Offset Right-Turn Lanes on State Highway Systems

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16. Abstract

This research focused on two aspects related to Offset Right Turn Lanes (ORTLs) on Nebraska state highway two-way stop-controlled intersections. The first was the crash safety and economic benefits of ORTLs compared to intersections with no right turn lanes or traditional right turn lanes. The second was driver stopping behavior at stop signs at two-way stop-controlled intersections equipped with ORTLs. The research team reviewed information from various published studies, analyzed crash data reported at 47 two-way stop-controlled intersections as well as collected and analyzed driver stopping behavior at six ORTLs in Nebraska. Traffic volume and reported crashes during 2012-2015 were statistically analyzed to assess safety effectiveness of three different types of right-turn lanes at two-way stop-controlled intersections. The three categories included intersections with ORTLs, no right turn lanes, and traditional right turn lanes. Cost-benefit analysis was conducted to ascertain viability of ORTLs. Driver stopping behavior on the intersection minor approaches (controlled by stop signs) at six intersections was examined to evaluate if drivers take advantage of the improved sight distance afforded by the ORTL at an intersection.

ORTLs had the lowest crash rates among the three intersection categories (intersections with ORTLs, no right turn lanes and traditional right turn lanes); however, the difference was statistically not significant. Average annual daily traffic was the only statistically significant factor related to crash frequency among these categories. The cost-benefit analysis indicated that compared to intersections with no right-turn lanes, ORTL intersections had an annual reduction of 0.202 crashes per million entering vehicles, which translates to $22,662 savings in crash costs per year. When compared with intersections having no right-turn lanes, a traditional right-turn lane reduced 0.0758 crashes per million entering vehicles annually or $8,504 savings in crash costs per year. Results of driver stopping behavior data analysis showed that number of through lanes, width of right-turn lane and width of the ORTL offset were statistically associated with driver's stopping position on the minor approach and overall observed drivers were in good position to take advantage of the ORTLs improved sight distance.

In general, ORTLs have safety and economic benefits compared to two-way stop-controlled intersections with no right turn lanes and with traditional right-turn lanes. Given evidence that stopped drivers are in position to take advantage of improved sight distance afforded by ORTLs, they should be considered in the design/redesign of two-way stop-controlled intersections on priority basis. This recommendation is subject to site-specific conditions, which may vary considerably. Removal of right-turn lanes created from re-striped shoulders to intersections without right turn lanes is not recommended due to potential increase in crash rates.

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costs per year. Results of driver stopping behavior data analysis showed that number of through lanes, width of right-turn lane and width of the ORTL offset were statistically associated with driver's stopping position on the minor approach and overall observed drivers were in good position to take advantage of the ORTLs improved sight distance.

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Chapter 1 Introduction

1.1 Background

Two-way stop-controlled intersections on high-speed highways in Nebraska may have a traditional right turn lane, an Offset Right Turn Lane (ORTL), or not have a right turn lane altogether on the major approaches of the intersections. An ORTL provides unobstructed sight triangle for a driver stopped on the minor approach (cross road) of the intersection by providing a raised or painted island between the mainline roadway and the right-turn lane. While lane widths depend on roadway functional class, traffic, and design speed, a minimum width of 10-ft is required for a standard right-turn lane as described in the 2010 AASHTO publication “A Policy on Geometric Design of Highways and Streets” (AASHTO 2010; commonly referred to as “the Green Book”). In addition to meeting the minimum standards, an ORTL must provide intersection departure sight distance to drivers that are stopped on the minor road approach and wish to enter or cross the major uncontrolled through traffic. However, no further detailed information is available in the 2010 Green Book and a review of the recently published 2018 edition of the Green Book also did not reveal any additional information on ORTL design.

In some instances, existing paved roadway shoulders are utilized as right-turn lanes by re-striping the pavement in Nebraska. The safety and economic benefits of these improvements are not well-documented. It is often the case with reconstruction projects that Nebraska Department of Transportation (NDOT) staff are faced with the question of whether a traditional right-turn lane or an ORTL should be provided at a two-way stop-controlled intersection on a high-speed facility. The situation is further complicated at locations where existing roadway shoulders have been re-striped into right-turn lanes; the improvised right-turn lane could be removed to restore the highway to its original design, replaced with a traditional right-turn lane, or reconstructed with an ORTL. NDOT's guidance indicates that an ORTL is generally used when recommended by the NDOT Traffic Engineering or at the discretion of the Assistant Design Engineer (ADE) (NDOT, 2012). NDOT prefers the use of a tapered ORTL with the panel between the through lanes and the right-turn lane gaining its full width only at the end of the turn lane. A parallel type, with the gap between the through lanes and right-turn lane a constant width, is a "should" design condition when spillback from the cross road is anticipated, such as when a train track runs parallel to the mainline or a congested driveway is downstream of the intersection on the cross road. Existing right-turn lanes are also reviewed on a case by case basis to determine if they should be offset, modified, removed, or remain in place unchanged. Items reviewed in the decision making process consist of existing and projected traffic volumes, crash history, Highway Safety Manual (HSM) predicted crash rates, and history of NDOT institutional knowledge of the site.

In 2012, NDOT sponsored research on the stopping behavior of motorists at two-way stop-controlled intersections showed that drivers on the cross road were stopping short of the stop bar thereby negating the advantage offered by the offset (Schurr and Foss, 2012). At the time there were relatively few ORTLs in Nebraska and observed drivers were not familiar with the operational characteristics of ORTLs. However, with the wider availability of ORTLs in Nebraska, drivers' stopping behavior on the cross road at ORTLs is worth re-investigation. The observation by NDOT is that ORTLs and drivers' behavior is particularly critical on two-lane state highways, which were the focus of this research.

1.2 Objectives

The objective of this research was to provide guidance to support NDOT's project development process and assist with decisions regarding provision of right-turn lanes at two-way stop-controlled intersections on high-speed roadways. A particular focus was on the decision making process of when to provide a right-turn lane, and when to provide an offset right-turn lane. Considerations that may impact the best-practice recommendations may include the type of project proposed, the existing or projected traffic volumes and benefit/cost analysis.

The research is intended to enable NDOT to make more informed and consistent decisions regarding provision of traditional right-turn lanes, ORTLs, or the removal of existing right-turn lanes at two-way stop-controlled intersections on state highways. The results will provide guidance on the efficient use of limited funds available for reconstruction of two-way stop-controlled intersections, assessing when ORTLs will best serve to help improve public safety.

1.3 Outline

This research was conducted in six stages. In the first stage, an initial meeting was held with the Technical Advisory Committee (TAC) members to discuss the research approach. The second stage sought out available literature with an emphasis on the policies of various state transportation agencies regarding the treatment of right-turn lanes on two-way stop-controlled intersections on state highways. Chapter 2 of this report presents a summary of the publications pertinent to this research. The third stage included descriptions of required data and the data collection process; both described in Chapter 3. The fourth stage assessed the collected data and provided analysis results as presented in Chapter 4. The fifth stage consisted of developing guidance for NDOT on best practices for right-turn lanes on two-lane high speed roadways, based on metrics such as annual average daily traffic (AADT) on major and minor approaches, right-turning traffic demand volumes, percentage of truck traffic, and crash history. The sixth and final stage of the project was the documentation of the final report, along with a presentation to the TAC members.

