Evaluation of Truck and Agricultural Vehicle Behavior at Reduced Conflict Intersections

Final Report
August 2016




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16. Abstract (Limit: 250 words)

In the US, some states have begun to address rural high-speed intersection crashes by physically restricting minor-road crossing movements (left and through turns) to simplify driver decision-making in terms of gap acceptance (the extent to which drivers will be able to utilize a gap in traffic of a particular size or duration). These treatments are referred to in Minnesota as reduced conflict intersections (RCIs).

Within Minnesota’s rural corridors, introduction of RCI design has been successful in preventing severe crashes; however, the unusual design has been met with some apprehension from operators of agricultural equipment and large trucks. This, in combination with a resistance to the unfamiliar, has created a desire for more information regarding RCI configuration safety impacts for these types of vehicles.

In response to these concerns, this study collected and evaluated large vehicle operational behavior at a set of RCIs and at similar standard control intersections in Minnesota. The researchers collected data in 2015 using a portable video trailer array and metrics on truck turning movements at three RCI intersections in Minnesota and three similar non-RCI intersections, which were proximate to the RCI intersections. The researchers compared travel time, evasive maneuvers, and other metrics for this study.

The researchers found no evidence that validated concerns expressed about large vehicle operation at RCIs. Exposure time was not increased at U-turn locations and evasive maneuvers were lower than at control locations.

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Evaluation of Truck and Agricultural Vehicle Behavior at Reduced Conflict Intersections

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Executive Summary

In the US, some states have begun to address rural high-speed intersection crashes by physically restricting minor-road crossing movements (left and through turns) to simplify driver decision-making in terms of gap acceptance (the extent to which drivers will be able to utilize a gap in traffic of a particular size or duration). These treatments are referred to in Minnesota as reduced conflict intersections (RCIs).

Although an RCI can restrict left turn movements from the major road, the typical Minnesota Department of Transportation (MnDOT) RCI restricts minor road vehicles from making left or through movements. Instead, these vehicles make a right turn and travel a short distance downstream on the major road and then execute a U-turn. Once back at the intersection, drivers who originally intended to turn left continue on the major road or drivers who originally intended to continue straight through the intersection make a right turn on the minor roadway.

Within Minnesota's rural corridors, introduction of RCI design has been successful in preventing severe crashes; however, the unusual design has been met with some apprehension from operators of agricultural equipment and large trucks. This, in combination with a resistance to the unfamiliar, has created a desire for more information regarding RCI configuration safety impacts for these types of vehicles.

Even though RCIs eliminate right-angle crashes, which are the most severe crossing conflicts at rural high-speed intersections, concerns have been raised that, as large trucks are required to make U-turn maneuvers, they occupy the travel lanes for longer than would be required for a left-turn or through maneuver from the minor road, and, consequently, are exposed to on-coming high-speed vehicles for longer.

In response to these concerns, this study collected and evaluated large vehicle operational behavior at a set of RCIs and at similar standard control intersections in Minnesota. The researchers collected data in 2015 using a portable video trailer array and metrics on truck turning movements at three RCI intersections in Minnesota and three similar non-RCI intersections, which were proximate to the RCI intersections. The researchers compared travel time, evasive maneuvers, and other metrics for this study.

The research team reduced video data and compared metrics between RCI and control intersections as noted below.

One of the main concerns expressed about RCIs is that large trucks/vehicles would take a significant amount of time to enter the traffic stream during U-turn maneuvers. This may result in large trucks/vehicles occupying the oncoming travel lanes for an increased period of time, which could lead to conflicts.

The researchers evaluated exposure time (when a vehicle occupies a non-travel lane while waiting for a gap or to complete a maneuver) for both RCI and control intersections. In all situations, large trucks were exposed for significantly less time during the U-turn than during a left or through maneuver at a control intersection.

The researchers also compared evasive maneuvers (situations where an on-coming vehicle has to brake, slow, or change lanes to avoid the large vehicle crossing the intersection). Opponents of RCIs had expressed the most concern about exposure and evasive maneuvers during the U-turn maneuver. The average number of evasive maneuvers created by large vehicles at the RCI U-turn locations was half as many as the average at the control intersections.

This study found no evidence that validated concerns expressed about large vehicle operation at RCIs. Exposure time was not increased at the U-turn locations and evasive maneuvers were lower than at control locations.

1. Introduction

1.1 Background

Rural multi-lane divided highways are generally characterized by higher posted travel speeds and a lower density of intersections (which are typically two-way stop controlled). The combination of multiple lanes of high speed traffic, at-grade access, and driver performance often leads to severe right angle collisions. Maze et al. (2010) reported that 57% of the intersection related crashes in Minnesota were right angle or turning crashes with similar results in Utah (69%) and Iowa (52%).

At-grade intersections along multi-lane roadways present challenging conditions for drivers in terms of judging gaps between high-speed traffic from two different directions separated by a median. Comprehension and understanding on whether to stop within the median or to cross the intersection in one movement has been shown to be problematic for drivers in rural settings (Maze et al. 2010).

In the US, some states have begun to address rural high-speed intersection crashes by physically restricting minor-road crossing movements (left and through turns) to simplify driver decision-making in terms of gap acceptance (the extent to which drivers will be able to utilize a gap in traffic of a particular size or duration). These treatments are referred to in Minnesota as reduced conflict intersections (RCIs).

Although an RCI can also restrict left turn movements from the major road, the typical Minnesota Department of Transportation (MnDOT) RCI restricts minor road vehicles from making left or through movements. Instead, these vehicles make a right turn and travel a short distance downstream on the major road and then execute a U-turn. Once back at the intersection, drivers who originally intended to turn left continue on the major road or drivers who originally intended to continue straight through the intersection make a right turn on the minor roadway.

1.2 Safety Impact of the Reduced Conflict Intersection

The following summarizes current literature regarding the safety impact of RCI intersections. It should be noted that different geometric designs are utilized so results across different studies are not necessarily comparable. The term RCI is used consistently throughout this report but many studies used different terminology to refer to the treatment (e.g., Restricted Crossing U-turn (RCUT), and J-Turn).

A study by Inman and Haas (2012) compared crashes for nine intersections in Maryland before and after installation of RCIs. This study showed a 62% decrease in crashes after the RCI treatment was installed and an overall reduction in crash severity after installation of the RCIs compared to conventional intersections. In addition, a 70% drop in fatal crashes and a 42% reduction in injury crashes, between the 3-year periods of installing the RCIs, was reported.

Edara et al. (2013) evaluated 5 intersections where RCI's were installed in Missouri. These sites were compared against control sites which had two way stop control. The authors used an Empirical Bayes analysis and showed a 35% reduction in all crashes and a 54% reduction for injury and fatal crashes while minor injury crashes were reduced by 50%. An overall 80% reduction in right angle crashes was noted for the five sites.

An initial analysis was conducted which compared truck crashes at RCIs in Minnesota and several other states (Hawkins et al. 2015). The study was based on concerns that trucks making a U-turn would occupy more time in the travel lane than a straight or left turn maneuver through a regular intersection. Based on the limited data available, the study showed no evidence that the frequency of truck crashes increased after the installation of an RCI. In addition, the installation of the RCI appears to have shifted crash patterns from the more severe right-angle crash to less severe rear-end and side-swipe crash. Evaluation of truck crash patterns before and after installation of RCIs did not suggest increases in the type of crash from increased truck exposure.

1.3 Objectives

This study collected and evaluated large vehicle operational behavior at a set of RCIs and also at similar standard control intersections in Minnesota. Truck turning movements at three RCI intersections in Minnesota and three similar non-RCI intersections were collected in 2015 and travel time, evasive maneuvers, and other metrics were compared.

Within Minnesota's rural corridors, introduction of the RCI design has been successful in preventing severe crashes, however, the unusual design has been met with some apprehension from operators of agricultural equipment and large trucks. This, in combination with a resistance to the unfamiliar, has created a desire for more information regarding RCI intersection configuration safety impacts for these types of vehicles. Even though RCIs eliminate right-angle crashes, which are the most severe crossing conflicts at rural high speed intersections, concerns have been raised that as large trucks are required to make the U-turn maneuver they are occupying the travel lanes for a longer period of time than would be required for a left-turn or through maneuver from the minor road and consequently are more exposed to on-coming high speed vehicles.

2. Site Identification

MnDOT identified eight RCI intersections for study consideration. Control sites with similar characteristics were also identified (along the same roadway, similar geometry (i.e. number of lanes, median type), similar surrounding land use, and traffic volumes.

Existing RCI and potential (non RCI) control sites are shown in Figure 1. Table 1 provides a summary of RCI treatment and control location characteristics.

