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Title: Developing Safety Performance Functions for 4-leg Single-lane Roundabouts Based on Oregon Data: A Case Study

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Roundabouts have become an alternative for traditional intersections due to the safer operational performance. Previous research has provided crash modification factors (CMFs) as a criterion based on before-after studies as to evaluate the safety performance of roundabouts. One drawback of assessment based on crash modification factors, however, is that a before-after study includes too many variations at a time that it only provides a general idea of the safety performance for roundabouts.

Since the industrial world is interested in the safety outcome of converting traditional intersections to roundabouts, safety performance functions (SPFs) will provide more specific details on estimating crashes than that of crash modification factors.

This thesis will adopt a similar methodology that has been used in the current *Highway Safety Manual* (HSM) (1) to develop safety performance functions for roundabouts based on Oregon data. The outcome of this thesis will help the Oregon Department of Transportation (ODOT) to evaluate existing roundabouts in the State of Oregon. Furthermore, this thesis will function as an additional case study from Oregon to contribute to the national effort of evaluating the safety performance of roundabouts.

Developing Safety Performance Functions for 4-leg Single-lane Roundabouts Based on Oregon Data: A Case Study

by

Jianfei Zheng

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jianfei Zheng, Author

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I want to thank my beloved parents who are always there for me.

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DEVELOPING SAFETY PERFORMANCE FUNCTIONS FOR 4-LEG SINGLE-LANE ROUNDABOUTS BASED ON OREGON DATA: A CASE STUDY

1. INTRODUCTION

1.1. A Brief History of Roundabouts

The United State introduced the traffic circle as a type of intersection around 1905 when William Phelps Eno designed one of the first circles, known as the Columbus Circle in New York City. The idea behind these traffic circles was helping to merge high speed vehicles. Since the entering traffic had the priority to negotiate through traffic circles at that time, drivers experienced severe crashes and congestion in many places. The performance of traffic circles in terms of both safety and operation was all negative (2).

Intersections that are currently called roundabouts refer to the modern roundabout that was developed in the United Kingdom as a way to rectify previous drawbacks of traffic circles. The United Kingdom adopted a rule that required entering traffic to yield to circulating traffic. In addition, roundabout construction included smaller footprints so that these modern roundabouts provided adequate horizontal curvature for slowing down both entering and circulating traffic speeds (2).

Since roundabouts appeared to be associated with a safer performance than conventional intersections, research efforts have focused on clarifying the relationship between roundabouts and conventional intersections. The implementation of roundabouts in the United States indicates that the conversion of roundabouts from traditional intersections reduces total crashes, especially injury crashes in a wide range of environmental settings (3).

1.2. Statement of the Problem

Previous research efforts developed crash modification factors (CMFs) as a way to evaluate the safety performance of roundabouts that were converted from traditional intersections. The CMFs give a safety relationship between pre-construction of the roundabout condition and post-construction based on a before-after study. The key problem with this approach for this study is that CMFs might provide a way to evaluate the safety benefits resulting from a conversion process. This type of CMF, however, cannot predict safety performance of a newly constructed roundabout facility. In other words, this method can only evaluate the condition where a pre-roundabout traditional intersection previously existed. Consequently the results from a before-after study can be misleading. The CMFs derived from a before-after study actually give a comparison between two concepts: the modern roundabout and the traditional intersection. The interpretation of CMFs is ambiguous since the conversion from a traditional intersection to a roundabout also involves many other changes. The safety benefits cannot be attributed to a specific mitigation of the intersection, since the construction of a roundabout changes the entire nature of the intersection.

The *Highway Safety Manual* (HSM) provides safety performance functions (SPFs) and derived CMFs for traditional intersections based on a cross-sectional study. This study adopts mathematical regression methodologies to build relationship between crash rates and traffic exposures and geometric features of the intersection. The CMFs that were derived for the HSM, based on corresponding regression functions, have reasonable interpretations and inherent advantages that capture the cause and effect (4).

The quantitative SPF for roundabouts is still unknown and requires further development efforts for the HSM. The goal of this thesis, therefore, is to develop SPFs for roundabouts based on data from Oregon.

The outcome of this thesis will help the Oregon Department of Transportation (ODOT) to develop SPFs for the State of Oregon. This thesis will also contribute to the national cooperated efforts for the HSM in developing SPFs of roundabouts as a case study from Oregon.

1.3. Organization of This Thesis

In this thesis, Section 2 summarizes the results of previous research efforts so as to provide a comprehensive review on the safety performance of roundabouts both within and outside of the United States. Section 3 reviews the two main methodologies that have been applied to the field of assessing the safety performance. The author then gives a brief discussion on each methodology and makes a comparison between these two approaches so as to indicate the one methodology that this thesis will adopt. Section 4 summarizes the data collection and reduction process that provide the raw data is used in this thesis for developing SPFs. Finally, Section 5 incorporates the results from data analyses for developing SPFs for roundabouts and compares these results with models from HSM. The thesis concludes with a conclusions section, Appendix items, and a list of references used in this document.

2. LITERATURE REVIEW

The successful implementation of roundabouts in Europe and Australia and the associated operational and safety benefits of those roundabouts has been a catalyst for constructing roundabouts in the United States. In many instances, new roundabouts have been constructed at locations where traditional intersections were previously constructed. Though overall the construction of these unique intersections appears to offer substantial safety benefits at select locations, there is a need to quantify when and where roundabouts will directly contribute to consistent crash reductions. Though international roundabout safety research appears promising, the modern roundabout constructed in the United States requires additional safety assessment due to differences in intersection design, driving conditions, drivers' knowledge, and drivers' expectancy.

The recently released HSM includes SPFs and corresponding CMFs for conventional intersections. However, the HSM did not include roundabout SPFs. Developing SPFs for roundabouts is of interest to reveal the nature of roundabout safety so as to quantify the safety effect of roundabouts.

Most of the previous literature focused on the safety effects of converting a traditional intersection to a roundabout. The results from literature suggested a wide range of potential safety effects.

2.1. Converting Traditional Intersections to Roundabouts

Several researchers have assessed the overall safety effects of converting traditional intersections to roundabouts. Retting et al. (2001) (5), for example, determined that a conversion of traditional intersections to roundabouts can provide a 38 percent reduction in total crashes (CMF = 0.62) and a 76 percent reduction (CMF = 0.24) in injury crashes. Their study evaluated 24 intersection locations and included an empirical Bayes before-after assessment. They also identified an expected reduction in fatal and serious injury crashes of approximately 90 percent (CMF = 0.10).

Rodegerdts et al. (2007) (3) performed an empirical Bayes before-after study for 55 intersections and estimated that the conversion of traditional intersections to roundabouts provided a 35.4 percent reduction in total crashes (CMF = 0.646) and a 75.8 percent reduction in injury crashes (CMF = 0.242). Similarly, Persaud et al. (2001) (6) determined the conversion from traditional intersections to roundabouts had a 40 percent total crash reduction (CMF = 0.60) and an 80 percent injury crash reduction (CMF = 0.20).

Isebrands (2009) (7) specifically focused on rural high-speed traditional intersection conversions to roundabouts at 17 sites in the United States. This before-after study identified an expected reduction of 52 percent in total crashes (CMF = 0.48) and an 84 percent reduction in injury crashes (CMF = 0.16). Isebrands also assessed crash severity and identified a 100 percent reduction in fatal crashes (CMF = 0.00), an 89 percent reduction in incapacitating crashes (CMF = 0.11), an 83 percent reduction in non-incapacitating crashes (CMF = 0.17), and no reduction in property damage only crashes. Isebrands also assessed changes in expected crash types and determined a reduction in angle crashes of 86 percent (CMF = 0.14) and rear-end crashes of 19 percent (CMF = 0.81). This research effort also determined an increase in fixed-object crashes of 320 percent (CMF = 4.20) and a 140 percent increase in sideswipe crashes (CMF = 2.40).

Collectively the overall effect of converting a traditional intersection to a roundabout resulted in a reduction in total crashes of approximately 35 to 40 percent, while conversions at high speed rural locations further reduced crashes to a total of approximately 52 percent.

2.2. Converting STOP-Controlled Intersections to Roundabouts

STOP-controlled intersections, when converted to roundabouts, may have varying safety effects depending on the number of legs with STOP control, the number of lanes for the roundabout, and the region (urban, suburban, or rural) where the intersection is located.

Persaud et al. (2001) (6) observed a 72 percent reduction (CMF = 0.28) in the number of total crashes at urban locations where STOP-controlled intersections were converted to single-lane roundabouts. They also noted an 88 percent reduction (CMF = 0.12) in injury crashes at the same locations. For similar STOP-controlled to single-lane roundabout conversions in rural areas, Persaud et al. observed crash reductions of 58 percent (CMF = 0.42) in the number of total crashes and 82 percent (CMF = 0.18) in the number of injury crashes. They did not observe any reduction in total or injury crashes for STOP-controlled intersection conversions to multi-lane roundabouts (CMF = 1.00).