Chapter 2 Literature Review

NDOT considers construction of ORTLs at intersections when there is evidence that right-turning vehicles are blocking sight lines of drivers stopped on the minor approach (NDOT, 2012; Schurr and Foss, 2012). While an ORTL provides a clearer intersection departure sight triangle to the drivers stopped on the minor approach, the construction costs associated with an ORTL may not be justified based on the anticipated benefits. This is particularly true, considering that many drivers stopped on the minor approach do not stop far enough forward to take advantages of ORTLs.

2.1 Offset Right-Turn Lane

According to the National Cooperative Highway Research Program (NCHRP) Report 500, Volume 5, installing a traditional right-turn lane at intersections could potentially lead to vehicles in the right-turn lane on major roads blocking minor-road drivers' view of traffic approaching on the major road (Neuman, 1965).

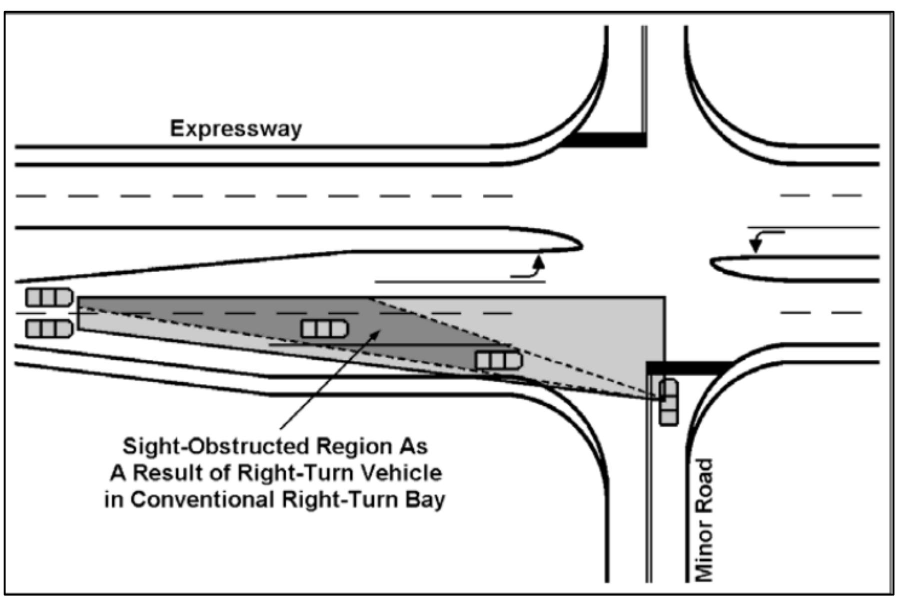

Figure 2.1 Potential Obstruction Created with Traditional RT Lane (Hochstein et al., 2007)

Maze et al. indicated that only 5 of 28 responding agencies had utilized ORTLs as a safety improvement measure at two-way stopped-controlled (TWSC) high speed roadway intersections (Maze et al., 2004). Since there are no guidelines on ORTLs in the Green Book or in other national-level manuals, guidelines for best practices are reviewed from various state agencies.

The Missouri Department of Transportation's Engineering Policy Guide suggests that ORTLs should be considered in locations with high mainline operating speeds, a large percentage of turning trucks, a unique sight distance issue or crash experience, where an investigation of crash diagrams indicates safety benefits may be obtained from an offset turn lane (MDOT, 2017). The North Dakota Department of Transportation guidelines list a few typical considerations in selecting an ORTL implementation, based on a prior recommendation of a traditional right-turn lane, which include a reduction of anticipated crash rates, a large volume of truck turning traffic, and sight distance concerns (NDDOT, 2018).

The design manual of the Iowa Department of Transportation includes recommendations for specific site constraints, such as the design of an ORTL at the base of a long or steep decline (grade = 5% or larger), or at the crest of a hill with a minimum K value (Iowa DOT, 2004). The South Dakota Department of Transportation Design Manual recommends the use of ORTLs at unsignalized intersections with a high frequency of crashes that can be attributed to limited sight distance due to (SDDOT, 2018).

Compared to other agencies, the Nebraska Roadway Design Manual has a more detailed design guidance for an ORTL (NDOT, 2012). It specifies geometric requirements for intersection sight distance. From a geometric design point of view, Schurr et al. recommends appropriate traffic control devices that meet the current Manual on Uniform Traffic Control Devices (MUTCD) guidelines to mitigate misleading visual cues and accentuate elements that reinforce the intended positive behavior at ORTL intersections for successful use of the laterally-offset right-turn auxiliary lane (Schurr and Foss, 2012; Schurr and Sitorius, 2010).

Hochstein et al. investigated the safety effects of offset right-turn lanes at two-way stop-controlled intersections on rural expressways based on a naïve before-after study, in which the counts in the after period were used to predict crash occurrence. It was found that two of the three locations showed reductions in near-side right-angle collisions (Hochstein et al., 2007). However, the study only included three sites, with fewer than 3 years of the after data. As a result, the crash frequency changes have low reliability for broad generalization to other locations.

Zhou et al. (2017) obtained traffic volumes on both major road and minor roads, and hence utilized Corridor Simulation (CORSIM) to calculate probabilities of potential conflicts. Crash histories and traffic data of four sites were used to assess relationships between waiting time, potential conflicts, and crash rates. The authors concluded that the effectiveness of an ORTL for improving safety depends upon the traffic demand volumes of the conflicting turning and through movements. Due to the small number of case study locations, the study was unable to arrive at statistically significant findings.

At some locations, the ORTL is separated by a raised channelizing island on the major approach. This design can provide an increased right-turn radius for right-turning movements. A channelized right turn with a larger radius would allow right-turning vehicles to travel at a higher speed, but would have no impact on the level of service, a measure developed by the Highway Capacity Manual, which assumes that all channelized right-turn movements incur zero delay, regardless of the radius of the channelized movement. In this case, a yield sign or an acceleration lane could be provided where the turning movements join the minor approach (McCoy and Bonneson, 1996). The channelized right turn lane can also address the issue of sight distance obstruction created by right-turning vehicles on the traditional right-turn lane instead of implementing ORTL with a large, unused pavement area (Recovery et al., 2006). However, the study by McCoy and Bonneson did not indicate any significant influence this approach had on the frequency or severity of crashes in the state of Nebraska (McCoy and Bonneson, 1996). Thus, the channelization of the right-turn lane is not incorporated as a design choice in the current study.

Overall, there is limited existing literature regarding ORTLs. While a number of state agencies have published guidelines on the implementation of ORTL, there has not yet been enough crash history data collected at these sites to develop a crash modification factor (CMF) type model similar to what is provided in the Highway Safety Manual (HSM). As such, the safety benefits shown in the literature relative to ORTL are currently anecdotal.

2.2 Driver Stopping Behavior on Stop-Controlled Approach

Offset right-turn lanes can remove the sight distance obstruction created by right-turning traffic on the traditional right-turn lane as illustrated above in figure 2.1. This benefit only works when drivers on the minor approach position themselves to optimize their view of approaching vehicles on the major roadway so they can choose an appropriate gap to safely enter the major road (Schurr and Foss, 2012). How much drivers benefit from ORTLs is an important factor on the effectiveness of ORTLs. Driver's stopping behavior at a stop sign has been studied extensively. However, neither stopping positions nor stopping behavior at intersections with ORTLs have received extensive attention.

The Nebraska Driver's Manual (NDOT, 2014) states that a driver must come to a complete stop before entering an intersection in the presence of a stop sign. The driver is required to stop at the stop line if one is present. A rolling stop is not considered a "complete stop." Since an ORTL intersection is not widely used, a driver's lack of experience with the design may impact their willingness to pull all the way forward to the stop bar.