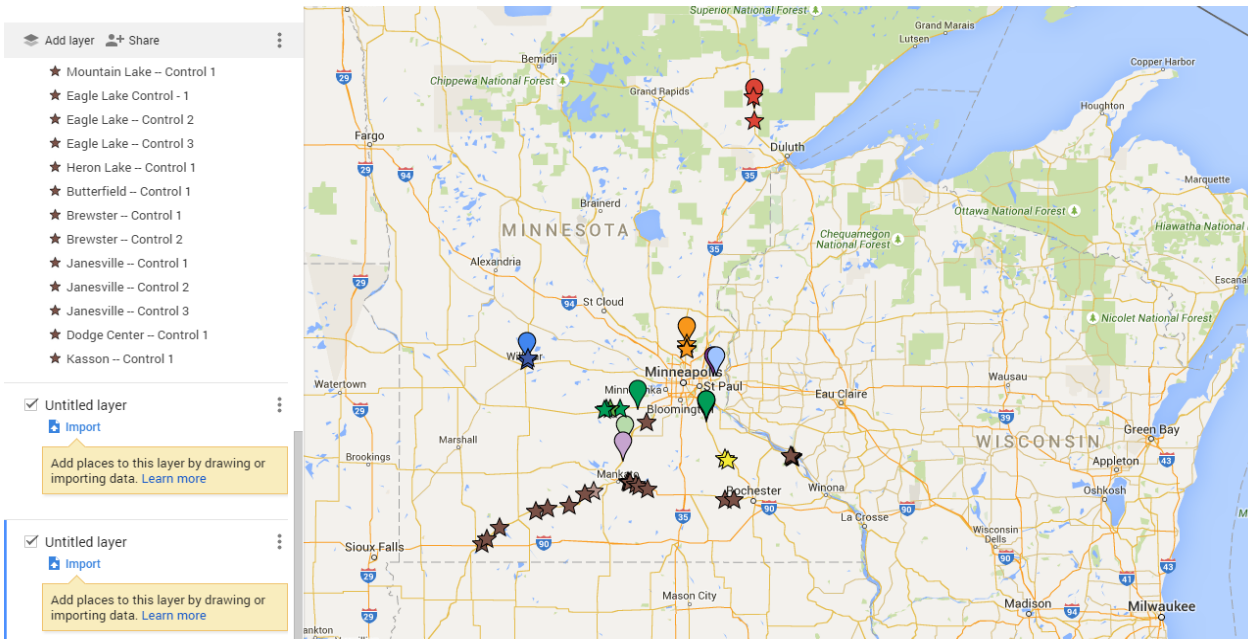

Figure 1: Location of RCI and potential control intersections in Minnesota

Table 1: Summary of RCI treatment and control locations

	Main Route	Intersecting Route
Cologne		
Test	US 212	County 53*
Control	US 212	County 1*
	US 212	MN 25/ County 131
	US 212	Morningside Ave
Cotton		
Test	US 53	County 52 (Comstock Lake Rd)
Control	US 53	County 133 (Berklund Rd)
	US 53	County 59 (W. Melrude Rd)
Ham Lake		
Test	MN 65	169th Ave
Control	MN 65	181st Ave NE
	MN 65	157th Ave NE
	MN 65	153rd Ave NE (McKay Dr)
Wilmar		
Test	US 71	County 24 (26th Ave)*
Control	US 71	County 25
	US 71	County 90 (37th Ave NE)*
Vermillion		
Test	US 52	County 66*
Control	US 52	County 57*
	US 52	County 62
County 36 & Demonstraville		
Test	County 36	Demonstraville Trail
County 36 & Keats		
Test	County 36	Keats Ave
Le Suer		
Test	US 169	County 93
St. Paul		
Test	County 22	W. St. Julien St

*Sites selected for analysis

Based on an evaluation of intersection conditions and in conjunction with the MnDOT project Technical Advisory Panel (TAP) the Cologne, Vermillion, and Wilmar locations were selected. The Vermillion and Wilmar locations represent rural conditions and Cologne provides for a good representation of a semi-urban location. Locations are shown in Figure 2.

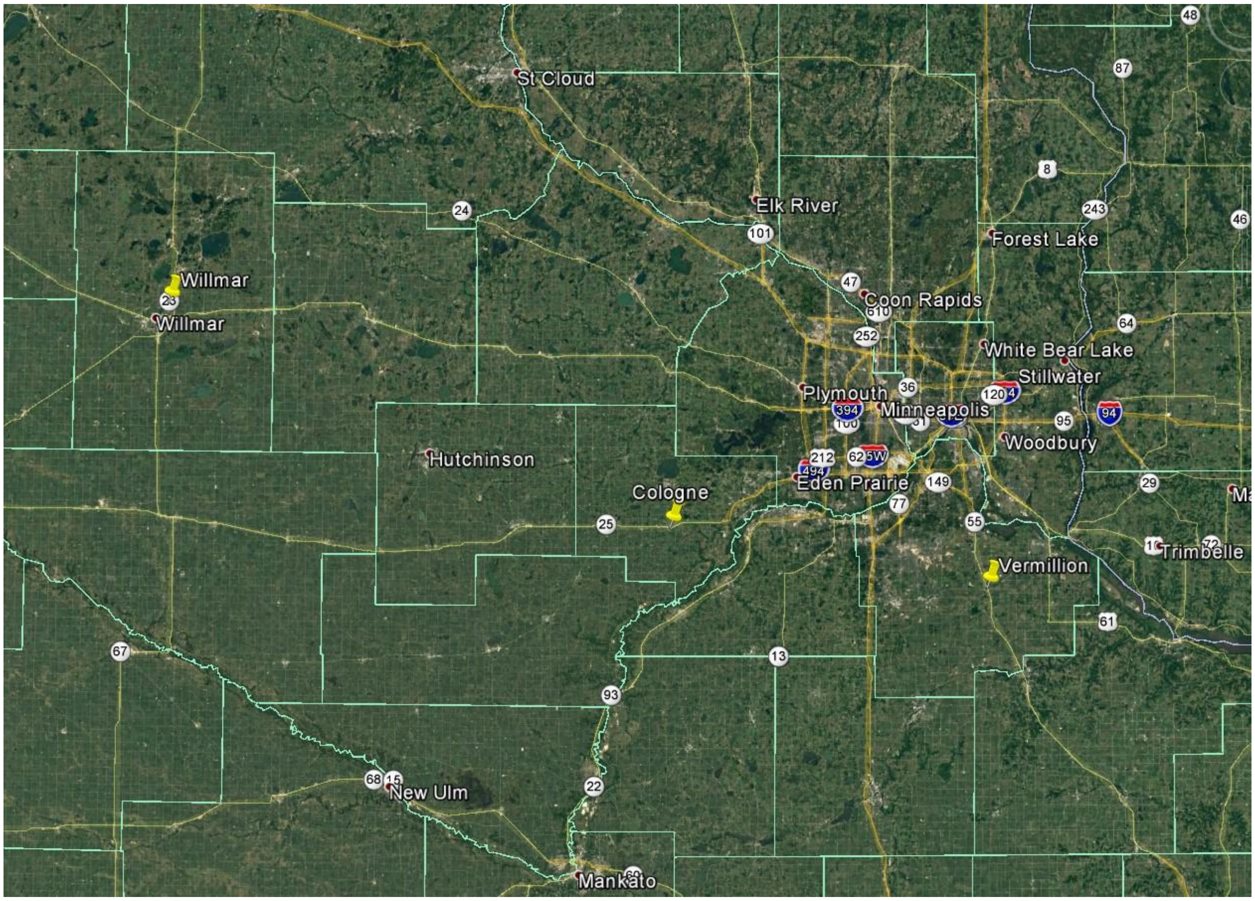

Figure 2: Selected Cologne, Vermillion, and Wilmar intersection locations in Minnesota

2.1 Description of Cologne Sites

Figure 3 shows the treatment and control intersections near Cologne.

The major roadway for both the treatment and control site is US 212. The treatment site is at US 212 and County 53/TH 284 and the control site is US 212 and County 1 in McLeod County. These intersections and are roughly 15 miles apart. The U-turns at the treatment site are labelled.

Figure 3: Cologne intersections

2.2 Description of Vermillion Sites

Figure 4 shows the treatment and control intersections near Vermillion. The major roadway for both the treatment and control site is US 52. These intersections are roughly 20 miles apart. No closer locations with similar characteristics were available. The treatment site is at US 52 and County 66 and the control is at US 52 and County 57. The U-turns at the treatment site are labelled.