Rodegerdts et al. (2007) (3) evaluated 10 sites where all-way STOP-controlled intersections were converted to roundabouts and observed a 3.3 percent increase in total crashes (CMF = 1.033) and a 28.2 percent increase in injury crashes (CMF = 1.282). Rodegerdts et al. separately assessed the conversion of two-way STOP controlled intersections to roundabouts and observed a 44.2 percent reduction in total crashes (CMF = 0.558) and an 81.8 percent reduction in injury crashes (CMF = 0.182) at all conversion sites. When they further assessed urban, suburban, and rural they identified expected crash reductions ranging from 11.6 percent up to 78.2 percent depending on unique intersection and roundabout configurations. This wide variability reinforces the hypothesis that unique site features may be critical to the expected safety benefits of the conversion.

2.3. Converting Signalized Intersections to Roundabouts

United States research regarding the conversion of signalized intersections to roundabouts is limited. Persaud et al. (2001) (6) evaluated roundabouts converted from signalized intersections and observed a 35 percent reduction in total crashes (CMF = 0.65) and 74 percent reduction in injury crashes (CMF = 0.26). Rodegerdts et al. (2007) (3) evaluated 9 signalized intersection conversions to roundabouts (4 in suburban regions and 5 in urban regions) and observed a 47.8 percent reduction in total crashes (CMF = 0.522) and a 77.7 percent reduction in injury crashes (CMF = 0.223); however, the small sample size cannot be assumed representative of the larger intersection population.

2.4. Recent International Research

Over the years, international researchers have conducted a variety of roundabout research assessments. Recent international studies can also help to provide insight into the expected safety performance for roundabouts at locations with speed variations as well as non-motorized users. De Brabander and Vereeck (2007) (8) conducted a before-after empirical Bayes study and determined that the overall effect of implementing roundabouts was positive. Overall, they found a 39 percent reduction in injury crashes (CMF = 0.61) with a 17 percent reduction in serious injury crashes (CMF = 0.83) and a 38 percent in minor injury crashes (CMF = 0.62). Their results varied considerably with changes in speed limits on major street and minor street as well as the “before” traffic control configuration. Generally, the higher the speed limit combination of the “before” major and minor street approaches resulted in the most effective “after” conditions. One important observation by de Brabander and Vereeck was that the number of injury crashes involving vulnerable road users, such as pedestrians and bicyclists, was found to increase on roundabouts following conversions from signalized intersections.

Daniels et al. (2008) (9) similarly noted an increased risk associated with injury crashes involving bicyclists at locations where roundabouts replaced traditional intersections. The before-after study with the empirical Bayes method for 91 roundabouts in Flanders, Belgium indicated that when converting traditional intersections to roundabouts, the overall effects on injury crashes and fatal crashes involving bicyclists were increased by 27 percent (CMF = 1.27) and 44 percent (CMF = 1.44), respectively.

Subsequently, Daniels et al. (2009) (10) determined that safety performance involving bicyclists varied with different types of bicycle facilities. They evaluated roundabout locations with 4 typical bicycle facilities: mixed traffic, bicycle lane within roundabout, separate bicycle path, and grade separated bicycle path. For total injury crashes, only roundabouts with bicycle lanes experienced a poorer safety performance.

In the Netherlands, Fortuijn (2009) (11) performed two before-after studies to measure safety performance on single-lane roundabouts converted from yield controlled intersections for different periods of time (39 intersections in the period 1991-2002 and 29 intersections in the period 1995-2002). They observed reductions in total injury crashes ranging from 78.7 percent (CMF = 0.213) to 68.1 percent (CMF = 0.319).

3. METHODOLOGY

The use of statistical methodologies provides a good approach to quantify the expected safety performance of roundabouts. Two methodologies that the transportation safety analysis community commonly uses include the before-after study and the cross-sectional study.

3.1. A Before-After Study

The before-after study serves as the most commonly used methodology to assess the safety effects of treatments. The simplest approach for using a before-after study for safety performance, known as a naive before-after study, is to compare the crash rate or crash frequency for a group of traffic crashes "before" and "after" the deployment of a safety treatment. This simple before-after study strategy might not fully capture the cause and effect of the treatments, since traffic volume is dynamic over time and other factors may also influence safety performance of the facility. For instance, it could be difficult to determine whether the safety effects resulted from the change of traffic volume or the deployed treatment at a location where a traffic calming treatment is constructed. The traffic calmed facility might reduce crashes as the result of reducing traffic speeds on the roadway. The reduction on crashes might also be attributed to the fact that the roadway experiences less traffic exposure due to normal systemic changes in traffic volumes.

To avoid this ambiguity about the interpretation of safety effects determined for naive before-after studies, the use of univariate analysis can be used in a manner similar to that commonly applied to biology and other fields in evaluating the effects of one treatment. In transportation safety analysis this before-after study can include the following two groups of facilities:

- Treatment group, and

- Comparison group.

The treatment group includes facilities where a treatment has been deployed. The comparison group includes facilities that serve as a control group and are similar to the treatment group sites but without any treatment deployed.

The before-after study includes two time periods:

- Before-treatment period, and
- After-treatment period.

The assumption of a before-after study is that the treatment group and comparison group share similar traffic exposures and geometric features during both "before" and "after" periods. Crash frequency from both groups then should be similar if countermeasures are not applied to the treatment group. The difference in crashes, if any, then could be attributed to any treatments applied to the treatment group during the "after" period (12). The basic strategy of a before-after study is shown in Figure 3.1.

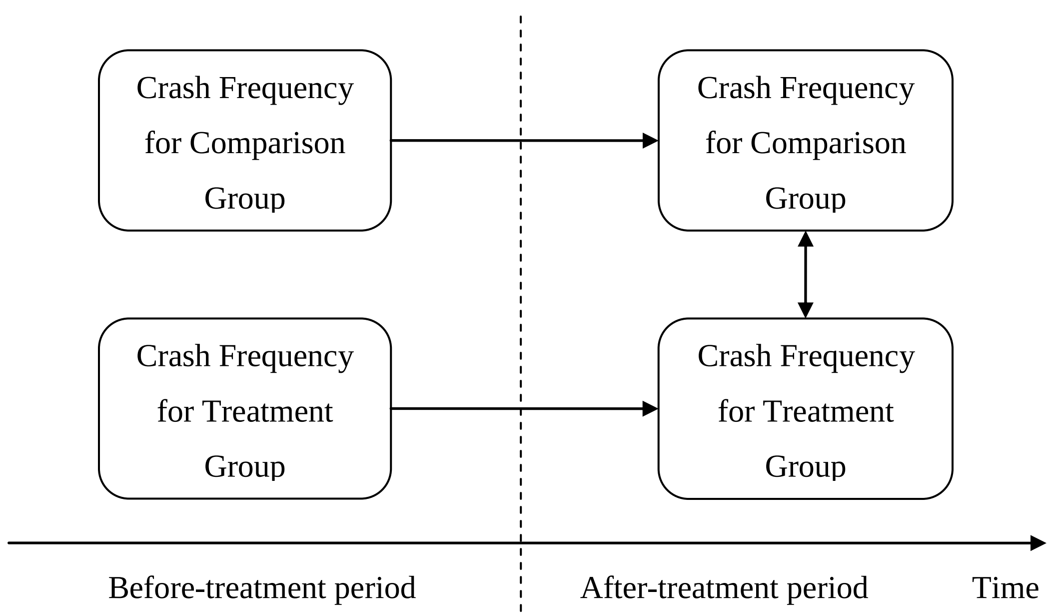


Figure 3.1: The basic strategy of a before-after study

Hauer (4) indicated that the disadvantage of a before-after study is the fact that one treatment might introduce many changes simultaneously to the facility that safety effects cannot be quantified by a specific change.

Converting a traditional intersection to a roundabout changes not only geometric features but also the nature of travel behavior. Though the intersection is under constant traffic exposure before and after the construction of the roundabout, the before-after study can only provide a general interpretation that the difference in crash frequency is associated with the construction of a roundabout.

3.2. A Cross-Sectional Study

A cross-sectional study can be used to assess safety performance using statistical regression methods to build relationships between crash frequency and important features of the facility. Hauer (4) pointed out that the cross-sectional study is a feasible and reliable approach to explore expected safety performance for traffic facilities. The current HSM provides all SPFs based on this methodology for traditional intersections. The CMFs derived for these functions then have the ability to represent safety effects of corresponding changes.

The Poisson distribution is a good approach to model frequency data such as the number of crashes. The Poisson regression then is used to regress crash data based on other independent features. As crash data appears to have the feature that the mean is less than the corresponding variance, many research efforts suggest the use of negative binomial regression to model the crash data (1, 13, 14). The fact that the variance of crash frequencies is larger than the corresponding mean under each scenario is known as over dispersion. The negative binomial regression serves as an alternative approach of the Poisson regression that has the ability to account for that over dispersion.

3.3. Introduction of Generalized Linear Model

The Poisson regression model and the negative binomial regression model belong to Generalized Linear Model (GLM) family of statistical models. The GLM consists of three elements:

- A probability distribution,
- A linear predictor $\boldsymbol{\eta} = \boldsymbol{X\beta}$ ($\boldsymbol{\beta}$ is a parameter vector that needs to be estimated), and
- A link function g such that $\boldsymbol{\mu} = g^{-1}(\boldsymbol{\eta})$.