Shurr and Foss (2012) utilized Auto-Scope to monitor drivers' stopping behaviors at both ORTL and traditional right-turn lanes in Nebraska. The research found that pickups or full-size SUVs are more likely to stop further away from the edge of the through roadway than a vehicle of another type. They also suggested that pavement geometry had an impact on driver's expectancy and performance.

2.3 Safety Effectiveness Studies of Traditional Right-Turn Lanes

With regard to the safety effectiveness of traditional right-turn lanes, a report by Federal Highway Administration (FHWA) (Harwood et al., 2003) collected geometric design, traffic control, traffic volume, and crash data from a total of 580 intersections, to conduct before-and-after studies. It concluded that only stop-controlled intersections in rural areas and signalized intersections in urban areas were found to have statistically significant improvements to safety as a result of installing right-turn lanes. Quantitatively, the installation of right-turn lanes at rural stop-controlled four-leg intersections reduced total crashes by 14% and intersection approach accidents by 27%. However, the safety effectiveness of right-turn lanes at three-leg intersections were not found to be as significant.

Poch and Mannering (1996) also suggested right-turn traffic volumes could increase the likelihood of an accident, especially without an exclusive lane. Without a dedicated right-turn lane, a 1% increase in right-turn volumes could increase accident frequencies by 0.92%. Some studies had different conclusions. For example, Vogt and Bared found that the presence of right-turn lanes at three-leg two-lane rural unsignalized intersections in Minnesota lead to a 27 percent increase in the total number of intersection-related crashes (Poch and Mannering, 1996; Vogt and Bared, 1998).

On the other hand, studies on offsetting at intersections were also examined. Though there is limited literature on ORTLs, offsetting opposing left-turn lanes showed significant improvements in safety according to a study in Lincoln, Nebraska (Naik et al, 2009). Analysis results from twelve treated intersection approaches and 36 non-treated approaches were included in the study. The estimate of safety effectiveness measure indicated a 1.5% reduction in crash rates by lane-line widening and improving sight distance.

The improved intersection sight distance for drivers waiting at the minor approach is the primary advantage of installing an ORTL. Intersections where there are frequent crashes attributed to turning vehicles with sight distance issues could potentially benefit from ORTLs. However, the lack of extensive safety data associated with this treatment prevents decision makers from assessing its effectiveness in terms of cost-benefit analysis. The current study aims to investigate these issues.

Chapter 3 Data Collection

3.1 Safety Data of Right-Turn Lanes

One method of conducting a safety assessment of right-turn lane treatments is to investigate safety data for intersections with various types of right-turn lanes. In total there are 47 intersections within Nebraska analyzed herein, categorized as locations with no right-turn lanes, with traditional right-turn lanes, and with offset right-turn lanes (ORTL). Safety data for each category was statistically analyzed, including traffic volume and police-reported crashes. Crash data from 2012 to 2015 and Annual Average Daily Traffic (AADT) collected in 2014 was used to assess the safety effect of different right-turn lane treatments. Characteristics of the intersections are shown below in table 3.1.

Table 3.1 Intersection Characteristics

Site ID	Location	Right Turn Lane Type	Intersection Type	AADT	Crash Count (2012-2015)
1	US-81 & N-41	Traditional	Four-leg	6150	5
2	US-81 & N-74	Traditional	Four-leg	6090	8
3	US-81 & N-32	Traditional	Four-leg	11355	10
4	US-81 & N-66	Traditional	T-intersection	4710	0
5	US-81 & S-85D	Traditional	T-intersection	5640	1
6	US-81 & N-8	Traditional	Four-leg	4705	8
7	US-81 & N-4 (South)	Traditional	T-intersection	6185	0
8	US-81 & N-4 (North)	Traditional	T-intersection	6235	0
9	US-81 & N-136	Traditional	Four-leg	5295	8
10	US-81 & S-85C	Traditional	T-intersection	6380	0
11	US-77 & N-91 (South)	Traditional	T-intersection	12880	11
12	US-77 & S-34D	Traditional	T-intersection	9095	0
13	US-77 & N-41 (West)	Traditional	T-intersection	9505	10
14	US-77 & N-41 (East)	Traditional	T-intersection	10120	3
15	US-77 & N-109 (South)	Traditional	Four-leg	5290	8
16	US-281 & N-58	Traditional	T-intersection	6085	0
17	US-281 & N-92 (South)	Traditional	T-intersection	6490	0
18	US-275 & N-15 (West)	Traditional	T-intersection	8270	3
19	US-26 & L-79E	Traditional	T-intersection	6710	7

Table 3.1 Continued Intersection Characteristics

Site ID	Location	Right Turn Lane Type	Intersection Type	AADT	Crash Count (2012-2015)
21	US-81 & N-64	No RT	T-intersection	9790	11
22	US-81 & N-92 (East)	No RT	T-intersection	8605	6
23	US-81 & N-13	No RT	T-intersection	11505	10
24	US-81 & S-71B	No RT	T-intersection	8750	4
25	US-81 & N-91	No RT	Four-leg	10470	22
26	US-81 & L-85F	No RT	T-intersection	4915	1
27	US-81 & S-93D	No RT	T-intersection	5405	2
28	US-77 & S-55H	No RT	T-intersection	10220	7
29	US-77 & S-55G	No RT	T-intersection	12150	7
30	US-77 & N-66	No RT	T-intersection	7335	1
31	US-75 & N-35	No RT	T-intersection	12085	20
32	US-385 & US-30	No RT	T-intersection	6380	4
33	US-34 & US-81 (South)	No RT	T-intersection	6490	11
34	US-34 & US-81 (North)	No RT	T-intersection	7245	10
35	US-30 & N-79	No RT	Four-leg	10880	18
36	US-275 & N-51	No RT	T-intersection	6245	0
37	US-275 & N-9	No RT	T-intersection	9015	3
38	US-275 & S-27D	No RT	T-intersection	7880	0
39	US-20 & N-110	No RT	T-intersection	9100	8
40	N-2 & N-67	No RT	Four-leg	9560	1
41	N-2 & S-66A	No RT	T-intersection	11615	1

Table 3.1 Continued Intersection Characteristics

Site ID	Location	Right Turn Lane Type	Intersection Type	AADT	Crash Count (2012-2015)
20	US-81 & N-22	ORTL	T-intersection	13920	6
42	Saltillo Rd. & S 56th St.	ORTL	T-intersection	5200	2
43	N-2 & S 66th St.	ORTL	T-intersection	NA	0
44	US-6 & Amberly Rd.	ORTL	T-intersection	10350	14
45	N-66 & Mahoney St. Park Entrance	ORTL	T-intersection	2835	0
46	US-77 & W Hickory Rd.	ORTL	Four-leg	NA	3
47	US-77 & Hospital Pkwy	ORTL	T-intersection	NA	0

Table 3.2 Crash Summary 2012-2016

Right Turn Lane Type	Number of Intersections	Property Damage Only	Injury	Severe Injury	Fatality	Total
No Right Turn Lanes	21	83 (35%)	34 (14.3%)	16 (6.8%)	4 (1.7%)	137 (57.8%)
Traditional Right Turn Lane	19	36 (15.2%)	24 (10.1%)	12 (5.1%)	4 (1.7%)	76 (32.1%)
ORTL	7	10 (4.2%)	11 (4.6%)	3 (1.3%)	0 (0%)	24 (10.1%)
Total	47	129 (54.4%)	69 (29.1%)	31 (13.1%)	8 (3.4%)	237 (100%)

3.2 Driver Stopping Behavior at the Intersections with ORTLs

A driver's stopping behavior on the stop-controlled approach indicates whether the driver utilized the additional sight distance afforded by the offset or not when the right-turning traffic is present in the ORTL. Six sites in Nebraska were selected for assessing drivers' stopping behaviors, which are sites 42-47 as previously listed in table 3.1. Aerial photographs of the sites are presented below, in figures 3.1 through 3.6.

