICWS. On the other hand, drivers may pay more attention if the warning system is activated.

Due to issues in the field, the side-facing cameras at the Pipestone and McLeod sites could not be oriented toward the treatment intersections appropriately to collect data. As a result, driver data were not available at all locations during the 12-month after period. Because there was significant variation between intersections, it was decided that presenting the 12-month after period data without including those two intersections would skew the results. Therefore, data for the five intersection pairs collected during the before period were compared to data for the same intersection pairs collected during the 1-month after period. The data collected during the before period were also compared to the 12-month after period data for the three locations where such data were available.

5.6.1 Glances by Stopping Behavior

Table 5-20 shows changes in left and right glances by type of stop for the 1-month after period. Due to the small sample size, vehicles that did not stop are not shown.

Table 5-20. Glances by type of stop for 1-month after period

	Treatment			Control		
	Before	1-mon	Change	Before	1-mon	Change
	Complete stop					
Left glances	1.61	2.12	0.52	1.68	1.48	-0.19
Right glances	1.38	2.00	0.62	1.47	1.92	0.45
	Rolling stop					
Left glances	1.06	1.17	0.12	0.97	1.10	0.13
Right glances	0.71	1.01	0.30	0.82	1.06	0.24

Table 5-20 provides data for all five treatment/control intersection pairs. The number of both right and left glances increased at the treatment intersections. For example, drivers who made a complete stop on average glanced left 1.6 times before installation of the ICWS and glanced left on average 2.1 times in the after period (increase of 0.5). Right glances increased on average from 1.4 to 2.0 times for complete stops. Similarly, glances increased for rolling stops. Table 5-20 also shows glances for control sites.

Glance location by stopping behavior at control intersections is provided in Table 5-21.

Table 5-21. Glances by type of stop for 12-month after period

	Treatment			Control		
	Before	12-mon	Change	Before	12-mon	Change
	Complete stop					
Left glances	1.51	1.70	0.19	1.56	1.96	0.39
Right glances	1.43	1.25	-0.18	1.39	1.51	0.12
	Rolling stop					
Left glances	0.94	1.17	0.24	0.94	1.27	0.33
Right glances	0.83	0.83	0.00	0.83	1.16	0.32

A small decrease in the number of left glances for complete stops was noted. However, an increase in the average number of left and right glances occurred for rolling stops, and an increase in right glances was observed for complete stops.

Overall, drivers coming to a complete stop glanced both left and right more frequently than did drivers who came to rolling stops. This was observed at both the treatment and control sites. When oncoming vehicles are present, drivers may be more likely to come to a complete stop than a rolling stop and may then engage in more intersection scanning. Alternatively, the type of drivers who come to a complete stop may be more likely to engage in better scanning behavior.

Because data were not available for all locations at 12 months, data collected during the before period and 12-month after period were summarized for the three intersections for which data were available at 12 months. For treatment sites, the average number of left glances increased for both types of stops. Right glances decreased slightly for complete stops and experienced no change for rolling stops. The number of left and right glances increased at the control sites for both types of stops.

5.6.2 Glances by Turning Movement

Glances by turning movement are shown in Table 5-22 for both the treatment and control intersections.

Table 5-22. Glances by turning movement for 1-month after period

	Treatment			Control		
	Before	**1-mon**	**Change**	**Before**	**1-mon**	**Change**
	Right					
Left glances	1.27	1.37	0.09	1.26	1.28	0.02
Right glances	0.31	0.95	0.64	0.22	0.88	0.66
	Through					
Left glances	1.33	1.88	0.55	1.39	1.58	0.18
Right glances	1.34	1.76	0.42	1.55	1.74	0.19
	Left					
Left glances	1.27	1.43	0.16	1.25	1.55	0.30
Right glances	1.26	1.32	0.05	1.44	1.72	0.28

Due to the low sample size, data were only available for three of the five control intersections (Cottonwood, Isanti, and McLeod). As a result, data were reduced for those three intersections for both the treatment and control sites. The number of glances increased for all movements at both the treatment and control sites. Right glances increased the most significantly for right turn maneuvers at both the treatment and control sites. Left glances increased the most for through movements at the treatment sites and for left turns at the control sites.

Once data were disaggregated by turning movement, sample sizes for the 12-month after period were too small to feasibly compare data. As a result, data are not shown for the 12-month after period.

5.7 CONFLICTS

All conflicts were recorded for each intersection, as shown in Table 5-23.