The probability distribution is the assumed distribution for modeling a dependent variable. In the simple linear regression modeling, the dependent variable is assumed to be represented by a normal distribution under each specific condition. For modeling the safety performance of an intersection, the crash frequencies are assumed to be governed by a Poisson or a negative binomial distribution under each condition. Understanding the nature of the dependent variable and its distribution will lead to determine the correct link function for applying the regression process and identifying reasonable estimates.

The linear predictor combined with the link function replaces unknown parameters for the assumed distribution. For instance, the Poisson distribution has only one parameter $\boldsymbol{\mu}$ representing the mean of Poisson distribution. $\boldsymbol{X\beta}$ provides a vector of linear combinations based on observational data $\boldsymbol{X}$ and unknown parameters $\boldsymbol{\beta}$. $g^{-1}(\boldsymbol{\eta})$ then replaces $\boldsymbol{\mu}$ to represent the mean of Poisson distribution. The joint probability that all of observations occurred is given by the likelihood $L(\boldsymbol{\mu})$:

$$L(\boldsymbol{\mu}) = \prod_{i=1}^{n} f(X_i |\, \mu_i) = \prod_{i=1}^{n} f(X_i |\, g^{-1}(\boldsymbol{\eta})) = \prod_{i=1}^{n} f(X_i |\, g^{-1}(X_i\boldsymbol{\beta}))$$

The *Maximum Likelihood Estimation* (MLE) method then attempts to determine the vector of $\boldsymbol{\beta}$ that will have this joint probability or the likelihood achieves its maximum value. In other word, if we observed an event has certain outcomes, we might expect intuitively that these outcomes somehow are more likely to happen than other possible outcomes. Then we might want to choose parameters that make this intuitive assumption come true, which is to choose parameters that maximize the likelihood of those outcomes.

4. DATA

4.1. Oregon Roundabouts Inventory Data

Modern Roundabouts - The Web Site (http://roundabout.kittelson.com) serves as a roundabouts inventory database including information of exiting roundabouts within the United States and Canada.

This thesis extracts all currently available 4-leg single-lane roundabouts from the State of Oregon as the original data set for analyses. The 4-leg single-lane roundabouts refer to a cross intersection with the roundabout facility in place that has one circulating lane. This type of roundabout provides a simpler operational regulation than the multi-lane roundabouts.

Google Earth serves as a good interactive source for location information. The inventory data of roundabouts from the Kittelson website include accurate coordinate data that enabled the author to locate and label each roundabout using Google Earth. As a result, 23 4-leg single-lane roundabouts are included in the data set for this thesis.

The current HSM adopts the cross-sectional study to assess contributions that traffic exposure and geometric features individually and collectively have on the safety performance of traditional intersections. Roundabouts, as an alternative intersection, also have a wide range of features that might influence their safety performance.

The HSM includes the Annual Average Daily Traffic (AADT) as the key independent variable in the cross-sectional study. Daniels et al. (2010) (13) confirmed that traffic exposure played an important role in explaining variation in the safety performance of roundabouts.

Although few studies have identified a strong relationship between crash frequency and the geometric features for roundabouts, the HSM procedures tested geometric features for traditional intersections as independent variables in explaining variation of crash frequency. An investigation of roundabout geometric elements is expected to demonstrate a similar strong relationship.

A wide variety of geometric features of roundabouts might potentially influence the safety performance. Key features are summarized as follows and represented in Figure 4.1. Appendix B provides a brief summary of inventory data for important geometric features that including:

- Inscribed circle,
- Central island,
- Truck apron,
- Circulatory lane,
- Bicycle lane / path,
- Sidewalk,
- Landscape buffer,
- Entry alignment,
- Offset alignment,
- Angle between intersection legs,
- Presence of splitter island and number of crosswalks,
- Number of approach curves,
- Number of approach with bypass for right turn, and
- Entry curve.

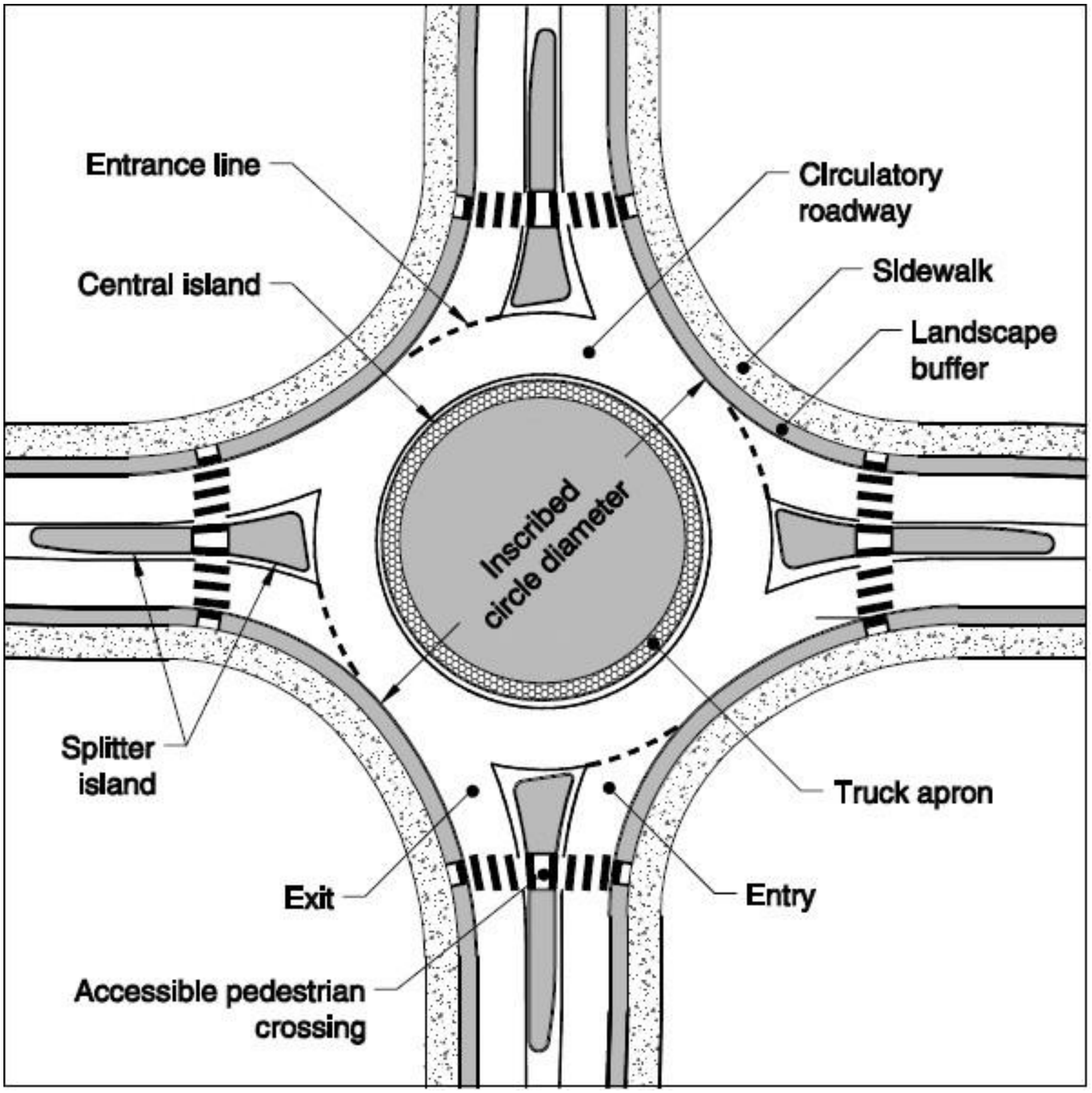


Figure 4.1: Geometric Features of a 4-Leg Single-Lane Roundabout (2)

4.1.1. Inscribed Circle Diameter

The inscribed circle diameter defines the outside edge of the circulatory lane (see Figure 4.1). The inscribed circle diameter is usually governed by design vehicles and speed. The larger inscribed circle diameter results in less deflection of circulating vehicles as they negotiate through the roundabout, which potentially increases circulating speed (2).

4.1.2. Central Island

The central island is usually constructed as a raised, non-traversable area that physically forces entering traffic to circulate around it. This feature reduces entering traffic speed by forcing an entry deflection and also reduces the number of conflict points from the 32 points associated with a traditional intersection to the 8 points typical of a roundabout. The entry deflection and the circulating characteristic of a roundabout substantially reduces the right-angle crashes often observed at the traditional intersection when vehicles turn left across the path of approaching traffic (2).

4.1.3. Truck Apron

The traversable truck apron is designed to provide extra space for heavy vehicles to negotiate through the roundabout without compromising the deflection for small vehicles. The truck apron is also designed for emergency vehicles quickly passing the roundabout while minimizing the influence of deflection (2).