Figure 3.1 Saltillo Rd. & S 56th St. (Site 42)

Figure 3.2 Nebraska Hwy 2 & S 66th St. (Site 43)

Figure 3.3 US-6 & Amberly Rd. (Site 44)

Figure 3.4 US-66 & Mahoney St. Park Entrance (Site 45)

Figure 3.5 US-77 & W Hickory Rd. (Site 46)

Figure 3.6 US-77 & Hospital Pkwy (Site 47)

Video data was collected to assess the drivers' stopping position on the minor street stop-controlled approach. Stopping positions were recorded relative to the front edge of the front bumper of a stopped vehicle, where the vehicle came to a full stop. Vehicles that performed a rolling stop were excluded from the data analysis, similar to the study described in NCHRP Report 383 (Harwood et al., 1996).

The video data collected includes a minimum of 460 video clips per site, totaling around 30 hours. The data collection periods include weekdays, weekends and public holidays (Memorial Day) to ensure that sufficient observations were collected to represent prevailing conditions. At least one twelve-hour period, including morning, noon, and evening peak traffic information was gathered for each site. In total, the data collection process yielded 7908 video clips, most of which were 30-second videos.

The cameras used to record videos were motion-activated trail cameras. Specifications of the cameras are included in Appendix 1. The trail camera was powered by both AA batteries and an internal battery, which could be charged by solar energy. SD memory cards were utilized to store the recorded videos. To prevent distracting drivers and to guarantee naturalistic observations, the cameras were mounted and concealed in traffic barrels. Field-testing was conducted on the cameras before being put into use. Video output was reviewed manually by the research team.

This study required cooperation and support from multiple sources, including NDOT's Traffic Division, state district personnel, county sheriffs and etc., for the installation of the devices. Usage of university vehicles was also required to transport personnel and equipment to the study site. Daily trips were required to replace discharged batteries or memory cards and to ensure that the recording equipment was functioning properly. Figure 3.7 shows the concealed camera equipment was located away from the shoulder to ensure clear site for drivers. Figure 3.7 shows the concealed camera equipment was located away from the shoulder to ensure clear site for drivers. Table 3.3 shows a summary of collected videos.

Figure 3.7 Installed Equipment at Site 43

Table 3.3 Summary of Collected Videos by Site

Site ID	Location	Start Date	End Date	Valid Hours	Videos	Valid Observations
42	Saltillo Rd. & S 56th St.	May 24, 2017	June 11, 2017	86	2258	1480
43	N-2 & S 66th St.	May 23, 2017	June 12, 2017	30	821	937
44	US-6 & Amberly Rd.	May 8, 2017	May 17, 2017	120	1773	651
45	N-66 & Mahoney St. Park Entrance	May 10, 2017	May 18, 2017	97	2066	611
46	US-77 & W Hickory Rd.	June 18, 2017	June 19, 2017	35	460	290
47	US-77 & Hospital Pkwy	March 8, 2017	March 10, 2017	45	530	180
Total	-	-	-	**413**	**7908**	**4149**

Data reduction of the video events yielded information that was recorded and coded into with a series of variables for use in statistical analysis. Geometric information from each site was also included with an effort to consider as many variables as possible. Table 3.4 below presents a list of variables collected and the corresponding coding. Note that none of the sites has a stop bar marking present on the stop-controlled road, so it was not incorporated into the analysis.

Table 3.4 List of Collected Variables

Variable	Information	Coding
Major.Thru	Presence of thru traffic on the major road	1 = present, 0 = no
Major.RT	Presence of right turn traffic on the major road	1 = present, 0 = no
Minor.Veh.Type	Type of the vehicle on the minor road	0=Passenger car; 1=SUV; 2=Minivan & van; 3=pickup truck;4=heavy truck; 5=Motorcycle/bicycle
Major.RT.Veh.Type	Type of the vehicle on the right-turn lane	0=Passenger car; 1=SUV; 2=Minivan & van; 3=pickup truck;4=heavy truck; 5=Motorcycle/bicycle
Duration.of.Stop.in.seconds.	Duration of Stop	Numeric value in seconds
MedianWidth	Median Width	Numeric value in inches
OffsetWidth	Offset Width	Numeric value in inches
SpeedLimit_major	Major road speed limit	Numeric value in mph
SpeedLimit_minor	Minor road speed limit	Numeric value in mph
ShoulderWidth	Shoulder width of the ORTL	Numeric value in inches
No_ofLanes	Number of Lanes in each direction on major road	Numeric value
RTLaneWidth	RT lane width	Numeric value in inches
IntersectionType	Intersection Type	1 = T-intersection, 2 = 4-leg intersection
Dis_stoptoMed	Distance from stop sign to median endpoint	Numeric value in inches

Table 3.4 Continued List of Collected Variables

Variable	Information	Coding
Dummy_(Site)	Dummy variables for site names	Ashland, Beatrice_1, Beatrice_2, Lincoln_hwy2, Saltillo, Waverly
Lighting	Daylight or dark	1 = dark, 0 = daylight
Cloudy	Weather cloudy	1 = yes , 0 = no
PartialCloudy	Weather partial cloudy	1 = yes , 0 = no
Rainy	Weather rainy	1 = yes , 0 = no
PM	Time p.m.	1 = yes , 0 = no
Stopping.position	Stopping position of observed vehicle on the minor approach	0=behind marking/shoulder; 1=ahead of RT marking/behind stop sign; 2=ahead of stop sign/behind median end; 3=ahead of median endpoint; 4=not applicable/non-stop;

The dependent variable of greatest interest is the stopping position of a vehicle on the stop-controlled minor street approach. The determination of stopping positions are divided into four zones, as shown in figure 3.8 below. The variations in geometric design across the sites was captured in the data analysis. Geometric characteristics of each site are shown in table 3.5.

Figure 3.8 Determination of Stopping Positions

Table 3.5 Geometric Characteristics of Each Site

Site ID	Distance from Stop Sign to Median Endpoint	Median Type	Median Width	Offset Width	Shoulder Width	RT Lane Width	No. of Lanes	Posted Speed Limit (Major)
42	82	Raised Concrete	176	106	113	139	1	55
43	84	Raised Concrete	58	207	48	146	2	55
44	25	Raised Concrete	47	59	97	145	2	55
45	55	Raised Concrete	58	159	53	150	1	60
46	128	Raised Concrete	59	234	58	141	2	60
47	161	Raised Concrete	58	202	54	150	2	50
unit	inch	-	inch	inch	inch	inch	-	Mph

Chapter 4 Analysis Results

4.1 Crash Analysis

4.1.1 Compare Crash Rates among Different Right-Turn Lane Types

Three kinds of right-turn lanes were considered in the data: no right-turn lane present, a traditional right-turn lane, and an ORTL. Crash rates of intersections that were installed with different right-turn lane types were assessed using crash counts from 2012 to 2016 and AADT data. As mentioned in the last section, the AADT was from year 2014. The boxplot can help to visualize the crash rates and provide some insights. As shown below, figure 5.1 illustrates the distribution of crash rates by right-turn types. The red diamond indicates the mean of crash rates in each group. There are some interesting findings revealed according to the boxplot:

- ORTLs have the lowest crash rate mean 0.24, followed by traditional right-turn lanes 0.33 and no right-turn lanes 0.41;
- The outlier in ORTL group refers to intersection No. 44, which has a much higher crash rate than other ORTL sites;
- Inclusion of a larger sample size of sites with ORTLs could lead to more findings.