Table 5-23. Conflicts at treatment and controls sites

		Near-crash	Applied brakes/slowed	Change lanes/other evasive maneuver
Treatment	Before	34	22	17
	1-month	26	22	6
	Change at 1-month	-8	0	-11
	12-month	25	49	2
	Change at 12-month	-9	27	-15
Control	Before	22	8	8
	1-month	35	28	8
	Change at 1-month	13	20	0
	12-month	22	39	1
	Change at 12-month	0	31	-7

Conflicts included near-crashes, evasive maneuvers, application of brakes or slowing, or changing lanes. The number of near-crashes decreased significantly at the treatment sites for both the 1- and 12-month after periods. Conversely, the number of near-crashes increased at the control sites by approximately 1/3 during the 1-month after period. Near-crashes decreased again in the 12-month after period and ultimately showed no overall change from the before period. An example of a near-crash at one of the study intersections is shown in Figure 5-4.

Figure 5-4. Example of a near-crash.

The number of drivers who applied their brakes during the 1-month after period at the treatment sites was the same as the number during the before period, with 27 more vehicles applying their brakes during the 12-month after period. At the control sites, the number of drivers applying their brakes increased by 20 during the 1-month after period and by 31 during 12-month after period. Lane changing and other evasive maneuvers decreased at control sites during the 12-month after period.

Overall, near-crashes and lane changing decreased at the treatment sites while these conflicts increased at the control sites. Because driver behavior did not change significantly at the control intersections, it is not known when near-crashes increased at the control sites. It is not likely to have been due to a spillover effect from the ICWS.

CHAPTER 6: VISSIM ANALYSIS

Another objective of the research was to determine the threshold combinations of mainline/minor approach volumes when the ICWS is likely to be continuously activated. At these thresholds, the system would nearly continuously display driver messages, and the system would no longer be dynamic while these volumes are maintained. The hypothesis is that drivers may pay less attention to the dynamic signs when they are continuously activated, leading to loss of effectiveness.

Ideally, a time period when a sufficient volume of traffic was present on the mainline that would have continuously triggered the ICWS would have been selected for evaluation. However, this situation did not occur for any sustained period in the field. As a result, microsimulation was used to identify when those thresholds would occur.

A model was developed in PTV VISSIM version 6.00-15 using one hour of data for the treatment site in McLeod County. The data used in development were collected from 8:45 a.m. to 9:45 a.m. on July 22, 2016. These data included vehicle volumes, turning movements, speeds on the mainline, and average delay on the minor approaches. Once the model was calibrated, an additional hour's worth of data from the same day was used to validate the data.

Data were collected during each VISSIM run to help determine the amount of time the sign was active within the hour. This was done by placing data collection points approximately 524 feet upstream of the intersection on both mainline approaches. This distance was used because it was 6.5 seconds upstream of the intersection if vehicles were assumed to be traveling at 55 mph. While the sign in the real world is dynamic based on a driver's speed, this was not possible within the confines of VISSIM. Using the time at which the vehicle passed the data collection point and the fact that the sign is active for 6.5 seconds, the amount of time the sign was active was able to be determined.

The model was run 25 times at a resolution of 10 simulation seconds per actual second using the validated data. The results of this initial run were compared to the hour of real world data. The results of the comparison showed that the model's estimate of the amount of time the sign was on was within 4% of the time it was on in the hour of real world data. This was deemed to be accurate enough for our purposes due to the random nature of arrivals.

The model was then run again with 5%, 10%, 15%, 20%, and 25% of the daily annual average daily traffic (AADT) and the turning percentages from the validated model. This amounted to 313, 625, 938, 1,250, and 1,563 vehicles per hour on the mainline. Each model was run 25 times using the same set of seeds and 10 simulation seconds per actual second. The average amount of time the sign was active was calculated, and an average across the 25 runs was calculated. Figure 6-1 shows the findings of the models.