4.1.4. Circulatory Lane

As depicted in Figure 4.1, the circulatory lane serves as the space dedicated for vehicles to travel. The width of the circulatory lane has influence on both safety and capacity. An excessively wide circulatory lane can have vehicles attempting to pass each other resulting in high speed driving. A circulatory lane that is too narrow, on the other hand, can be difficult to maneuver and result in additional travel delay and limit the capacity of the roundabout (2)

4.1.5. Bicycle Lane or Path

Three typical bicycle facilities are designed for bicyclists to negotiate through the roundabout. The *shared lane* design is similar to a sharrow as bicyclists have the priority while sharing the circulatory lane with vehicles. The *bicycle lane* design provides bicyclists an individual lane adjacent to circulatory lane so that bicyclists and vehicles can travel side by side. The bicycle path is usually designed as a physically separated bicycle facility often combined with a sidewalk (2).

In a Belgium study, Daniels et al. (2009) (10) noted that roundabouts with bicycle lanes were associated with a 93 percent increase in total injury crashes that involved bicyclists. The use of a bicycle lane does allow the bicycle to have a dedicated lane located immediately adjacent to the circulatory lane; however, at each access point the bicycle and the motor vehicle can encounter potential conflicts. Alternatively the use of a shared lane does not give the bicycle any additional buffer area between it and a vehicle, but does enable the cyclist to "own the lane." The shared lane technique can be subject to motor vehicles attempting to pass a bicycle if the bicycle does not move to the center of the lane to prevent such a maneuver.

4.1.6. Sidewalk

A sidewalk can be constructed outside of the circulatory lane, usually physically separated by a landscape buffer area. A common roundabout design combines sidewalk and bicycle lane together as an elevated area that separates vulnerable road users, such like bicyclists and pedestrians, from the active traffic region of the roundabout (2). Three recommended bicycle ramps for connecting the approaching bicycle lane with the sidewalk/shared use path are shown in Figure 4.2.

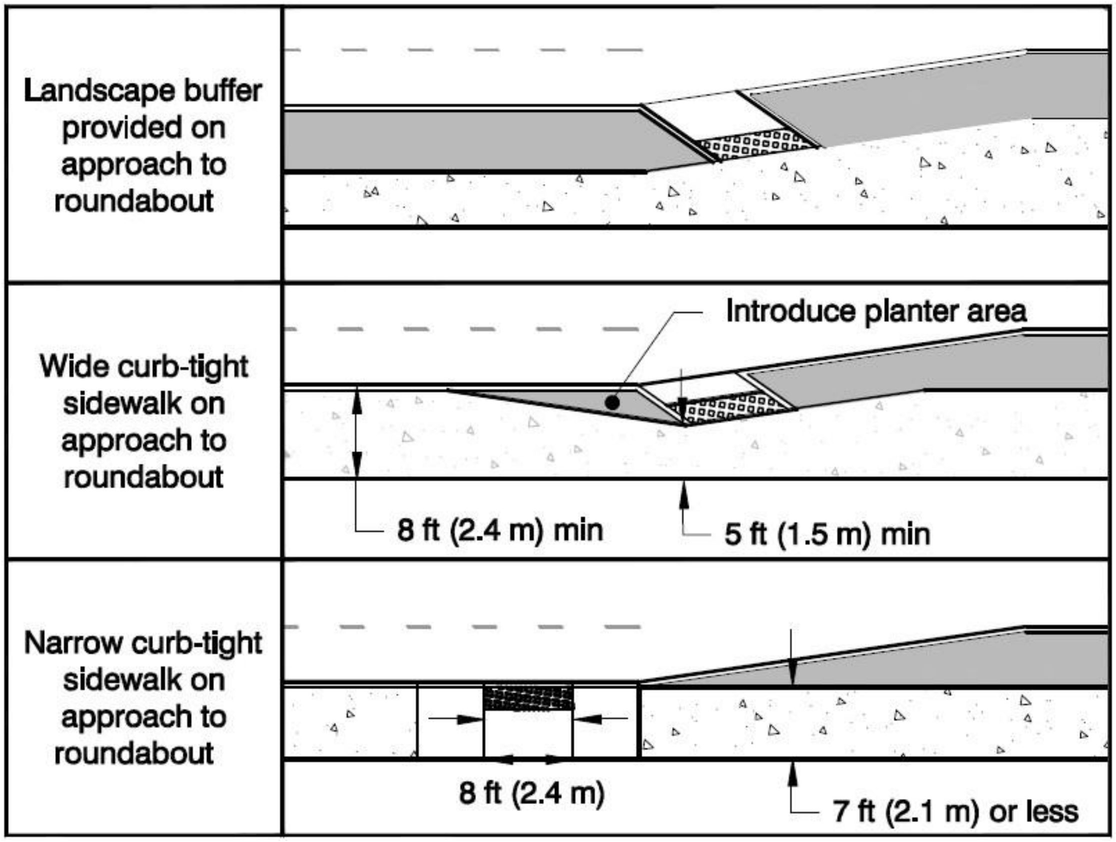


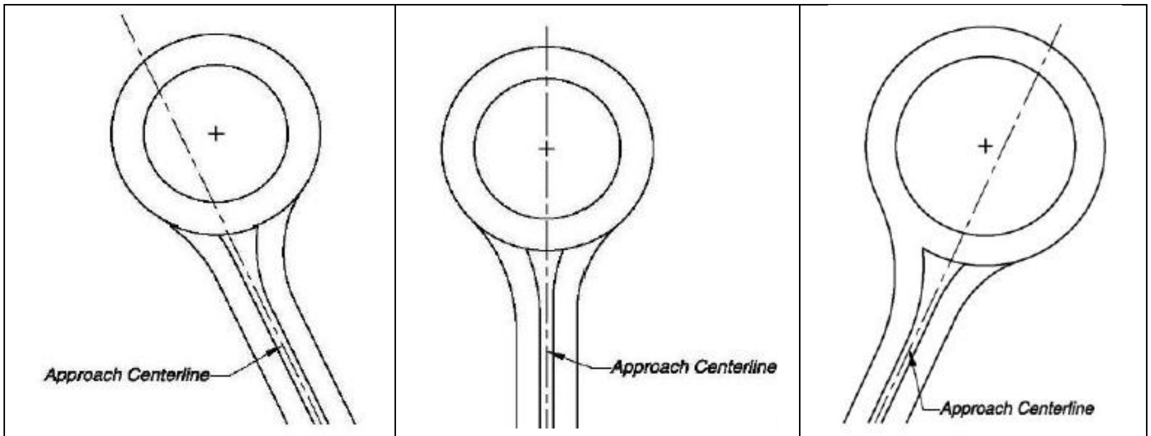
Figure 4.2: Regular Bicycle Ramps (2)

4.1.7. Landscape Buffer

A landscape buffer located between the circulatory lane and sidewalk is reserved as an area for snow storage, street furniture, traffic control sign, street lights and other utilities. The most important role of the landscape buffer is to delineate the sidewalk so as to help to guide pedestrians, including those with visual impairments, to designated crosswalk locations (2).

4.1.8. Entry Alignment and Offset

The center of an inscribed circle is usually aligned with the central line of the approach leg. An entry offset may be needed when there are environmental restrictions or geometric requirements for the construction of roundabouts. The left or right offset alignment can influence the extent of deflection that in turn affects the entering speed and exiting speed (2). Three typical alignment and offset setting are shown in Figure 4.3.



(a) Alignment Offset to the Left of Center

(b) No Offset -- Alignment Through Center

(c) Offset alignment to the right of center

Figure 4.3: Roundabout Offsets (2)

4.1.9. Angle between Intersection Legs

As an intersection, an optimal 4 leg roundabout has the 4 legs perpendicular to each other (2). The relatively large angle between legs might result in speeding while excessively sharp angles might contribute to under steering.

4.1.10. Presence of Splitter Island and Number of Crosswalks

The splitter island is reserved as an area for mounting traffic control sign and providing pedestrians a refuge to cross the traffic separately. The splitter island also deflects entering traffic as to reduce entering speed and separates entering and exiting vehicles (2).

4.1.11. Number of Approach Curves

The approach curve is design along the approach legs as a traffic calming facility used to reduce vehicles' speed as they approach the roundabout. An excessively small approach curve radius can cause driver expectancy issues and result in additional rear-end crashes (2).

4.1.12. Number of Approaches with a Right-Turn Bypass

The construction of a right-turn bypass is desirable when a location has a high right-turn traffic volume. The right-turn bypass can increase the capacity and efficiency of a roundabout with high right-turn volume while it might introduce more conflict points among vehicle, bicyclists and pedestrians and merging conflicts downstream (2).

4.1.13. Entry Curve

In addition to the entry width, circulatory roadway width, and the central island geometry, the entry curve and its associated curb radius helps to influence the amount of deflection required of a vehicle entering the roundabout. The entry curve can be a single, simple circular curve or it can be constructed as a 3 centered curve. Very large entry curb radii, for example, are more likely to be associated with faster entry speeds. Sharp entry curves, however, can be too abrupt and contribute to single-vehicle crashes at the roundabout entry location (2).