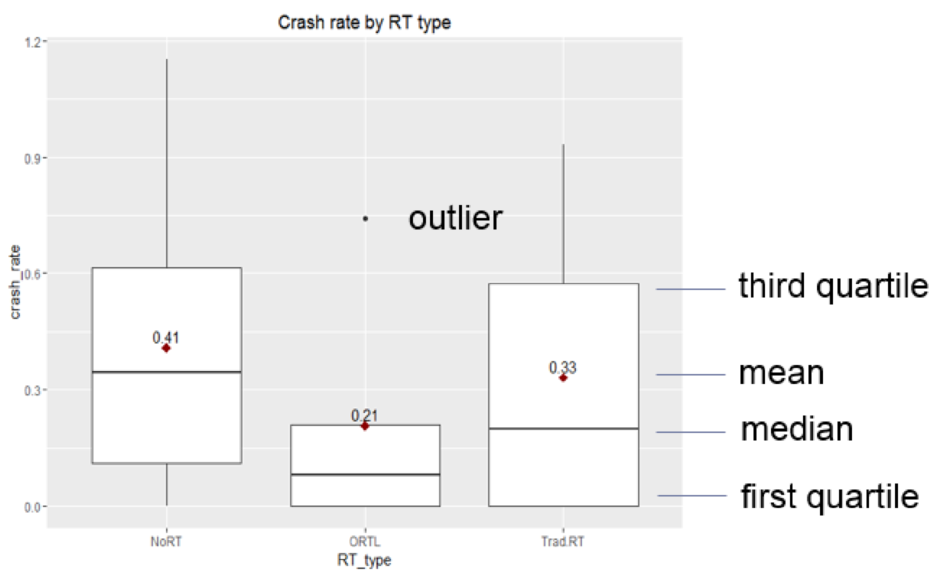

Figure 4.1 Boxplot of Crash Rates by RT Types

The means of crash rates from the three different groups are examined to determine whether there is a statistically significant difference in expected safety outcomes. The computations to test the means for equality are one-way analysis of variance (ANOVA) tests. Observations that did not have available AADT were excluded in the computations.

The ANOVA procedure tests these hypotheses at $\alpha = 0.05$ significance level:

Null hypothesis H_0: $\mu_1 = \mu_2 = \mu_3$, all the means are the same;

Alternative hypothesis H_a: two or more means are different from the others.

The results are shown in table 4.1.

Table 4.1 ANOVA Table Testing Between Right-Turn Types

	DF	**Sum Sq**	**Mean Sq**	**F value**	**p-value**
RT Types	2	0.137	0.06872	0.598	0.555
Residuals	42	4.827	0.11493	-	-

The obtained p-value is 0.555, larger than alpha level 0.05, which indicates failure to reject the null hypothesis, concluding that the mean of crash rates is not statistically different. Student's t-tests also showed the same results that no statistical difference was found between any two groups.

4.1.2 Crash Frequency Analysis

Based on the crash history data from 2012 to 2016, figure 5.2 presents the total number of crashes by year and right-turn lane types. Intersections with ORTL had the lowest crash count.

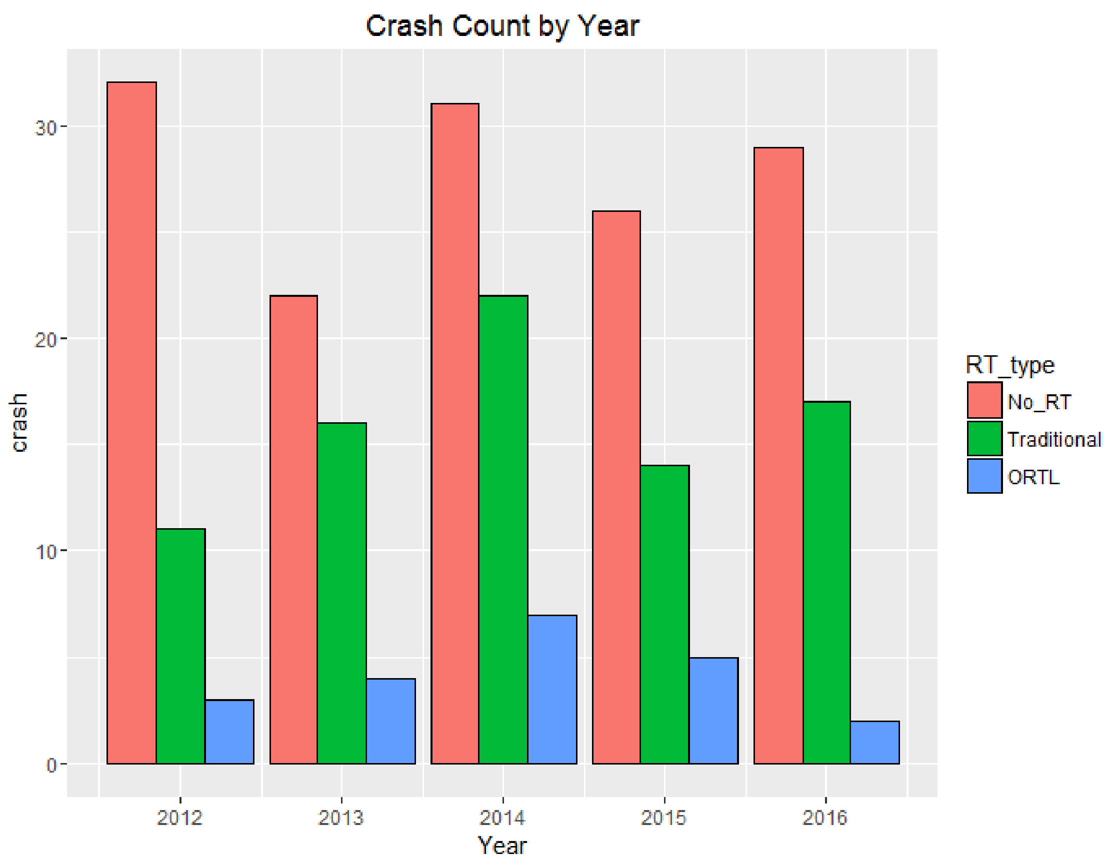

Figure 4.2 Crash Count by Year and Right-turn Lane Types

Table 4.2 Number of Studied Intersections

Right-Turn Lane Type	**Number of Intersections**	**Crashes in 2012-2016**
No Right-Turn Lanes	21	147
ORTL	7	25
Traditional Right-Turn Lane	19	82
Total	47	254