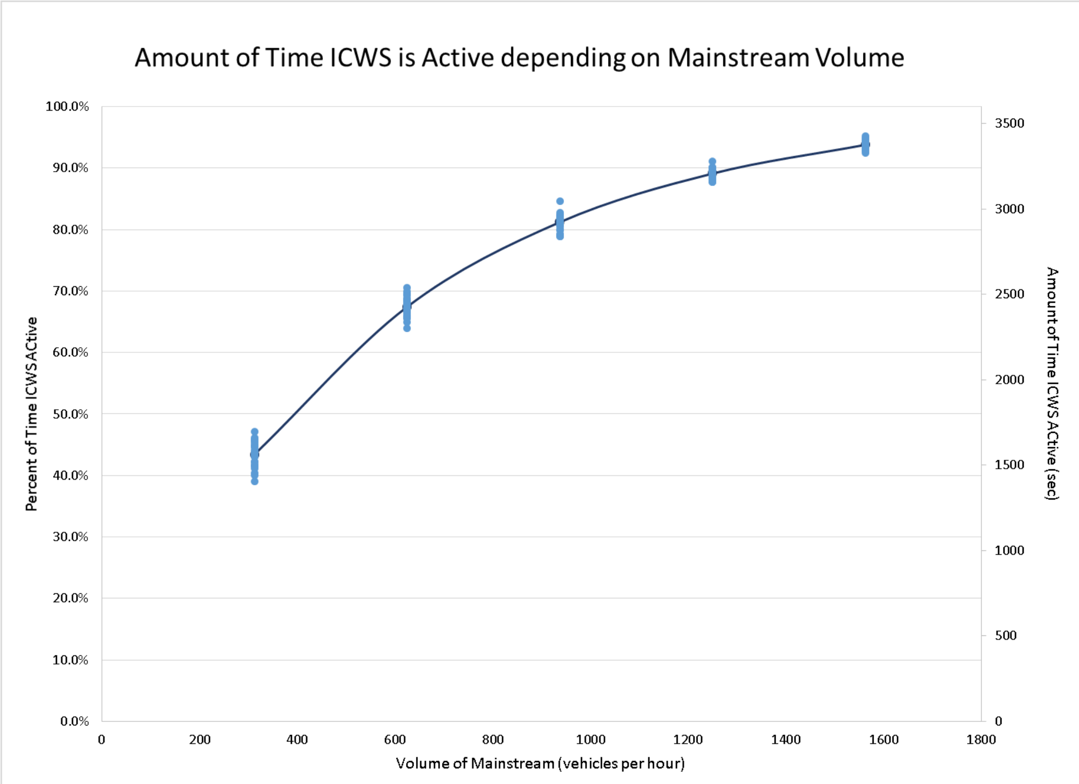


Figure 6-1. ICWS activation status using simulation.

Figure 6-1 can be used to help determine the traffic volume at which the sign is active a certain percentage of the time. For instance, when the mainstream volume reaches 1,600 vehicles per hour, the system is nearly continuously activated. This relationship would differ based on different geometric characteristics. However, the relationship provides a good indication of when the system will be continuously activated and therefore less effective.

In summary, the analysis indicated the following:

- At about 400 vph, the ICWS is activated about 50% of the time.
- At about 800 vph, the ICWS is activated about 75% of the time.
- At about 1,390 vph, the ICWS is activated about 90% of the time.

While it was not possible to assess driver behavior under situations with continuous ICWS activation, the system is likely to lose its effectiveness when drivers are presented with what appears to be a static system. Although actual system performance is dependent on a number of factors, the use of ICWS may not be advisable when mainline volumes are greater than 1,400 to 1,600 vehicles per hour.

CHAPTER 7: SUMMARY AND CONCLUSIONS

Various metrics were used to compare changes in driver behavior, as summarized below.

7.1 STOPPING

Stopping behavior overall was assessed. The percentage of drivers in the minor stream making complete stops at stop signs was found to increase for three of the five treatment intersections when stopping behavior was assessed both 1 month and 12 months after ICWS installation (0.4% to 7.0%). A corresponding decrease in rolling stops occurred. Little change was noted in non-stops. Complete stops decreased at two of the treatment intersections (4.0% to 37%). No discernable pattern was noted at control intersections. In some cases, the percentage of complete stops increased, and in others a decrease was noted.

Stopping behavior was also compared by type of turn. In most cases, the percentage of vehicles making a complete stop during a left turn at treatment intersections decreased (-0.2% to 12.5%). Additionally, the percentage of vehicles making a complete stop during a through maneuver increased (0.4% to 8.4%). Complete stops also increased for right turns at most locations (3.0% to 19.3%). No discernable pattern was noted for control sites. Roughly equal numbers of increases and decreases were noted.

Stopping behavior by ICWS activation was also evaluated. Stopping behavior when the system was activated was compared against stopping behavior when the system was not activated for treatment sites. Drivers came to a complete stop between 71% and 75% of the time when the ICWS was active. In contrast, drivers only came to a complete stop about 30% of the time when the system was not active.

The results suggest that the system encouraged appropriate stopping behavior when active. However, drivers may become conditioned not to stop when the system suggests there is no need. No change in stopping behavior was noted at control sites. This indicates that only drivers at the actual ICWS were changing their stopping behavior. In essence, no spillover effect was noted.

7.2 GAP SIZE

Gap size was another metric that was evaluated. Accepted gap size by type of turn was compared for the periods before and after installation of the ICWS. In general, the number of gaps ≤ 6 seconds for all turning maneuvers was found to decrease when gap size was assessed 1 month and 12 months after ICWS installation at the treatment sites. No discernable pattern was noted for control sites during the period 1 month after ICWS installation at the corresponding treatment sites. The percentage of gaps ≤ 6 seconds at the control sites was found to decrease for all turning maneuvers 12 months after ICWS installation at the corresponding treatment sites.