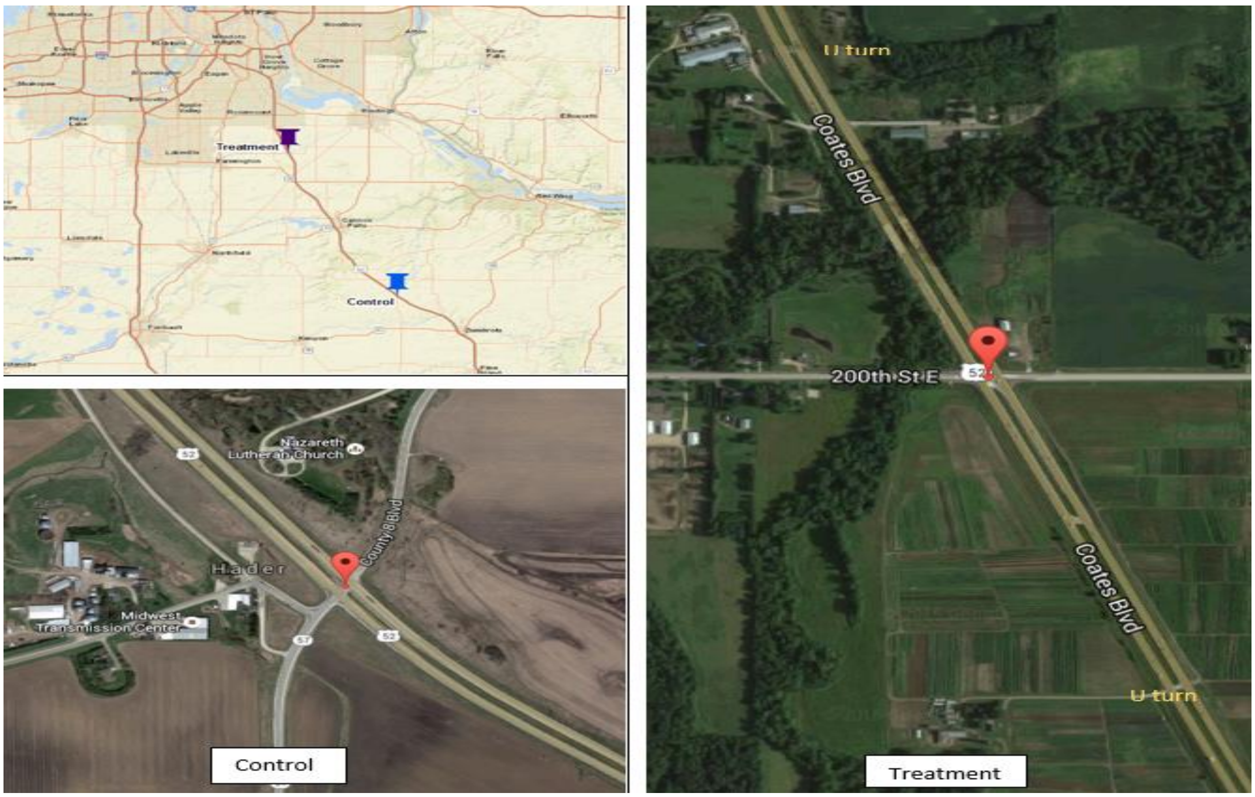

Figure 4: Vermillion Intersections

2.3 Description of Wilmar Sites

Both the Wilmar treatment and control intersections are shown in Figure 5. The major roadway for both the treatment and control site is US 71. The RCI is located at US 71 and County 24 (26th Ave) and the control site is County 90 (37th Ave NE). These intersections are roughly 1 mile apart. The U-turns at the treatment site are labelled.

Figure 5: Wilmar intersections

3. Data Collection

Data were collected at the three test and three control locations, as shown in Table 2, between mid-September and mid-October 2015 using a portable video trailer array as shown in Figure 6.

Table 2: Data collection

	Main Route	Intersecting Route	Data Collected
Cologne			
Test	US 212	County Hwy 53	Sept 21 – 28, 2015
Control	US 212	County Hwy 1	Sept 21 – 28, 2015
Willmar			
Test	US 71	County 24 (26th Ave)	Sept 28 – Oct 5, 2015
Control	US 71	County 90 (37th Ave NE)	Sept 28 – Oct 5, 2015
Vermillion			
Test	US 52	County 66	Oct 5 – 12, 2015
Control	US 52	County 57	Oct 5 – 12, 2015

Figure 6: Data collection array

The late season observation period was deliberate to include truck and farm equipment activity from the fall harvest. Data were collected for treatment and control locations at the same time. Weather forecasts were used in planning the data collection efforts to avoid extreme weather.

Data were collected at each intersection for one week by CCTV cameras. The cameras were accessible via cell modem so that adjustments could be made throughout the week specific to view angle and confirmation that cameras were online and collecting video.

Two solar powered trailers were used at each intersection with two cameras per trailer. At the treatment intersections, one camera was directed towards the U-turn portion of the RCI to optimize collecting evasive maneuvers while heavy vehicles were performing the U-turn movement. The second camera was directed towards the intersection to collect evasive maneuvers within the weaving section for the opposite direction of travel. The second trailer was used to collect the opposite direction of travel. At the control intersections (non RCI standard two way- stop control), only one camera was used since it was able to capture all of the directions.

The data collection set-up is shown in Figures 7 and 8. The cameras were positioned to track vehicles from the minor road right turn through exiting the intersection.

Figure 7: Data collection layout at Cologne RCI

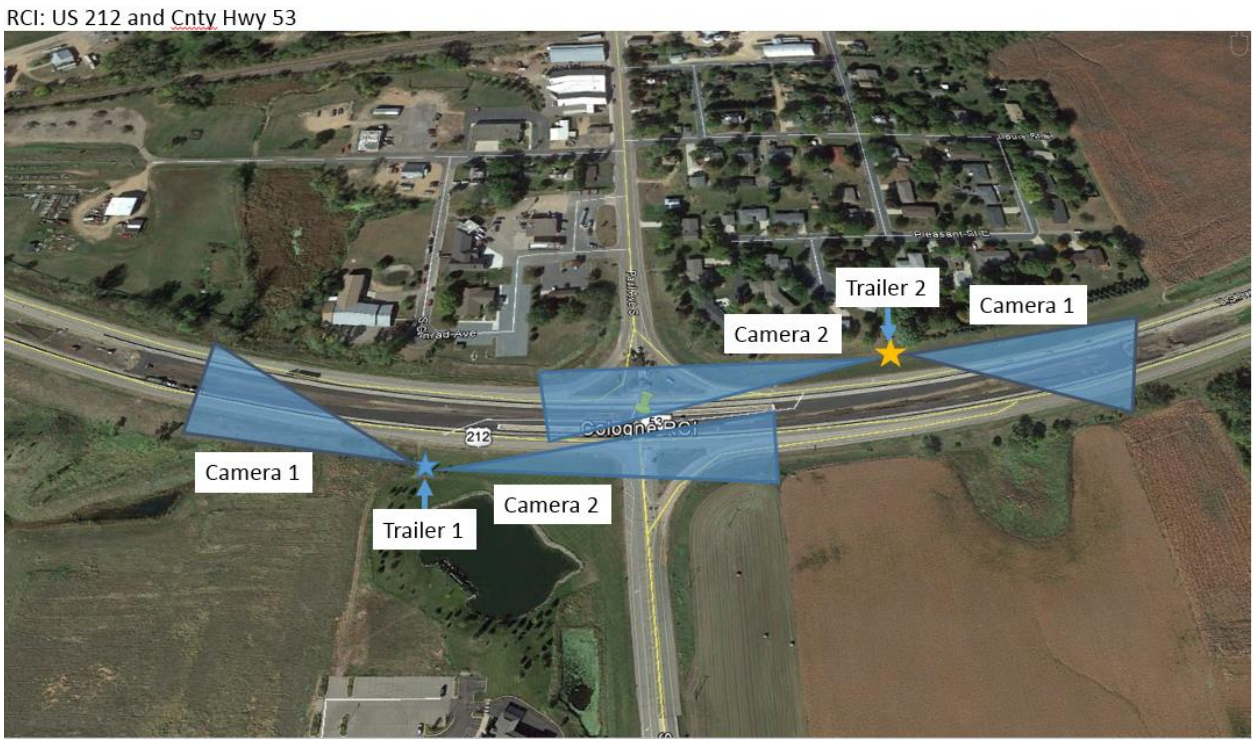

Figure 8: Data collection setup

4. Data Reduction

Data were reduced for 3 control and 3 RCI intersections as shown in the Table 3. Data were reduced for all large trucks (single unit and larger). The table also shows the number of vehicles reduced. The Wilmar sites had significantly lower numbers of trucks than the Cologne or Vermillion sites.