Examining the association between crash frequencies and right-turn lane types can be useful in addition to an intuitive comparison of crash frequencies. Poisson regression could be applied to create a linear equation that captures crash count as the dependent variable (Lord and Mannering, 2010). In a Poisson regression model, the probability of an intersection i having y_i crashes in a certain time period is calculated by:

$$P(y_i) = \exp(-\lambda_i)\lambda_i^{y_i} / y_i \tag{4.1}$$

Where $P(y_i)$ is the probability of intersection i having y_i crashes and λ_i stands for the Poisson parameter for intersection λ_i, as well as the expected number of crashes per year $E(y_i)$. The application of Poisson models on crash frequency analysis has been implemented for decades. However, Poisson models cannot deal with over-dispersion or under-dispersion within the data since it can produce biased results. For instance, an extension of the Poisson model that can deal with over-dispersion is the negative binomial (NB) model. The NB model assumes the Poisson parameter follows a gamma distribution and allows the variance to differ from the mean, as in:

$$Var\left[y_i\right] = E\left[y_i\right] + \alpha E\left[y_i\right]^2 \tag{4.2}$$

The NB model is one of the most frequently used methods in crash frequency modeling. However, the NB cannot handle under-dispersed data either. To determine if the data is over-dispersed or under-dispersed, the following test on Poisson model parameters was implemented.

$$Var[y] = \mu + \alpha * f(y) \qquad (4.3)$$

Null hypothesis H_0: $\alpha = 0$

Alternative hypothesis H_a: $\alpha \neq 0$

A positive α value means over-dispersion and a negative value means under-dispersion. The result was 0.355 with the p-value at 0.004. This indicated that over-dispersion was found within the data and the NB model would yield more reasonable results.

Table 4.3 Negative Binomial (NB) Model Results

Coefficients	**Estimate**	**Std. Error**	**Z value**	**p-value**
(Intercept)	-0.462	0.323	-1.419	0.156
ORTL	-0.332	0.310	-1.072	0.284
Trad_RT	0.0630	0.181	0.349	0.727
AADT	9.649e-05	3.304e-05	2.921	0.00349

Based on the NB model parameter results, only AADT was statistically significant. No statistical significance was found for right-turn lane types, which is consistent with the crash rate comparison. It also indicated that crash frequency increases along with AADT since higher traffic volume would lead to more exposure.

4.1.3 Crash Severity Analysis

The severity of a crash is usually classified into several categories describing the injury level of the most severely injured highway user involved in the crash. Injury levels can range from the least severe (property damage only) to fatalities. Various methodological techniques have been applied to analyze crash severity data. As in this study, the dependent variable of crash injury severity is a nominal response variable. Thus the multinomial logit model was adopted to model crash injury severity. The probability of a crash being classified with severity outcome i is written as:

$$P_n(i) = P\left(U_{ni} \geq U_{nj}\right) \tag{4.4}$$

Where U_{ni} is a defined linear function determining the injury severity, and i is a set of I possible mutually exclusive severity categories for observation n. Thus:

$$U_{ni} = \beta_i X_{ni} + \varepsilon_{ni} \tag{4.5}$$

Where β_i is a vector of estimable parameters, X_{ni} is a vector of observed characteristics that are associated with injury severity; ε_{ni} is a random error term that accounts for unobserved effects. ε_{ni} is assumed to be identically and independently distributed as generalized extreme value distributed. Hence, the multinomial logit model can be described as:

$$P_n(i) = \exp(\beta_i X_{ni}) \Big/ \sum_i \exp(\beta_i X_{ni}) \tag{4.6}$$

Even though the multinomial model does not account for the ordering of the dependent variable, it is more flexible, allowing the independent variables to have a non-monotonic effect on the dependent variable. Injury severity levels were categorized as: fatality coded as 3, serious injury coded as 2, visible injury as 1, and property damage as 0.

Pertaining to the model selection, a process of stepwise selection was applied, in which the variables are added or removed at each level (Liao et al., 2008). In this study, Akaike information criteria (AIC) evaluated the significance of all existing variables with the addition of new variables. Existing variables that become superfluous with regard to other variables can also be removed in the stepwise process. Using AIC as the criteria, the selected model yielded is as follows:

Table 4.4 Multinomial Logit Regression Results for Crash Severity

Coefficients	$\log(\hat{\pi}_1/\hat{\pi}_0)$	$\log(\hat{\pi}_2/\hat{\pi}_0)$	$\log(\hat{\pi}_3/\hat{\pi}_0)$	**LR Chi-sq**	**p-value**
Intercept	-1.284	-2.083	-4.111	-	-
ORTL	1.165	0.331	-20.479	5.829	0.120
Trad_RT	0.434	0.362	0.609	2.039	0.564
Rear_end_acc	-0.084	-28.299	-11.899	8.288	0.040
Angle_acc	0.632	0.959	1.761	7.824	0.050
Alcohol_related	2.168	2.571	2.585	12.269	0.007
Residual: 455.3; AIC: 491.3					
$\hat{\pi}_0$: *PDO*, $\hat{\pi}_1$: *injury*, $\hat{\pi}_2$: *severe injury*, $\hat{\pi}_3$: *fatality*					

The LR Chi-sq is the Likelihood Ratio (LR) Chi-Square test that for the three equations at least one of the predictors' regression coefficient is not equal to zero. Hence, the p-value was compared to alpha level at 0.05. The results showed marginal evidence that rear-end and angle crash types were significant in the models. However, the 'alcohol related crashes' coefficient showed significance. If a crash were alcohol-related rather than non-related, the multinomial log-odds for involving fatality in the crash would expect to increase by 2.585 units while holding all other variables in the model constant.

Because the log-odds are being modeled directly in a multinomial regression model, relative risk ratios allow an easier interpretation that calculates the exponentiated value of the logit coefficients.

Table 4.5 Relative Risk Ratios of Multinomial Coefficients

Coefficients	$rr\left(\hat{\pi}_1/\hat{\pi}_0\right)$	$rr\left(\hat{\pi}_2/\hat{\pi}_0\right)$	$rr\left(\hat{\pi}_3/\hat{\pi}_0\right)$
ORTL	3.207**	1.393	0.000***
Trad_RT	1.544	1.436	1.838
Rear_end_acc	0.919	0.000***	0.00001
Angle_acc	1.881*	2.608**	5.821
Alcohol_related	8.745***	13.076***	13.265***
			*Note: *p<0.1; **p<0.05; ***p<0.01*
			$\hat{\pi}_0$: *PDO,* $\hat{\pi}_1$: *injury,* $\hat{\pi}_2$: *severe injury,* $\hat{\pi}_3$: *fatality*

From table 4.5, it can be indicated that keeping all other variables constant, if the alcohol-related variable increases one unit, the crash is 13.265 times more likely to be associated with fatality (the risk or odds is 1227% higher). Similarly, holding other variables constant, ORTL intersection-related crashes are 100% times less likely to be associated with fatality. Rear-end accidents were found to be negatively related with severe crashes while angle accidents indicated relationships with both injury and severe injury. However, the dataset used here for ORTL was relatively small. Including more instances would possibly reveal more information regarding crash injury severity.

4.2 Driver Stopping Behavior Analysis

For this section, six sites in Nebraska were selected for assessing drivers' stopping behaviors, which are sites 42-47 as previously listed in table 3.1. As indicated in figure 4.3, highway users' stopping positions could be categorized into four levels except for non-stopped vehicles. 47.8% of total observations were non-stopped vehicles, including rolling stops. Among the vehicles that did stop, 80% of the drivers stopped at positions 1 and 2, as shown in figure 4.4.