Critical gaps were also calculated using Raff's method. The critical gap was larger for four of the five treatment intersections during the 1-month after period than during the before period (0.3 to 2.4 seconds). The critical gap at the fifth intersection was similar to that during the before period. The critical gap increased during the 12-month after period for all treatment intersections (1.2 to 2.4 seconds), except for one intersection where a small decrease occurred (-0.4 seconds).

The critical gap increased at three of the control intersections during the 1-month after period (increases of 0.4 to 1.0 seconds). The other two intersections experienced decreases of 0.5 and 1.1 seconds. During the 12-month after period, the critical gap increased at three control intersections (0.3 to 4.5 seconds), while the gap decreased at the two other intersections by 0.6 and 1.0 seconds.

7.3 GLANCES

The number of times drivers looked left or right (glances) was evaluated at different time periods to determine whether drivers improved intersection scanning. On the one hand, there was a concern that drivers may scan less if they overly rely on the ICWS. On the other hand, drivers may pay more attention if the warning system is active.

The average number of left and right glances was estimated by type of stop. At treatment intersections, drivers who made a complete stop on average glanced left 1.6 times before installation of the ICWS and glanced left on average 2.1 times after (increase of 0.5). Right glances increased from an average of 1.4 to 2.0 times for right turns when drivers came to a complete stop. Similarly, the number of glances increased for drivers who made a rolling stop.

The number of glances by stopping behavior at control intersections decreased slightly in terms of the number of left glances for complete stops. However, an increase in the average number of left and right glances occurred for rolling stops and for right glances for complete stops.

Overall, drivers coming to a complete stop were found to glance both left and right more frequently than drivers coming to a rolling stop. This was observed at both the treatment and control sites. When oncoming vehicles are present, drivers may be more likely to come to a complete stop than a rolling stop and may then engage in more intersection scanning. Alternatively, the type of drivers who come to a complete stop may be more likely to engage in better scanning behavior.

The change in the number of glances by turning movement was also evaluated. The number of glances increased at both the treatment and control sites for all turning maneuvers. The average number of glances to the right increased most significantly for right-turn maneuvers at both the treatment and control sites. Left glances increased the most for through movements at the treatment sites and for left turns at the control sites.

7.4 CONTINUOUS ACTIVATION USING SIMULATION

Another objective of this research was to determine the threshold combinations of mainline/minor approach volumes for which the ICWS is likely to be continuously activated. At these thresholds, the system would nearly continuously display driver messages, and the system would no longer be dynamic for the duration of the time that these volumes are maintained. The hypothesis is that drivers may pay less attention to the signs when they are continuously activated, leading to a loss of effectiveness.

Microsimulation modeling was used to assess the mainline/minor approach volumes for which the system would be continuously activated.

A graph was developed that can be used to help determine the volume at which the sign is active for a certain percentage of the time. For instance, when the mainstream volume reaches 1,600 vehicles per hour, the system is nearly continuously activated. This relationship would differ based on different geometric characteristics. However, the relationship provides a good indication of when the system would be continuously activated and therefore less effective.

While it was not possible to assess driver behavior in situations with continuous ICWS activation, the system is likely to lose its effectiveness when drivers are presented with what appears to be a static system. Although actual system performance is dependent on a number of factors, the use of ICWS may not be advisable when mainline volumes are greater than 1,400 to 1,600 vehicles per hour.

7.5 CONFLICTS

All conflicts were recorded for each intersection. Conflicts included near-crashes, evasive maneuvers, application of brakes or slowing, or changing lanes. Application of brakes or changing lanes was typically observed for mainline drivers, but any situation where evasive maneuvers were noted was coded as a near-crash. The number of near-crashes was observed to decrease significantly at the treatment sites both 1 month and 12 months after ICWS installation. Conversely, the number of near-crashes increased at the control sites by approximately 1/3 during the 1-month period after ICWS installation at the corresponding control sites. Near-crashes decreased again in the 12-month after period and ultimately showed no overall change from the before period.

The number of times drivers applied their brakes was used as one measure of conflict. The number of drivers who applied their brakes during the 1-month after period at the treatment sites was similar to the number in the before period. More braking was noted during the 12-month after period (increase of 27 instances). The number of drivers applying their brakes increased significantly at the control sites between the 1-month and 12-month after periods.

Overall, near-crashes and other conflicts decreased at the treatment sites while they increased at the control sites. It is unknown why this was the case, but the team felt that these trends were not related to a spillover effect from the treatment sites.

7.6 SUMMARY

In general, no negative behaviors were noted for either the treatment or control intersections. Stopping behavior appeared to improve marginally overall. The most significant impact was the improvement in stopping behavior when the system was active. Drivers were nearly one and half times more likely to come to a complete stop when the system was active compared to when the system was not active.

Gap size increased after installation of the ICWS, suggesting that drivers were more likely to select more appropriate gaps. Finally, the number of times drivers scanned the intersection generally increased.

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