Table 3: Data collection at treatment and control sites

Intersection	Type	Data collection date		Data reduced	
		Start	End	Total days	Number of trucks
Cologne	**Treatment**	9/29/2015	10/5/2015	5	467
	Control	9/29/2015	10/5/2015	5	401
Vermillion	**Treatment**	10/6/2015	10/12/2015	5	63
	Control	10/6/2015	10/12/2015	5	225
Wilmar	**Treatment**	9/22/2015	9/28/2015	5	24
	Control	9/22/2015	9/28/2015	5	21

Only large trucks and agricultural vehicles were reduced from the collected video. Vehicles were classified into three groups based on their length. Group 1 consisted of single unit vehicles with either double axle or 3-axle or 4 or more axle (FHWA Vehicle Class 4 to 7) including school buses. Group 2 included single or multi-trailer trucks (FHWA Vehicle Class 8 to 12). Group 3 included all types of agricultural vehicles. Figure 9 shows the classification by FHWA class. Only three groups were created given that further disaggregation would have resulted in small sample sizes.

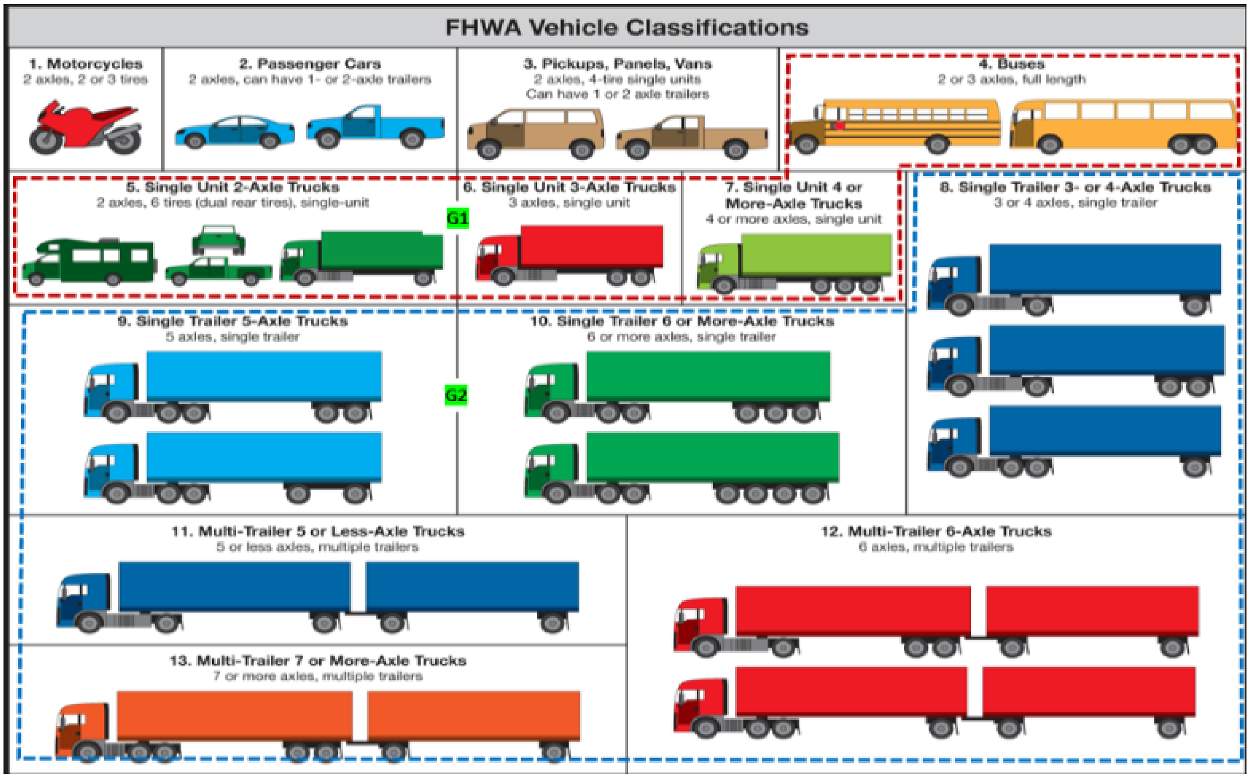

Figure 9: Truck classification

Only minor road vehicles turning left and moving straight were coded both in the control and treatment sites. It was assumed that the presence of an RCI does not affect right turn movements.

The data were reduced from the point the vehicle arrived at the minor road stop-bar until it departed the intersection. These instances were considered as the start and end times. The details of the data coding procedure for the treatment and control sites is described in detail below.

A set of truck operational factors of interest, such as queue time, were identified and then manually extracted from the video. A data reduction protocol was developed so that results were consistent across data reductionists.

4.1 Data Items Reduced at RCIs

Data were reduced for the minor road vehicles who, without the RCI in place, would have turned left or traveled through the intersection. Several of the data collection points are shown in Figure 9.

4.1.1 Queuing Time

Queuing time included time at which the vehicle stopped on the minor road approach, waiting for a gap, until the vehicle began to make the right turn. At the U-turn, queueing time was denoted from the point the vehicle stopped at the U-turn location until they began to move into the adjacent lanes.

4.1.2 Type of Merging

Three different types of merging from the minor road to the U-turn location were noted as shown in in Figure 9. Type 1 movement is characterized by vehicles moving directly from the minor road to the merging lane. Type 2 movements are trucks which first merge into the main stream where they travel for some distance before crossing to the merge lane. Type 3 movements are characterized by vehicles entering the acceleration lane and traveling some distance before directly crossing to the merge lane.

4.2.3 Exposure Time for Crossing Merge

Exposure time during the initial merge was defined as the time a vehicle departed the minor road and was in the process of crossing lanes to reach the merge lane. During these maneuvers large trucks were exposed to potential conflicts with on-coming vehicles. The amount of time vehicles were traveling within a lane before beginning the merge maneuver was not included. Exposure time for the crossing merge is shown using the yellow lines in Figure 10.

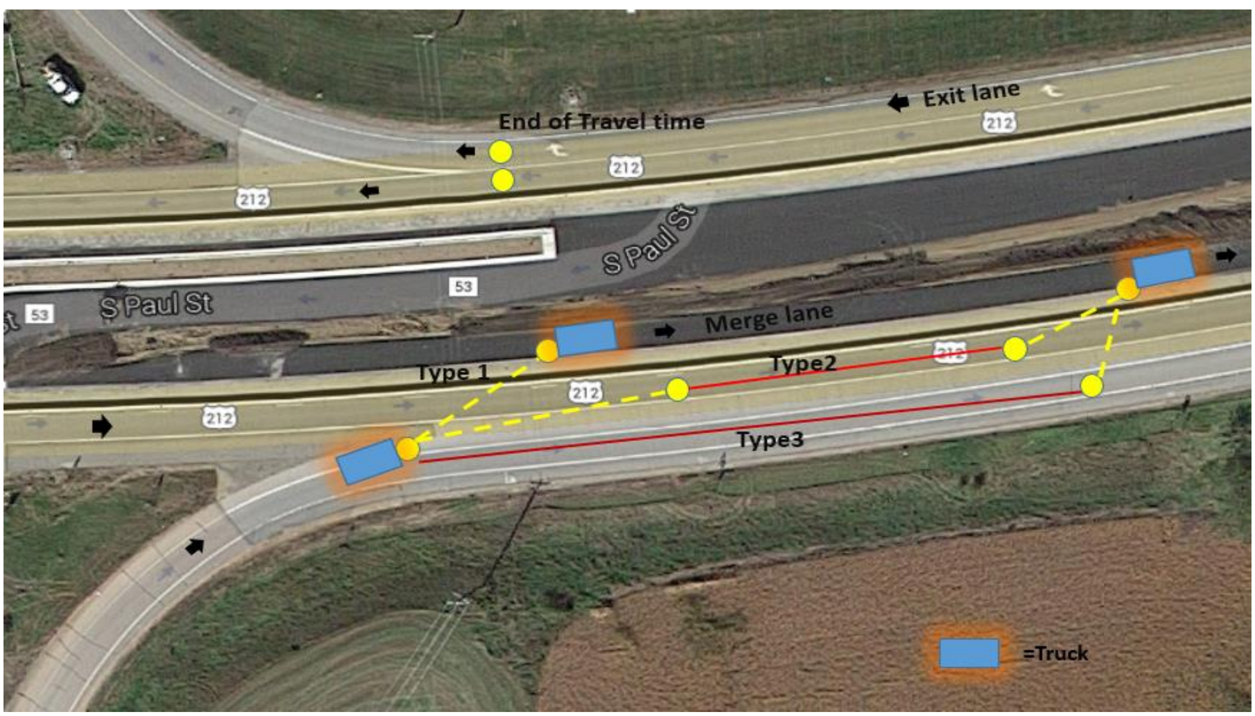

Figure 10: Different types of merges from minor approach

4.2.4 Evasive Maneuvers

An evasive maneuver was defined as a situation where an on-coming vehicle had to brake, slow, or change lanes to avoid the crossing or merging large vehicle. No crashes were noted during the study period. Near crashes were defined as when an on-coming vehicle nearly collided with the subject vehicle. When brake lights were noted, it was coded as "Applied brake." If brake lights were not apparent, but obvious slowing of an on-coming vehicle was observed, it was coded as "Slowed down." A slow down where the major stream vehicles almost stopped was coded as "Almost stopped." In addition, when a major stream vehicle changed lanes to avoid the merging large vehicle, it was coded as "Changed lane." Evasive maneuvers occurred both at the first merge from the minor approach as well as at the U-turn.