4.2. Traffic Volume Data

Daniels et al. (2010) (14) suggested that the entering traffic volume is one of the most important factors that affect the safety performance of traffic facilities. Similarly, the HSM uses traffic volume as a key explanatory variable in the base condition safety performance functions. Roundabouts, as alternative intersections, are therefore likely to have a similar traffic volume influence on expected safety performance.

Local agencies and jurisdictions' websites can provide traffic volume information. Some of the agencies use interactive maps to display traffic data while others provide data files. Based on these online sources, the author acquired traffic volumes for all 28 roundabouts included in the data set. Only 12 of these roundabouts had complete traffic volume information. This fact led the author to execute a traffic data collection effort to provide supplemental information.

4.2.1. Projecting Historical Data

The traffic volume data found based on online sources should be projected to the current year as a way to have the representative for the use in safety performance functions. There are several steps to project historical traffic volumes to the current year as reasonable traffic volumes for modeling use.

Online sources usually provide traffic volumes in the roadway level. In other word, they usually point out the counting location on the road and provide directional volumes and the total volume at that counting point. The type of traffic volume provided in the website of local engineering section is Average Daily Traffic (ADT). Since the most roundabouts are locating in local area where usually no permanent counting devices exist, the ADT serves as a good estimate of AADT as in modeling safety performance.

Table 4.1 shows the roundabout with a site ID of OR-S4-3. This roundabout is located in Bend, Deschutes, Oregon. The street name of its north leg is Mt Washington. This data entry records the traffic volume from the north leg in both directions. The type of traffic volume is ADT.

Table 4.1: Traffic Volume Data Example

Traffic Volume Profile for One Leg of a Roundabout				
Basic Information		Historical Traffic Count		
		Year	Count	
Site ID	OR-4S-3	2005	6823	--
City	Bend	2006	--	--
County	Deschutes	2007	--	--
Street Name	Mt Washington	2008	--	--
Location of Leg	North	2009	8724	8720
Traffic Direction	Both	2010	--	--
Traffic Volume Type	ADT	2011	--	--
		2012	--	--

The construction year of the roundabout was 2005. Before the construction year, there was no historical data for this leg. After the construction year, there was one year of traffic volume data (2005). Two 2009 data sources provide similar traffic volume information (one from ODOT and the other one from the county resource).

The traffic growth rate is used to project historic traffic volume data to the current year. The annual population growth rate served as a key reference for the traffic growth rate. On the Indexmundi (http://www.indexmundi.com/facts/united-states/quick-facts/oregon/population-growth#table), there is a table of resident total population change from April 1, 2000 to April 1, 2010 by counties in Oregon. The average annual population growth rate could be calculated by using the following equation:

$$Pop_{future} = Pop_{present} \times (1 + R)^n$$

Where:
$Pop_{future} = Future\ population, people$
$Pop_{present} = Present\ population, people$
$R\ =\ Average\ annual\ growth\ rate\ (unknown)$
$n\ =\ Number\ of\ years$

The interactive map from the United States Census 2010, (http://2010.census.gov/2010census/data/), provides census results for the year of 2010 for all counties in Oregon. Based on the 10-year period growth rate, the population for the year of 2000 could be calculated. Excel provides a specific function that could be perfectly used to calculate average annual population growth rate, even though it is originally designed for calculating growth rate in financial field. The function name is RATE. The first entry data is the number of period, which indicates the number of years, n. The second entry data should be set to empty. The third entry data is the present population in a negative format. The last entry data is the future population. For instance, given that population of 2000 was 338,427 and population of 2010 was 375,992, the average annual growth rate would be 1.06% as a result of the function of RATE (10, ,-338427, 375992).

Based on this method, the author calculated average annual growth rate for all counties where roundabouts of interest were located as shown in Table 4.2. The author assumed that the average annual growth rate is a constant value over the time to the year of 2012.

Table 4.2: Annual Population Growth Rate for Counties

County Name	Population 2010 (People)	Total Population Percent Change 4/1/2000 to 4/1/2010	Population 2000 (People)	Annual Percentage Growth Rate
Clackamas	375,992	11.10%	338,427	1.06%
Deschutes	157,733	36.70%	115,386	3.18%
Multnomah	735,334	11.30%	660,677	1.08%
Lane	351,715	8.90%	322,971	0.86%
Linn	116,672	13.20%	103,067	1.25%
Washington	529,710	18.90%	445,509	1.75%
Jackson	203,206	12.10%	181,272	1.15%

As noted before, there are two traffic volume data points for the north leg of roundabout OR-S4-3 in both directions. The author developed a method to determine one data point that has a traffic volume of the average value of all historical data with an associated average year. The author then used this one data point to project traffic volume for the year 2012 by applying the growth rate. Table 4.3 is an example of developing traffic volume of the year 2012 in both directions for the north leg of roundabout OR-S4-3. Since there are two volumes for the year 2009, the average value is calculated to represent the traffic volume for that year. An average value of traffic volume from the year 2005 and 2009 represents the traffic volume of the year of 2007, which is the average year of 2005 and 2009. The author estimated the traffic volume of the year 2012 by combining this interpolated volume of the year 2007 and the average annual growth rate.

The final conservative estimate of the ADT was the one with the highest volume after the construction year. The highest volume represents the largest exposure condition that the corresponding roundabout experienced.

Table 4.3: Projecting Traffic Volume to the Current Year

Projecting Traffic Volume Process					
Year				Projecting year	Growth Rate
2005	2005*	2009	2009*	2012	
6823	--	8724	8720	9088	3.18%

Projecting Calculation:

$$Traffic\ Volume_{2012} = \frac{6823 + \frac{(8724+8720)}{2}}{2} \times (1 + 3.18\%)^{\left(2012 - \frac{2005+2009}{2}\right)} = 9088$$

4.2.2. Traffic Volume Collection and Estimation

Insufficient traffic volume data is a common problem that needs to be addressed during transportation research efforts. Based on the data set the author used, there were 16 roundabouts that had incomplete traffic volume information. As previously indicated, most roundabouts located in residential areas or that serve as the junction of roadways with local jurisdictions did not have associated traffic data.

The traffic volume data collection process should capture both morning peak hour traffic and afternoon peak hour traffic and provide a relatively clear traffic distribution over the data collection day. The author collected traffic volume one day for one roundabout for 2 hours in the morning and 2 hours in the afternoon. The one day data collection strategy is a reasonable approach to collect representative traffic volume with limited budgets and labor efforts.

The basic idea of projecting one day of traffic volume data to the equivalent AADT or ADT is to make use of the following equation:

$$DDHV = AADT \times D \times K$$

Where:
DDHV = Directional Design Hourly Volume, vehicle/hour
AADT = Annual Average Daily Traffic, vehicle/day
D = Percentage of Peak Directional Traffic Volume
K = Percentage of the AADT that occurs in the peak hour, day/hour

This equation provides a relationship between peak hour volume and average daily traffic. Dividing both sides of this equation by D, results in:

$$\frac{DDHV}{D} = AADT \times K$$

The left side of the new equation represents the peak hour traffic volume, which is in accordance with the definition of K as the proportion of daily traffic occurring during the peak hour.

Since the author conducted a data collection effort for all roundabouts with incomplete traffic data, the left side of equation can be calculated from traffic volume field data. The author proposed an approach to estimate traffic volumes for all legs that have no associated historical data by combining the use of K values and observed traffic distributions.

Based on the traffic volumes collected during typical morning and evening peak hour, the author calculated the peak hour volume for each leg and developed associated traffic distributions. Select approach legs already had associated historical traffic data, and they could directly yield K values based on the equation above. The author then categorized legs that have similar K values into different groups. Post-grouped traffic distribution graphs then can be developed. Legs in the same group are assumed to have similar traffic distribution.

Legs that have no historical traffic volume data then can be fit into each group based on the similarity between their traffic distributions and groups' trends. Once legs that have no historical data find their group, their average daily traffic could be calculated by using the equation above with the average K values in that category and their peak hour volumes.

Several of the study roundabouts are located in front of a school, church or exclusive area so that one of roundabout legs serves as the only entrance and exit for that area. These land use areas generate different traffic distribution over the entire day compared to adjacent collectors. As a result, the author decided that it was not a reasonable approach to estimate traffic volumes for these special areas based on empirical traffic counts the author collected during typical morning and afternoon peak hours.

The *Trip Generation Manual* provides ADT for different land uses based on three different categories: weekday, Saturday and Sunday. For instance, the roundabout OR-4S-1 is located in front of a church. The west leg of this roundabout serves as one of two entrances and exits. The *Trip Generation Manual* provides three different charts for estimating ADT based on gross floor area. The weekday chart provides the estimated average trip ends that a church with known gross floor area generates on a weekday. The Saturday chart provides the estimate average trip ends generated on Saturday. A similar chart is available for Sundays.