Figure 4.3 Overall Stopping Positions

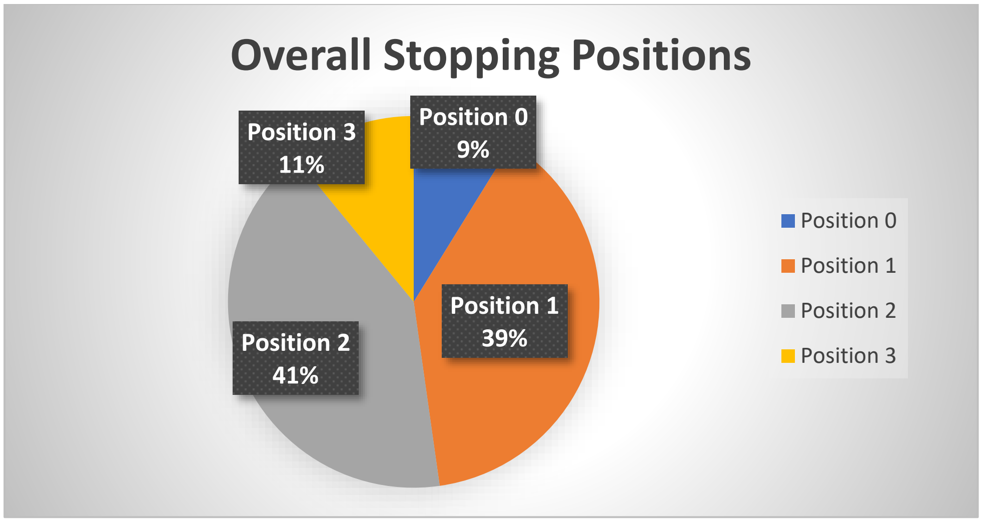

Figure 4.4 Overall Stopping Positions of Vehicles that Stopped

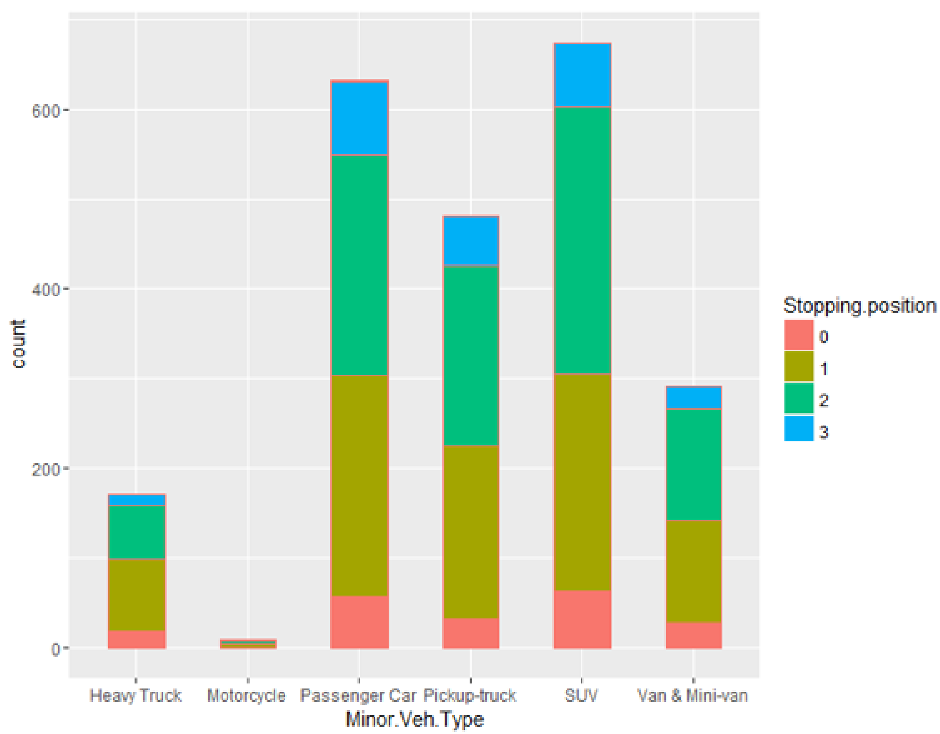

Figure 4.5 Vehicles Stopped on the Minor Approach

Table 4.6 Percentage of Vehicle Types among Vehicles Stopped on the Minor Approach

Type of vehicle on minor approach	Percentage of stopping at position 2 or 3
Overall	52.23%
Heavy truck	42.11%
Pickup truck	53.22%
Passenger Car	51.98%
SUV	54.75%
Van	51.20%

As shown in table 4.6, 52.23% of vehicles tended to stop at positions 2 and 3, which are ahead of the stop sign, while only 42.11% of heavy trucks preferred to stop at positions 0 and 1. This might be because heavy trucks can provide better sight and requires more space to operate.

Table 4.7 Percentage of Vehicle Types When there is Traffic in the Major RT Lane

Type of vehicle on RT approach when present	Percentage of stopping at position 2 or 3
Overall	44.83%
Heavy truck	57.14%
Pickup truck	44.44%
Passenger Car	45.98%
SUV	41.49%
Van	42.5%

Another interesting finding is that, when there was a heavy truck in the right-turn lane on the major approach, vehicles on the minor approach were more likely to stop at a more forward position, as indicated in table 4.7.

Additionally, a multinomial logistic regression model was applied to model stopping positions as the dependent variable. Thus, the driver's stopping behavior can be analyzed in a similar manner as in section 4.1.3. The results are shown in tables 4.8 and 4.9.

Table 4.8 Multinomial Logit Regression Results for Stopping Positions

Coefficients	$\log(\hat{\pi}_1/\hat{\pi}_0)$	$\log(\hat{\pi}_2/\hat{\pi}_0)$	$\log(\hat{\pi}_3/\hat{\pi}_0)$	**LR Chi-sq**	**p-value**
Intercept	-21.923	-15.600	24.541	-	-
No. of Lanes	0.109	-0.215	-4.978	38.129	2.655e-08
DisStoptoMed	0.00677	0.0174	0.0154	2.693	0.441
RTLaneWidth	0.159	0.116	-0.175	11.695	0.00851
OffsetWidth	-0.00396	-0.00737	0.0408	11.422	0.00965
Residual: 1330.954; AIC: 1360.954					
$\hat{\pi}_0, \hat{\pi}_1, \hat{\pi}_2, \hat{\pi}_3$: *Stopping positions 0,1,2,3*					

As shown in table 4.8, “type of right-turn lanes” was not statistically significant in the estimated parameters. Number of lanes, right-turn lane width and offset width were significantly associated with driver’s stopping position. To investigate their effectiveness in more detail, relative ratios were examined as well.

Table 4.9 Relative Risk Ratios of Multinomial Coefficients pt.2

Coefficients	$rr(\hat{\pi}_1/\hat{\pi}_0)$	$rr(\hat{\pi}_2/\hat{\pi}_0)$	$rr(\hat{\pi}_3/\hat{\pi}_0)$
No. of Lanes	1.115	0.807	0.007**
DisStoptoMed	1.007	1.018*	1.016
RTLaneWidth	1.172***	1.123***	0.840***
OffsetWidth	0.996	0.993	1.042***
*Note: *p<0.1; **p<0.05; ***p<0.01*			
$\hat{\pi}_0, \hat{\pi}_1, \hat{\pi}_2, \hat{\pi}_3$*: Stopping positions 0,1,2,3*			

The relative risk ratio results show an increased number of lanes would discourage drivers to stop at position 3, which is stopping beyond the stop sign and the raised median. The reason could be that more lanes usually relates to heavier traffic. Drivers were less likely to stop close to busy traffic. On the other hand, with increased right-turn lane width, drivers were more likely to stop at positions 1 and 2, instead of position 3. Offset width was also significant in position 3 vs. position 0, but the impact was relatively small. Overall, it seemed that drivers were positioned to take advantage of the improved sight distance from ORTLs

4.3 Cost-benefit analysis

Since the type of right-turn lane was not statistically significant in the crash frequency model nor in the crash injury severity model, a cost-benefit analysis can help quantify the effectiveness of constructing an offset right-turn lane.