4.2.5 Exposure for U-turn

Figure 11 shows two different U-turn merging maneuvers that were observed. Exposure time was coded as the time for a vehicle to enter the main traffic stream until the driver completed the turn and merged or straightened their vehicle into the desired travel lane.

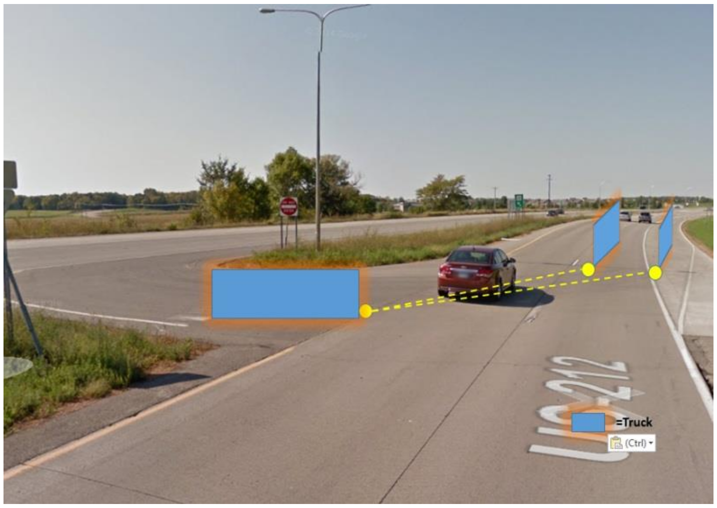

Figure 11: Exposure time during U-turn

4.2.6 Running Time

Net travel time was coded as the time for a vehicle to depart the minor street, merge to the U-turn location, and then complete the U-turn. It does not include the waiting time to first turn right or the time spent waiting to find an acceptable gap at the U-turn location.

4.2 Control Sites

The control sites evaluated all have medians along the major routes so at the intersections the through and left turn minor road vehicles are able to use the median break to complete their movement in two stages if desired. The data reduction for the control sites is described in the sections as below.

4.2.1 Queuing Time

The time when a vehicle arrived at the stop bar of the minor approach was noted. The time a vehicle spent queuing on the minor approach waiting for a gap was estimated using the arrival and departure time of vehicle. The type of turn was coded as left or through. Right turns were not included.

4.2.2 Exposure Time

Exposure time was defined as the period of time that trucks were exposed to the major route traffic while waiting to complete the left or through maneuver. As shown in Figure 12, the yellow lines show the duration of the exposure time coded. This includes crossing both approaches to complete either the left turn or straight maneuver.

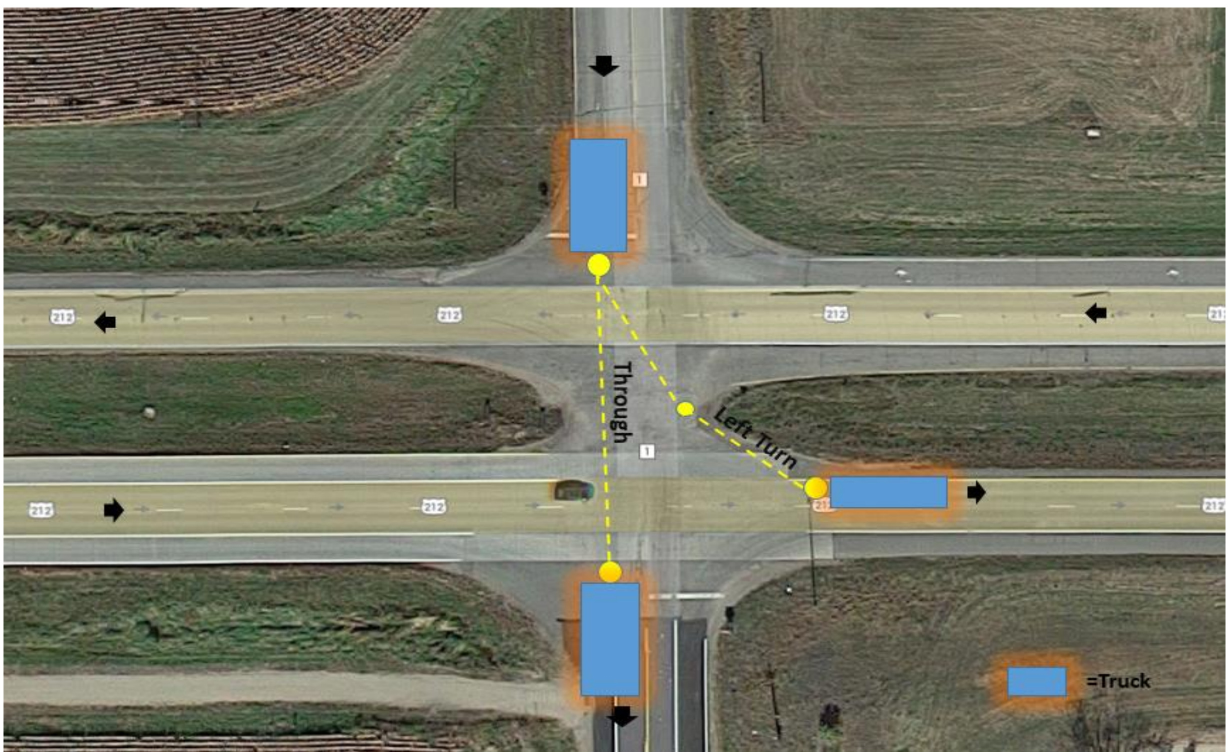

Figure 12: Exposure time at control sites

4.2.3 Evasive Maneuvers

Evasive maneuvers were coded the same as for the RCI intersections.

5. Results

Vehicle data were reduced only for weekdays assuming different traffic pattern and truck volumes during the weekends. Table 4 shows the distribution of trucks by category at the six different locations. Cologne had the highest number of trucks in all categories among the three sets of intersections. The majority by vehicle type were Group 1 and Group 2. There were significantly more agriculture vehicles (Group 3) for the control site than for the treatment site.

At the Vermillion sites, there were more than 5 times as many trucks at the control site as the treatment site with very few vehicles in Class 2 and none in Class 3 at the treatment site.

Wilmar had a low number of trucks overall (18 at the treatment and 15 at the control). No agriculture vehicles were present at either Vermillion site.

Table 4: Sample size by location

Truck Category	Cologne		Vermillion		Wilmar	
	Treatment	Control	Treatment	Control	Treatment	Control
Group1 (G1)	292	171	31	50	16	12
Group 2 (G2)	138	178	9	170	2	3
Group 3 (G3)	18	51	0	5	0	0

Analyses were conducted to compare exposure time, travel time, queuing time, evasive maneuver, types of evasive maneuvers and number of vehicles affected at the treatment versus control sites for each set of sites.

5.1 Cologne, Minnesota Sites

5.1.1 Exposure Time at Cologne

Table 5 shows exposure time by vehicle group type for the Cologne (RCI and control) intersection locations.

Table 5: Exposure time by truck category at Cologne intersections

Truck Category	RCI		Control
	Exposure Time		Exposure time
	Merging	U-Turn	
G1	6.0	6.1	9.8
G2	8.0	8.9	11.5
G3	8.1	7.4	12.8
Average	6.7	7.0	10.9
Standard deviation	2.2	2.5	5.5

As shown, exposure time (time when a vehicle occupied a non-travel lane while waiting for a gap or to complete a maneuver) was divided into two types for the RCI intersection (Merging and U-turn). Individually the average exposure time at the RCI (6.7 at the merge and 7.0 at the U-turn) was more than 4 seconds less than the average exposure time at the control intersection (10.9).