Table 4.4: Example of the Use of *Trip Generation Manual*

Trip Generation Manual 7th Ed Volume 3 of 3			
Land Use Code		560	
Land Use Name		Church	
Condition: Average Vehicle Trip Ends vs: 1000 Sq. Feet Gross Floor Area			
On a:	Weekday	Saturday	Sunday
Input Variables	1000 Sq. Feet Gross Floor Area	1000 Sq. Feet Gross Floor Area	1000 Sq. Feet Gross Floor Area
Input Value (1000 Sq. Feet)	27	27	27
Input Source	Google Earth	Google Earth	Google Earth
Fitted Curve Equation	Not Given	Not Given	Not Given
Average Vehicle Trip Ends (Vehicles)	250	260	824
Estimate ADT = 824/2 = 412 veh/day			

In Table 4.4, the Sunday chart provides the highest trip ends estimate and represents the highest traffic exposure that this west leg could experience during a week. Based on the conservative estimate principle, the author chose the highest traffic exposure that the *Trip Generation Manual* could provide as the estimated ADT for responding legs. Since this roundabout serves as one of two entrances to this church, the author assumed that half of these trip ends were distributed on this west leg. As a result of this estimation, the expected ADT for the west leg of roundabout OR-4S-1 is 412 vehicles per day for both directions.

4.2.3. Finalizing Traffic Volume Data for Modeling Use

The roundabout is usually an intersection between a major road and a minor road. The HSM uses two types of traffic exposure as one of the explanatory variables. The first strategy uses the major road's AADT and the minor road's AADT as traffic exposures. The second one uses the total traffic volume from the major and minor road.

The major traffic volume of an intersection represents the total entering traffic to that intersection from the major road. The minor traffic volume of an intersection represents the total entering traffic to that intersection from the minor road. For an intersection with four legs, there are two entering traffic streams from the major road and another two entering streams from the minor road. As a conservative estimating approach for the major traffic exposure, the author used the two-directional traffic volume from one of two major legs that had higher value as the total entering volume for the corresponding major road. The same strategy applied to the estimation of total entering volume for the minor road.

Table 4.5: Finalizing Traffic Volume

Site ID	Site No.	County	Location of Leg	Direction	Volume Type	AADT or ADT (veh/day)
OR-S4-1	123	Clackamas	N	Both	ADT	6250
OR-S4-1	123	Clackamas	E	Both	ADT	1400
OR-S4-1	123	Clackamas	S	Both	ADT	7575
OR-S4-1	123	Clackamas	W	Both	ADT	412
Major ADT (veh/day):			7575			
Minor ADT (veh/day):			1400			
Total ADT (veh/day):			$7575 + 1400 = 8975$			

The major road is not always two opposite direction roadways. The determination of the major road lies on the traffic volumes from all four legs. The author chose to use the two legs with the highest volume as the major road. From Table 4.5, the north and south legs then represent the major road. The major ADT is the highest volume value for this major road, or 7575 vehicles per day. This estimate technique yields the minor ADT or approximately 1400 vehicles per day. The total ADT for this roundabout then is the combination of the major and minor volumes directly. The Appendix C includes two tables. Table 10.1 includes projected raw traffic volume data based on online sources and empirical collection efforts. Table 10.2 provides traffic volumes for modeling use.

4.3. Crash Data

Crash data plays an important role in safety performance analyses since crash information, such as the number of crashes and crash severity, quantifies safety in a way so that mathematical methods can be applied to enhance the evaluation process.

4.3.1. Area for Defining Roundabout Related Crashes

The upstream corridor where intersection related crashes are defined is of importance in locating and selecting crash data from a database. Crash data included that is based on an improper area will lead to either under evaluating or over evaluating the safety performance of the intersection.

Intersection related crashes are those that occur in the physical intersection area of two roadways and those located within the intersection functional area. The conventional intersection functional area is the area beyond the physical intersection of two roadways that comprises stopping sight distance area and any required vehicle storage area. A similar functional area should be applied to roundabouts.

For the purpose of this research effort, the author assumed that the vehicle storage area serves 4 vehicles with average distances of 25 feet each including the average vehicle length and required safe gap in front of the vehicle. Thus the vehicle storage area length is 100 feet beyond the physical inscribed circle area.

The stopping sight distance is represented by the following equation:

$$SSD = 1.47Vt + 1.075\frac{V^2}{a}$$

Where:
$SSD = stopping\ sight\ distance, ft$
$V = speed, ft/s$
$t = perception\ reaction\ time, sec., typically\ 2.5\ sec.\ for\ design$
$a = deceleration\ rate, ft/s^2, typically - 11.2\ ft/s^2$

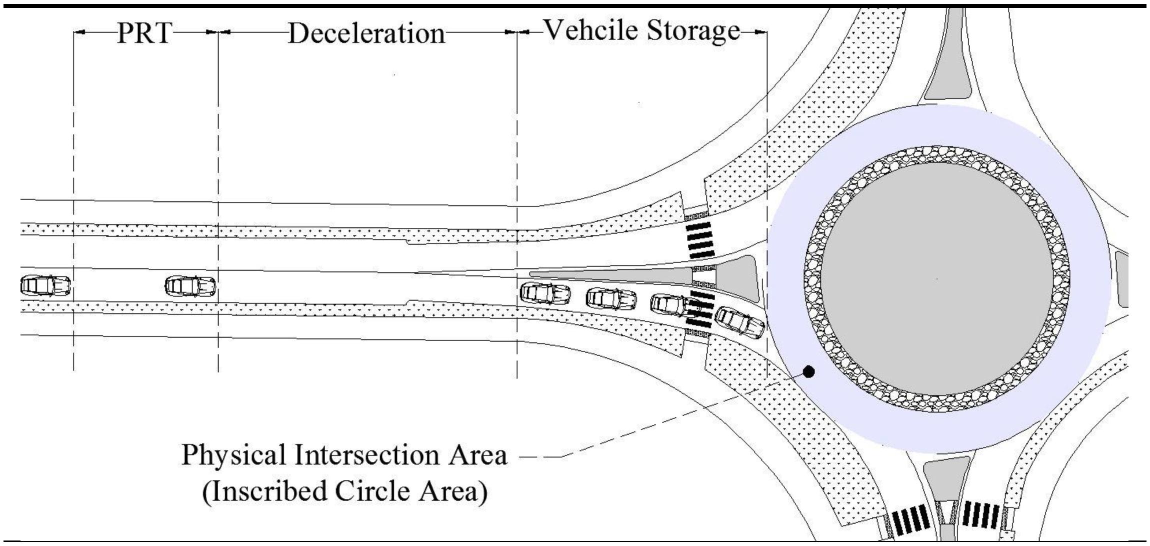
The current AASHTO Green Book provides the stopping sight distance equation. All the default assumptions are based on a conservative evaluation for the stopping sight distance. The perception reaction time is 2.5 seconds. The deceleration rate is assumed to be $-11.2\ ft/s^2$. The author chose to use the design speed for making a conservative evaluation, since the posted speed should be less than the designed speed.

The radius of area where roundabout related crashes are defined comprises:

1. The largest inscribed circle radius from the data set,
2. The length of required vehicle storage area, and
3. The length of conservative stopping sight distance based on the highest design speed in the data set.

Figure 4.4 illustrates components critical to defining roundabout related crashes.

Table 4.6 demonstrates this calculation. The final distance is rounded up to 800 ft to be conservative.



Notes:

1. PRT distance represents the distance a drive will travel during perception reaction time,
2. Deceleration distance represents the distance a drive will travel during decelerating until stop, and
3. The stop sight distance is composed of PRT distance and deceleration distance.

Figure 4.4: Area of defining roundabout related crashes

Table 4.6: Calculation of the Area of Defining Roundabout Related Crashes

The Radius of Area for Defining Roundabout Related Crashes	
The Radius of the Largest Inscribed Circle (ft.)	192
The Length of Required Vehicle Storage Area (ft.)	$4 \times 25 = 100$
The Highest Posted Speed from Data Set (mph)	40
The Corresponding Designed Speed (mph)	50
The Length of Conservative Stopping Sight Distance (ft.)	$1.47 \times 50 \times 2.5 \times 1.075 \times \frac{50^2}{11.2} = 424$
Total (ft.)	$716 \approx 800$

4.3.2. Crash Data Source

The ODOT provides the Digital Video Log as an access to the crash data system. Since all the roundabouts in the data set serve as junctions of local roads, the author downloaded crash data from the local road option. The option of Street Segment and Intersectional under Select Query Type section includes a report of all crashes that occurred on the corresponding road. The report locates each crash by providing the distance beyond an intersection of the corresponding road and a crossing road. This distance variable was helpful in filtering roundabout related crashes by comparing with the threshold calculated from section 4.3.1. A crash was included if its distance from the intersection was less than 800 ft. Otherwise, the crash was not treated as a roundabout related crash.

4.4. Data Distribution

4.4.1. Crash Data Distribution

There are 23 roundabouts in the data set. On these roundabouts, a total of 131 crashes occurred during a 5-year period from year 2007 to year 2011 (5.7 annual crashes per roundabout), with a total of 52 injury crashes and a total of 79 property damage only crashes. There were not any fatal crashes associated with these target roundabouts during the 5-year period. The major collision type observed was the rear-end crash, 67 crashes out of 131 total crashes. Figure 4.5, Figure 4.6, Figure 4.7, Figure 4.8 and Figure 4.9 provide a brief graphical summary of crash data. Figure 4.5 first demonstrates the distribution of number of crashes from 23 roundabouts during current 5 years by crash severity. Figure 4.6 illustrates the distribution for total crashes. Figure 4.7 and Figure 4.8 provide the distributions of injury crashes and property damage only crashes in the same manner, respectively. Figure 4.9 shows the distribution of total crashes by collision type. Table 4.7 provides the bivariate distribution of total crashes between crash severity and collision type.