Assuming installing an offset right-turn lane cost approximately $316,000 and a 20-year life-cycle at 2.8% discount rate, the estimated annual cost would be approximately $20,800 (Persaud et al., 2010). According to the FHWA comprehensive crash cost estimates, the inflated estimate without regard to injury severity for 2017 is $112,188 (Council et al., 2005). Based on the crash rate results in this study, compared to intersections with no right-turn lanes, ORTL intersections have an annual reduction of 0.202 crash per million entering vehicles, which translates to a reduction of $22,662. Compared to intersections with traditional right-turn lanes, ORTL intersections can save $14,158 annually per million entering vehicles. When compared with intersections including no right-turn lanes, a traditional right-turn lane can reduce 0.0758 crash per million entering vehicles annually, which translates to $8,504 cost reduction. Among the three groups, adding an offset right-turn lane to an intersection without any right-turn lanes can be beneficial. In addition, the criteria of reaching one million entered vehicles should also be considered in this manner.

Assuming crash injury severity is also considered in the decision making process, the estimated fatal crash cost is $3,960,000. The estimated crash costs for severe injury, injury, and PDO are $276,000, $92,000 and $6,500, respectively. The annual reductions of ORTL opposed to no right-turn lane and traditional right-turn lane would be $175,248 per site and $172,247 per million entering vehicles. The variations are much larger because the ORTL intersections in this study did not have any fatal crashes in the specific period, as shown in table 3.2. Inclusion of more data may lead to a different outcome.

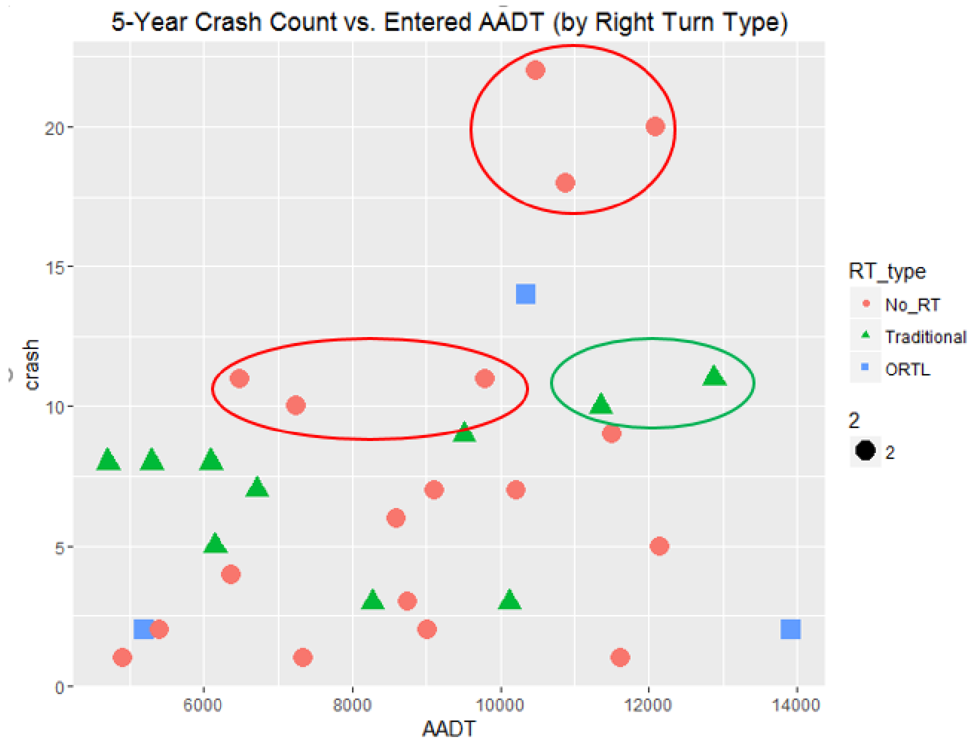

Figure 4.6 Five-year Crash Count vs. Entered AADT

Overall, the benefit of transforming an existing intersection to an ORTL intersection becomes larger with history of higher crash frequency. By examining the five-year crash counts studied sites and entered AADT, certain intersections with relatively higher crash frequency (shown in circles) can consider reconstruction or alternative safety measures, as shown in Figure 4.6. Note that even though Study Site No. 44 has an offset for the right-turn lane, the geometric design did not meet the standards in MUTCD. Thus, it is suggested the crash history at this site should be investigated besides the inclusion of an offset right-turn lane.

Chapter 5 Concluding Remarks

This report aimed to investigate two aspects related to offset right turn lanes (ORTLs) in state highway systems; the first was the safety and economic benefits of the improvements, and the second was driver stopping behavior at the stop sign in these intersections.

Several research methods were implemented, including literature search, statistical crash analysis, and cost-benefit analysis. Limited literature focused on the safety and economic benefits of ORTLs while comprehensive guidance and best practices for decision makers are in need. Data from 47 intersections in Nebraska, including traffic volume and crash history from 2012 to 2015 has been statistically analyzed to assess safety effectiveness. These study sites were categorized as intersections with no right-turn lanes, with traditional right-turn lanes, and with offset right-turn lanes. In addition, data on driver stopping behavior was collected from 6 ORTL intersections to evaluate how much the drivers take advantage of the offset. At last, cost-benefit analysis of ORTL versus the other two types of intersections were performed.

The current study found ORTLs have the lowest crash rates, compared to intersections with traditional right-turn lanes and intersections with no right-turn lanes. However, the difference was not statistically significant. Only AADT was found to be the significant contributing factors in the crash frequency modeling results. In terms of driver stopping behavior, number of lanes, right-turn lane width and offset width were found significantly associated with driver’s stopping position. The study also suggested that, holding other variables constant, ORTL intersection-related crashes are 100% times less likely to be associated with fatality. However, the data set used here for ORTLs was relatively small. Including more instances would possibly reveal more information regarding crash injury severity. Lastly, if considering average crash rates, cost-benefit analysis suggested constructing ORTLs would have an annual estimated reduction of $14,158 per million entering vehicles compared to traditional right-turn lanes, and $22,662 compared to intersections with no right-turn lanes.

In conclusion, ORTLs appear to have safety and economic benefits compared to two-way stop-controlled intersections with traditional right-turn lanes and no right-turn lanes. They should be considered for construction with appropriate research and design, where feasible. Removal of right-turn lanes created from re-striped shoulders to intersections without right turn lanes is not recommended due to potential increase in crash rates.

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Appendix

The motion detector camera used in this study has a built-in solar panel to charge its internal rechargeable battery. The fastest trigger speed is 0.07 sec. Captured HD videos are in color by day & black-and-white by night. It saves videos and photos to an SD/SDHC card up to 32 GB for subsequent analysis. Mount height is 1/4"-20 tripod. Dimension specifications are 3.8" W x 6.9" H x 3.9"D (9.6 cm W x 17.5 cm H x 9.9 cm D).

Figure A.1 Motion detector camera