Collectively the total exposure times (Merging plus U-turn) were around 2 seconds more at the RCI intersection than at the control. However, the two-stage movement breaks the exposure into two stages minimizing the amount of time a vehicle is exposed at any given time.

One of the original concerns about RCI was that trucks would occupy the on-coming lanes for a significant amount of time while attempting to execute a U-turn increasing risk and exposure for on-coming vehicles. The U-turn exposure time at the RCI is also more comparable to the left-turn or through movement at the control intersection.

Additionally, truck exposure at the merging maneuver is more likely to result in a rear-end or sideswipe and exposure at the U-turn is more likely to result in a sideswipe compared to the control intersection where a right angle crash is the more likely result of a vehicle conflict. The average standard deviation time was also much greater for the control intersection which suggests that a number of trucks had much longer exposure times. Exposure for a large truck which is merging from the minor approach is shown in Figure 13.

Figure 13: Truck exposure during merge from minor approach

Additionally as noted, the merge time was greater for larger trucks (G1) for all metrics than for single unit trucks (G1). Exposure times for large trucks (G2) and agriculture vehicles was similar. Exposure during a U-turn is shown in Figure 14. Exposure time during a maneuver at a control intersection is shown in Figure 15.

Figure 14: Exposure time during U-turn

Figure 15: Exposure time at control

Although all exposure is important, one of the main concerns by the public for RCI is that large trucks/vehicles would take a significant amount of time to enter the traffic stream during the U-turn maneuver. This would result in large trucks/vehicles occupying the on-coming travel lanes for an increased period of time which could lead to conflicts. As noted in Table 5, exposure time during the U-turn was 3.6 second lower for Group 1 vehicles than for the same type of vehicle at the control intersection. Exposure time was 2.7 seconds less for Group 2 and 5.4 seconds lower for Group 3. As a result, exposure time during the U-turn was less in all situations that exposure time for regular intersections. There is some portion of the U-turn that right angle crashes are possible due to the turning configuration of the large vehicle in relation to the major road traffic. However, most crashes which occur during the U-turn are likely to be side swipe or rear end. In contrast, the most likely crash during a regular maneuver (non RCI) is a right angle.

5.1.2 Running Time at Cologne

Running time is shown in Figures 16 and 17. Running time only includes the time a vehicle is in motion. The distribution of running time for all categories of trucks is shown in Figure 16 at the Cologne RCI intersection. As shown, the mean running time is around 53 seconds (std = 11.3 sec). Most vehicles have a running time of 80 seconds or less.

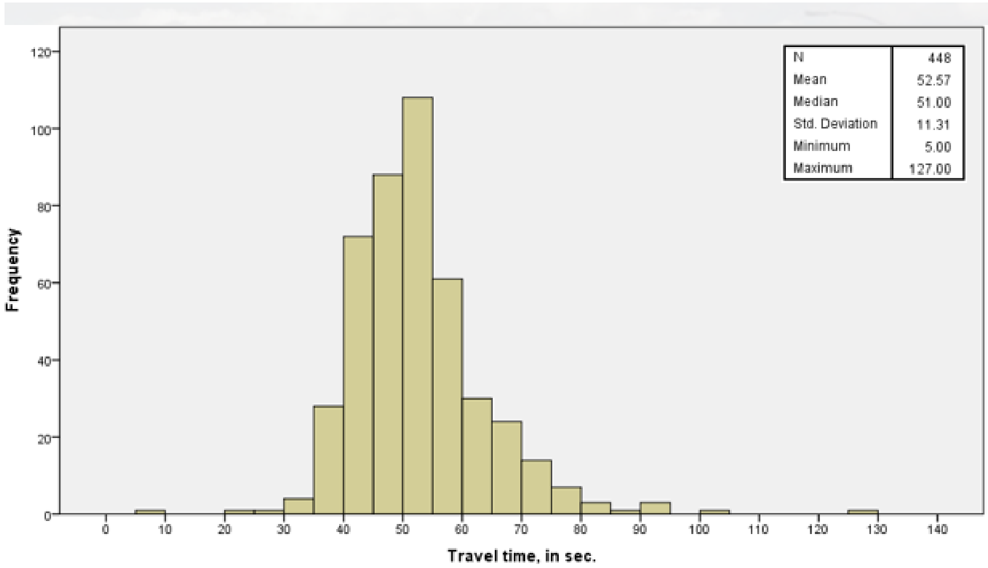

Figure 16: Distribution of running time at the Cologne RCI intersection

Figure 17 shows the running time distribution at the control intersection for all categories of trucks. As noted, the mean running time is 11 seconds (std = 10 seconds). Most vehicles had a running time of 25 seconds or less.

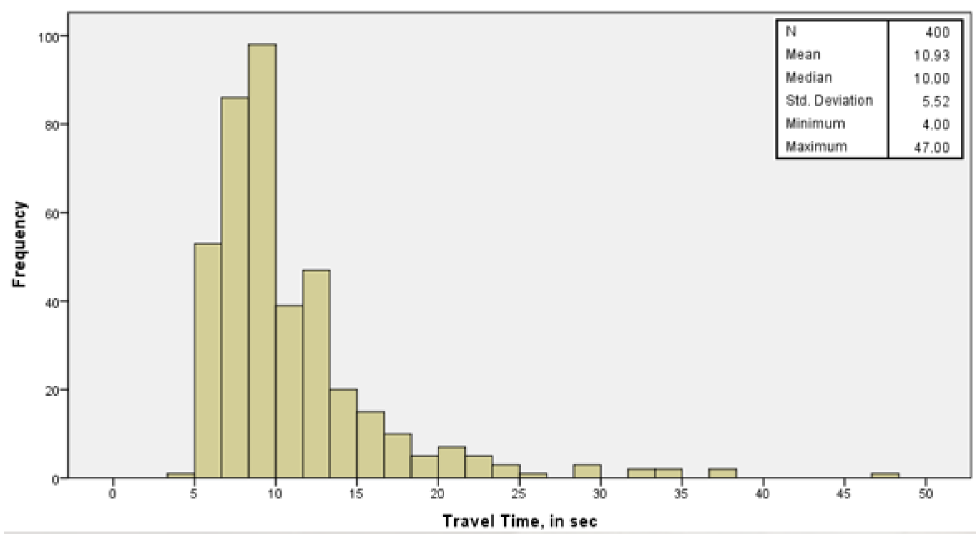

Figure 17: Distribution of running time at the Cologne control intersection

5.1.3 Queuing

Table 6 shows the queuing time at both the Cologne RCI and control sites. The average amount of time a vehicle waited at the RCI intersection before turning right as they moved towards the merging point was only 5 seconds while vehicles waited an average of nine seconds before they could make a U-turn (total wait time of 14 seconds). Vehicles at the control location spent significantly more time in queue while waiting for a gap at control sites (18 seconds).

Although the collective queue time was similar at both intersections, queue time at each individual maneuver was around half of the queue time at the control intersection. Vehicles waiting for a significant period before finding an acceptable gap are likely to accept a smaller gap.

Total travel time is also shown in Table 6 (queue plus travel time).The total of the travel and waiting time can be defined as the time elapsed between the instant trucks approached the stop bar to the instant they arrived at a defined location after which their travel time at that intersection was supposed to end. Table 6 shows that total travel time including waiting time is more than a minute for a treatment site and almost a half-minute at the control site.

Table 6: Travel time and queuing time at Cologne intersections

	RCI		Control
	at minor approach	U-turn	at minor approach
Mean Queuing Time (sec)	9.6	9.4	18.3
Moving Time (sec)	52.6		10.9
Total Travel Time (sec)	71.6		29.3

5.1.4 Evasive Maneuvers at Cologne

Evasive manuevers between turning trucks and vehicles along the major approaches were reduced for each manuever type for the Cologne locations. A total of 70 evasive manuevers were noted at the merging manuever and 48 evasive manuevers occurred at the U-turn as noted in Table 7. When normalized by number of vehicles, this represents 0.16 evasive manuevers per vehicle (70 ÷ 448 vehicles) at the merge and and 0.11 evasive manuevers per vehicle at the U-turn. A total of 131 evasive manuevers occurred at the control intersection. When normalized by number of vehicles this resulted in a rate of 0.33 evasive manuevers per large vehicle (131 ÷ 400). The fraction of vehicles involved in evasive manuevers between treatment and control intersections was compared using a test of proportions. In all cases, the proportion of vehicles with evasive manuevers at the control intersection was higher than the proportion for any type of manuever at the RCI.