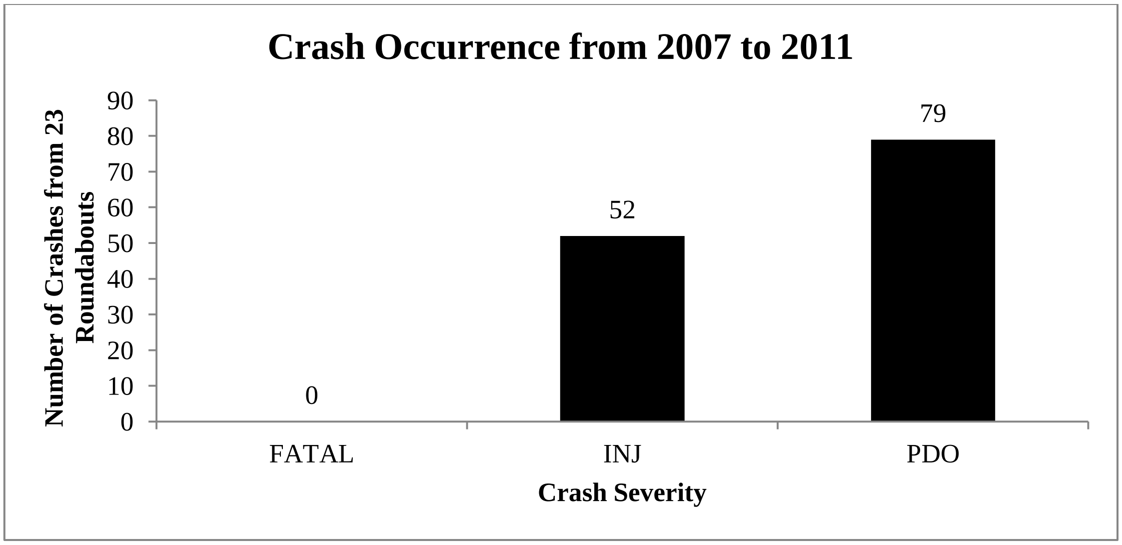


Figure 4.5: Number of total crashes by severity levels

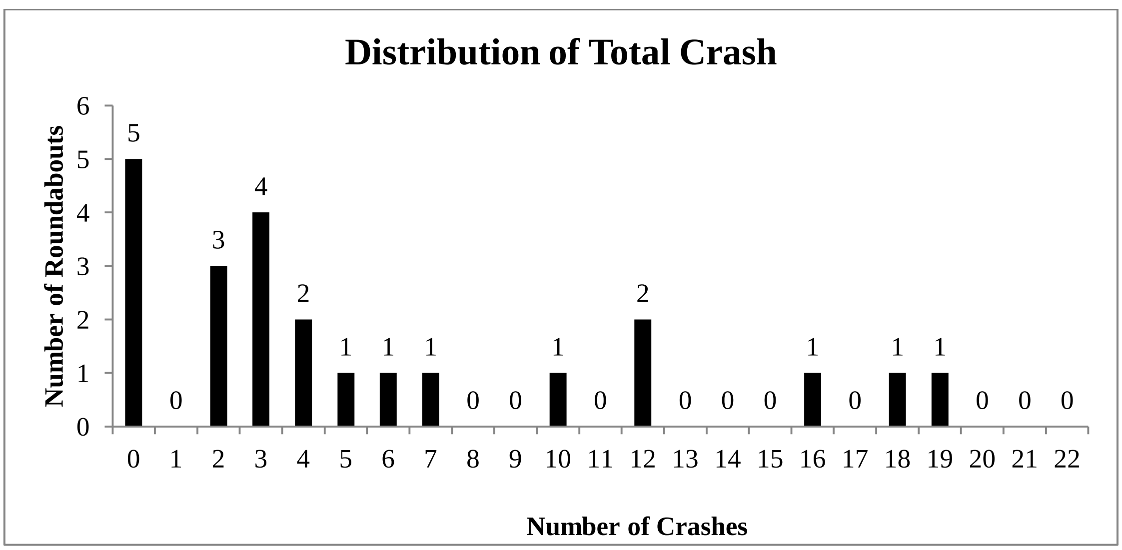


Figure 4.6: Distribution of total crash

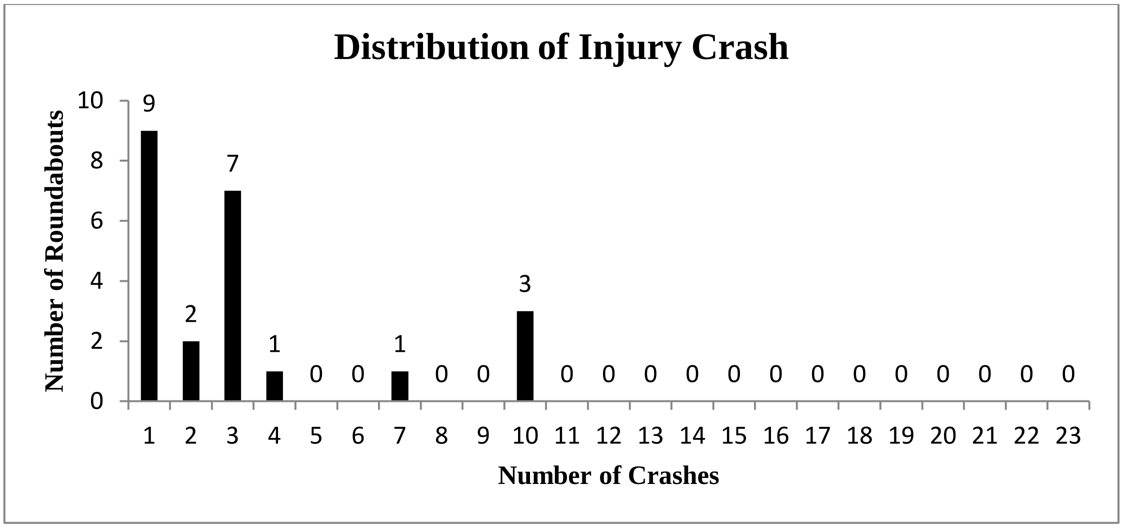


Figure 4.7: Distribution of injury crash

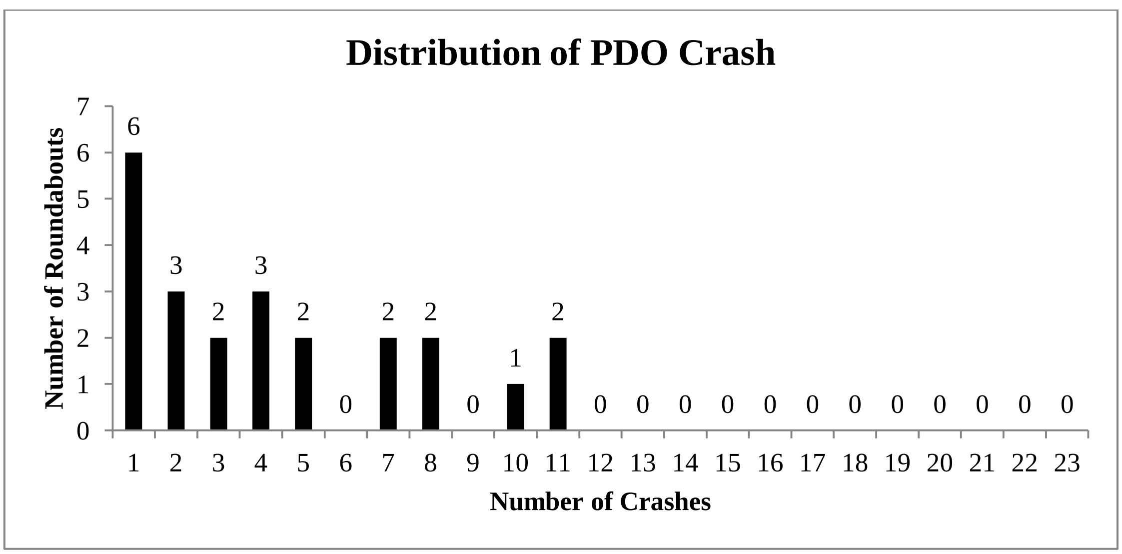


Figure 4.8: Distribution of PDO crash

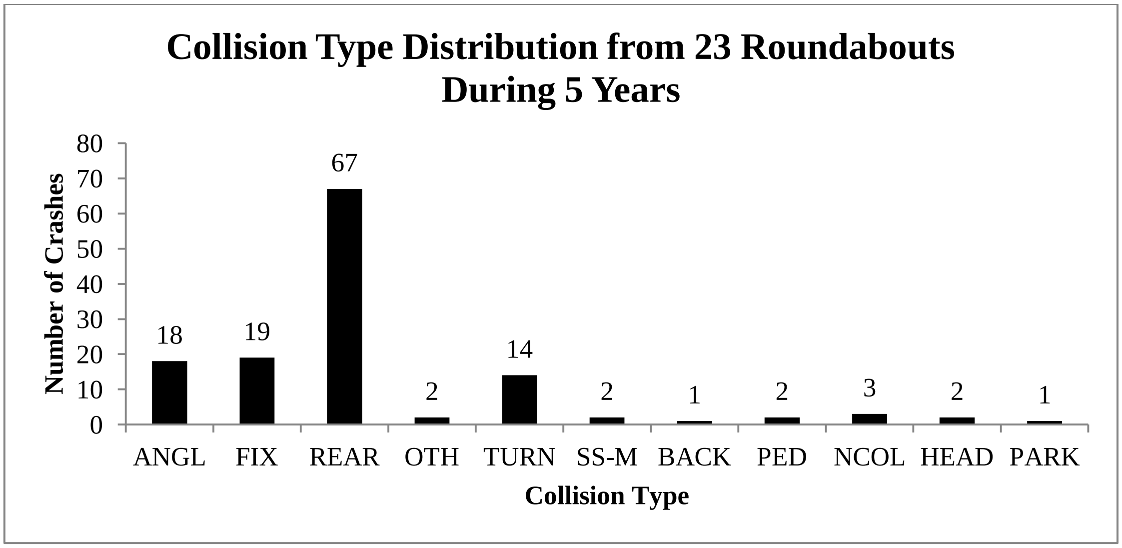


Figure 4.9: Distribution of collision type

Table 4.7: Bivariate distribution of total crashes

Distribution of total crashes by crash severity level and collision type			
Collision Type	Injury	PDO	Total
Angle Collision	4	14	18
Fix Object or Other Object	8	11	19
Rear - end Collision	29	38	67