It should be noted that evasive maneuvers occurred at 2 locations at the RCI and only at one location at the control intersection. When combined total evasive manuevers (118) at the RCI resulted in an average of 0.26 evasive manuevers per large truck which is still lower and statstically different ($p = 0.02$) than at the cotnrol intersections. Additionally, evasive maneuvers at the U-turn were of the most interest since there was concern that large trucks would occupy on-coming lanes for an extended period of time leading to an increased potential for crashes. The results indicate that the odds of having an evasive maneuver at a control intersection were 3.1 times more likely than at the U-turn location ($p << 0$).

Table 7: Different types of evasive maneuvers at Cologne treatment and control sites

Type of evasive maneuver	Merge		U-Turn		Control	
	Evasive Maneuvers	Large trucks involved	Evasive Maneuvers	Large trucks involved	Evasive Maneuvers	Large trucks involved
near-stop/slowed	38	26	43	28	75	53
applied brake	26	19	0	0	39	31
near crash	4	4	5	4	8	7
changed lane	2	2	0	0	9	4
total by turn type	**70**	**51**	**48**	**32**	**131**	**95**
total vehicles (trucks)	448		448		400	
Evasive maneuver/trucks involved	0.73 (p = 0.48)		0.67 (p = 0.22)		0.73	
evasive maneuvers / total trucks	**0.16 (p << 0)**		**0.11 (p << 0)**		**0.33**	

One question that was raised was whether a small number of vehicles caused a large number of evasive maneuver or whether evasive maneuvers were caused by a large number of vehicles and whether this differed between the treatment and control site. At the merge location 70 evasive maneuvers were caused by 51 vehicles (1.37 evasive maneuvers per large vehicle involved) and 48 evasive maneuvers were caused by 32 large vehicles (1.5 evasive maneuvers per large vehicle involved) at the U-turn. At the control location 131 evasive maneuvers were caused by 95 large vehicles (1.37). As noted in Table 7, the differences were not statistically significant indicating large vehicles caused evasive maneuvers at the same rate at both the RCI and control intersections.

Figure 18 shows a typical evasive manuever at the U-turn.

Figure 18: Vehicles nearly stopping during U-turn

Figure 19 shows vehicles going around a large truck which is blocking the on-coming lane in prepartion for a left turn. Several vehicles are also slowing in advance of the large truck.

Figure 19: Vehicles diverting around and slowing for truck at control

5.1.5 Number of Involved Vehicles at Cologne

The number of large vehicles involved in evasive maneuvers was reduced to assess whether a specific group of large truck contributed to more evasive maneuvers. Table 8 shows the number of vehicles involved in a evasive maneuver for the Cologne RCI by vehicle group.

Table 8: Number of major approach vehicles involved in evasive maneuvers at Cologne RCI

Truck Category	**Vehicles Recorded**	**Merge**		**U-turn**	
		Vehicles involved in Evasive maneuver	**Number of Evasive maneuvers**	**Vehicles involved in Evasive maneuver**	**Number of Evasive maneuvers**
Group 1	292	33 (1.3)	25	16 (1.2)	13
Group 2	138	34 (1.3)	24	27 (1.7)	16
Group 3	18	3 (1.4)	2	5 (1.7)	3
Total	448	70	51	48	32
Total vehicles per evasive maneuver		1.4			1.5

For instance, out of 292 Group 1 vehicles which were recorded during the study period, 25 created evasive maneuvers with other vehicles as they merged from the minor approach to the U-turn locations. Thirty three vehicles on the major approach were affected by the merging vehicles. This was an average of 1.3 vehicles per evasive maneuver (33 ÷ 25). A similar pattern was noted for Group 2 and 3 vehicles which had an average of 1.3 and 1.4 vehicles per evasive maneuver respectively. At the U-turn, 13 Group 1 vehicles created evasive maneuvers with 16 other vehicles for an average of 1.2 evasive maneuvers per vehicle. Sixteen Group 2 vehicles created 27 evasive maneuvers resulting in an average of 1.7 vehicles involved per evasive maneuver. Similarly 3 Group 3 vehicles at the U-turn affected 5 vehicles which was also an average of 1.7 vehicles per evasive maneuver.

Table 9 shows the number of vehicles affected by vehicles at the Cologne intersection.

Table 9: Number of major approach vehicles involved in evasive maneuvers at Cologne control

Truck Category	Vehicles Recorded	Vehicles involved in Evasive maneuver	Number of Evasive maneuvers
Group 1	171	28 (1.3)	21
Group 2	178	88 (1.4)	64
Group 3	51	15 (1.5)	10
total	400	131	95
Total vehicles per evasive maneuver		1.4	

A total of 400 large trucks were extracted at the control location and 95 large trucks created evasive maneuvers with 131 other vehicles during the straight or left turn maneuver. As a result, each large truck affected an average of 1.4 vehicles. Out of 171 Group 1 vehicles at the control, 21 created evasive maneuvers with 28 other vehicles for an average of 1.3 vehicles involved per evasive maneuver. Group 2 had 64 vehicles create evasive maneuvers involving 88 other vehicles for an average of 1.4 and 10 Group 3 vehicles created evasive maneuvers involving 15 other vehicles (average of 1.5 vehicles per evasive maneuver).

Overall, both the RCI and control intersection had similar number of vehicles affected. Different groups of large vehicles had similar rates of involvement.

5.2 Vermillion, Minnesota

A similar analysis was conducted for the RCI and control intersections at Vermillion. As noted in Table 4 (beginning of Section 5), the number of trucks collected at the RCI are significantly less than at the treatment site (40 versus 225) which makes it difficult to compare metrics. Due to the low sample size, this analyses did not break trucks down by category type.

5.2.1 Exposure Time at Vermillion

Table 10 shows exposure time for the Vermillion intersections.

Table 10: Total travel time and exposure time at Vermillion intersections

<table>
<tr><th rowspan="3"></th><th colspan="2">RCI</th><th>control</th></tr>
<tr><th colspan="2">exposure time (sec)</th><th rowspan="2">exposure time (sec)</th></tr>
<tr><th>merging</th><th>U-turn</th></tr>
<tr><td>mean</td><td>6.7</td><td>7.9</td><td>12.9</td></tr>
<tr><td>standard deviation</td><td>2.2</td><td>2.9</td><td>9.6</td></tr>
</table>

The exposure time during the merging and U-turn was found to be around 7 seconds as compared to 13 seconds at the control site. Total exposure time was slightly more than 1 second longer than at the control site (14.6 versus 12.9 seconds). The standard deviation for control site was larger than the RCI which indicated a significant amount of variation in exposure times.

5.2.2 Running Time at Vermillion

Figure 20 shows the distribution of running time at both Vermillion intersections. The mean running time includes the amount of time the vehicle was moving (does not include queue time). The mean running time for the Vermillion RCI intersection was 55 seconds in comparison with at the control location which was around 13 seconds.

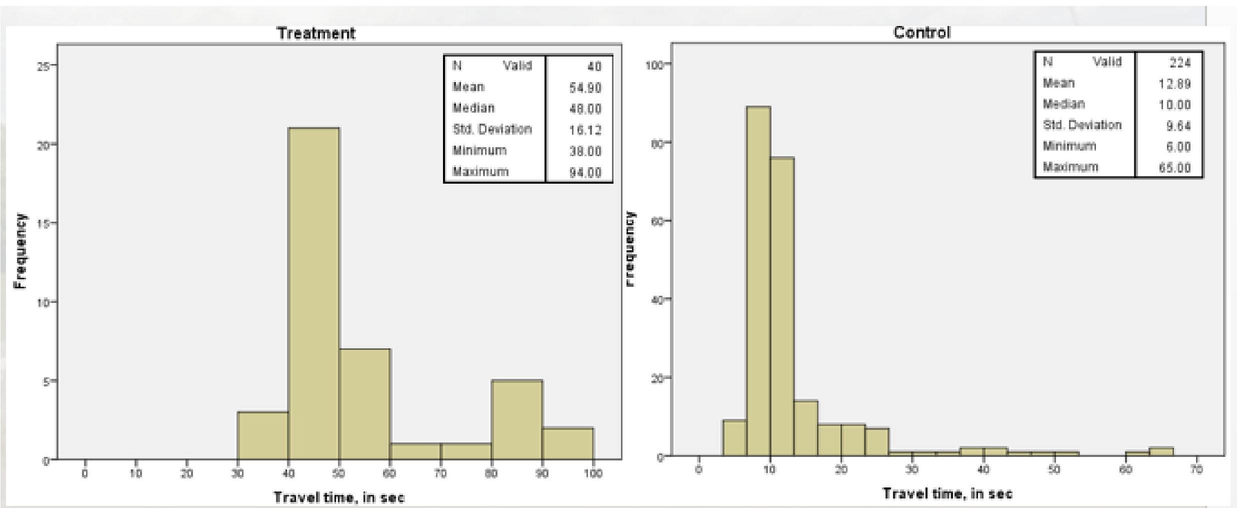

Figure 20: Distribution of travel time at treatment and control site

5.2.3 Travel and Queuing Time at Vermillion

Table 11 shows the mean travel time and the queuing time at the RCI and control intersections by turning movement.

Table 11: Waiting time at different approach for Vermillion

	RCI		Control
	at minor approach	U-turn	at minor approach
mean queuing (sec)	25.1	23.5	34.9
running time (sec)	54.9		12.9
total travel time (sec)	104.9 seconds		47.9 seconds

As noted, the average queuing time at the minor approach, while waiting to turn right, and merge to the U-turn location was 25 seconds and time in queue waiting for a gap to make a U-turn was

24 seconds on average. In contrast, the mean queue time at the control site was 35 seconds. Total travel time was significantly longer at the Vermillion RCI compared to the control site.

5.2.3 Evasive Maneuvers at Vermillion

Evasive maneuvers were analyzed at each turning maneuver location as shown in Table 12.

Table 12: Different types of evasive maneuvers at Vermillion treatment and control sites

Types of evasive maneuver	Merge		U-Turn		Control	
	Evasive Maneuvers	Large trucks involved	Evasive Maneuvers	Large trucks involved	Evasive Maneuvers	Large trucks involved
near-stop/slowed	0	0	4	3	12	7
applied brake	1	1	1	1	16	11
near crash	0	0	0	0	5	5
changed lane	6	6	1	1	51	37
total by turn type	**7**	**7**	**6**	**5**	**84**	**60**
total vehicles (trucks)	40		40		225	
evasive maneuvers / trucks involved	**1.00**		**1.20**		**1.40**	
evasive maneuvers / total trucks	**0.18 (p = 0.015)**		**0.15 (p= 0.006)**		**0.37**	

As noted, only 7 evasive maneuvers resulted at the merge point and 6 occurred at the U-turn. A much larger number of evasive maneuvers resulted from the control site (84) although most of the difference may be due to higher truck volumes. The RCI intersection analysis included 40 trucks in contrast to 225 at the control location.

The evasive maneuver rate for the merge location was 0.18 and 0.15 for the U-turn while the evasive maneuver rate for the control location was 0.37 evasive maneuvers per vehicles. The evasive maneuver rate for both movements at the RCI was 0.33 evasive maneuvers per vehicle which was still smaller than for the control intersection. However, the types of possible evasive maneuvers are much less likely to be as severe for either the merge or U-turn locations (sideswipe or rear-end versus right angle).

A test of proportion was used to compare whether the fraction of vehicles experiencing evasive maneuvers was statistically significant. As indicated, the number of evasive maneuvers per vehicle at the U-turn point was lower and statistically different than for the control site. Evasive maneuvers per vehicle at the merge point were lower, but not statistically different than the control site, and the total number of evasive maneuvers (merge and U-turn) was higher but not statistically different than control sites. Results should be used with caution given the small sample sizes.

The number of large trucks which causing the evasive maneuvers is also shown in Table 12. AS noted, 7 vehicles caused 7 different evasive maneuvers at the Merge (1.0 evasive maneuvers/large truck) and 5 vehicles caused 6 maneuvers at the U-Turn (1.2 evasive maneuvers/large truck). At the control location, 60 vehicles were responsible for the 84 evasive maneuvers (1.4 evasive maneuvers/large truck) which is slightly higher than at the RCI.

5.3 Wilmar, Minnesota

Only 15 trucks were observed at the Wilmar RCI and another 18 at the control site. No evasive maneuvers were recorded during the five day observation period. Thus for this site only exposure time and waiting time were calculated.

5.3.1 Exposure Time at Wilmar

Table 13 shows exposure time for the Wilmar intersections.

Table 13. Detail of exposure time at Wilmar treatment and control site

	RCI		Control
	Exposure Time, in sec		Exposure time, in sec
	Merging	U-Turn	
Average	6.1	6.9	17.3
Standard deviation	1.1	2.2	8.5

The exposure time during the merging and U-turn movements was 7 seconds compared to 17 seconds at the control site. Total exposure time was 13 seconds which was still less than at the control site. Standard deviation of exposure time was also significantly larger at control site than at the treatment site.

5.3.2 Travel Time at Wilmar

Table 14 shows the travel time and the waiting time at the Wilmar RCI and control intersections.

Table 14: Travel time and waiting time at Wilmar treatment and control sites

	RCI		Control
	At minor approach	**U-turn**	**At minor approach**
Avg. waiting time (sec)	7.2	7.0	11.1
running time (sec)	41.7		17.3
Total travel time (sec)	55.8 seconds		27.3 seconds

The result was similar to that from the sites in Cologne area. The total travelling time including the waiting time for a treatment site was around a minute and for a control site it was about a half of total time of the treatment site.

6. Summary and Conclusions

Within Minnesota's rural corridors, introduction of the RCI design has been successful in preventing severe crashes, however, the unusual design has been met with some apprehension from operators of agricultural equipment and large trucks. This, in combination with a resistance to the unfamiliar, has created a desire for more information regarding RCI intersection configuration safety impacts for these types of vehicles. Even though RCIs eliminate right-angle crashes, which are the most severe crossing conflicts at rural high-speed intersections, concerns have been raised that, as large trucks are required to make U-turn maneuvers, they occupy the travel lanes for longer than would be required for a left-turn or through maneuver from the minor road, and, consequently, are exposed to on-coming high-speed vehicles for longer.

In response to these concerns, this study collected and evaluated large vehicle operational behavior at a set of RCIs and at similar standard control intersections in Minnesota. The researchers collected data in 2015 using a portable video trailer array and metrics on truck turning movements at three RCI intersections in Minnesota and three similar non-RCI intersections, which were proximate to the RCI intersections. The researchers compared travel time, evasive maneuvers, and other metrics for this study.

One of the main concerns about large vehicle operation at RCIs was increased exposure during the actual U-turn. Exposure time (when a vehicle occupies a non-travel lane while waiting for a gap or to complete a maneuver) was divided into two parts for the RCI intersection (merge and U-turn). At the Cologne locations, the average exposure time at the RCI was 6.7 seconds at the merge and 7.0 at the U-turn, which was more than 4 seconds less than the average exposure time at the control intersection (10.9 seconds). The Vermillion and Wilmar sites had a much smaller sample size but showed similar results. Consequently, concerns that the U-turn causes excessive exposure as large trucks complete the maneuver are unfounded.

Collectively, the total exposure time at the Cologne RCI was 13.7 seconds, which was about 2 seconds more than at the control intersection. However, the two-stage movement (merge and U-turn) breaks the exposure into two stages, minimizing the duration that a vehicle is exposed at one time. In addition, truck exposure during the merging maneuver is more likely to result in a rear-end crash or sideswipe and exposure during the U-turn is more likely to result in a sideswipe, while a right-angle crash is the more likely result of a vehicle conflict for the control intersection. The average standard deviation time was also much greater for the control intersection, which suggests that a number of trucks had much longer exposure times.

Queue time at the Cologne RCI was about 9 seconds for both the merge and U-turn locations and about 18 seconds at the control. Although the collective queue time was similar for both types of intersections, queue time for each individual maneuver at the RCI was about half the queue time of the control intersection, and drivers waiting for a significant period before finding an acceptable gap are more likely to accept a smaller gap. Travel time, as expected, was significantly longer at the Cologne RCI (72 versus 29 seconds). The researchers found similar results for the Wilmar and Vermillion locations.

Finally, the researchers compared evasive maneuvers (situations where an on-coming vehicle has to brake, slow, or change lanes to avoid the large vehicle crossing the intersection). The average number of evasive maneuvers per large vehicle at either the merge or U-turn location were much lower than for the control intersection. Collectively, the average evasive maneuvers per large vehicle at the Cologne control site were 26% higher than for both movements at the RCI. At the Vermillion intersection, evasive maneuvers were significantly lower at the U-turn location and total evasive maneuvers at the RCI were not statistically different than at the control location.

This study found no evidence that validated concerns expressed about large vehicle operation at RCIs. Exposure time was not increased at the U-turn locations and evasive maneuvers were lower than at control locations.

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