Miscellaneous	2	0	2
Turning Movement	4	10	14
Sideswipe - Meeting	0	2	2
Backing Movement	1	0	1
Collision with Pedestrian	2	0	2
Non - Collision	2	1	3
Head - on Collision	0	2	2
Parking Maneuver	0	1	1
Total Crashes	52	79	131

4.4.2. Traffic Volume Data Distribution

Figure 4.10 provides the distribution of ADT for all major streets. Figure 4.11 shows the distribution of ADT for all minor streets. Figure 4.12 illustrates the distribution of total traffic volume of roundabouts.

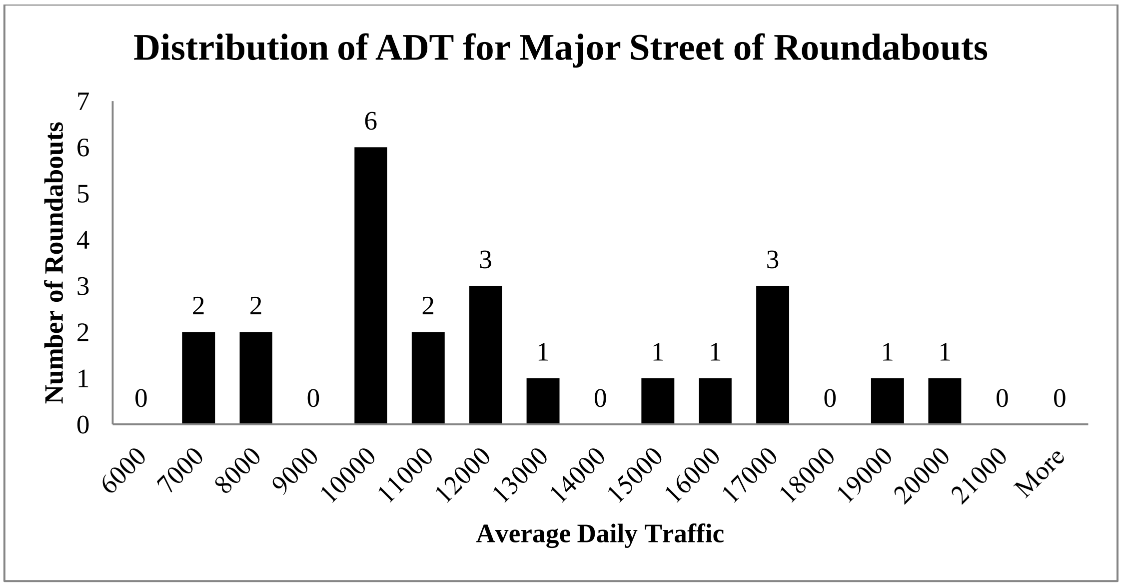


Figure 4.10: Major ADT distribution

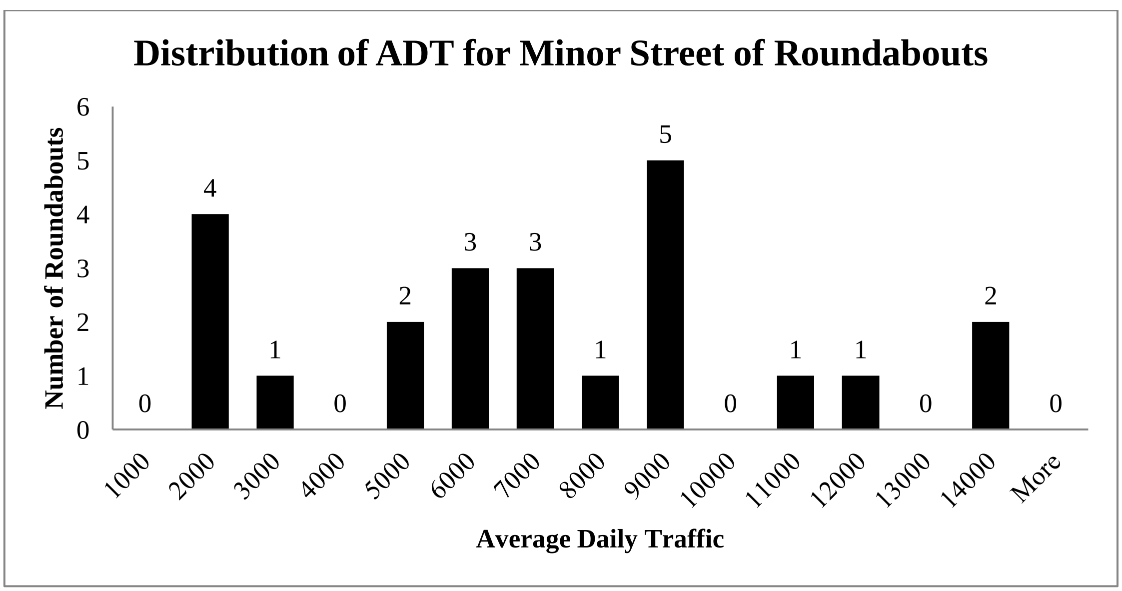


Figure 4.11: Minor ADT distribution

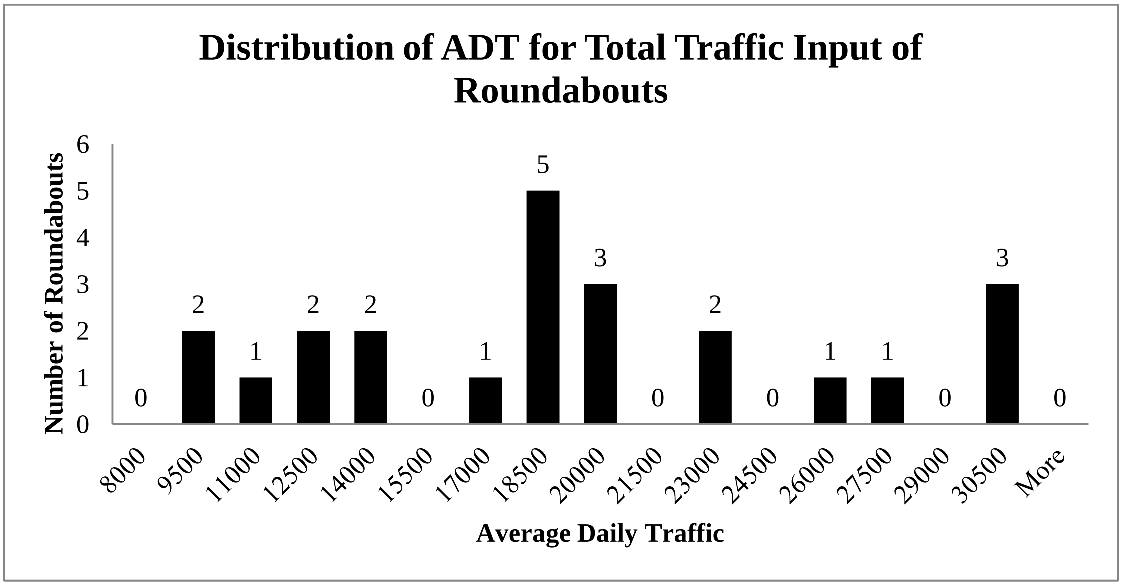


Figure 4.12: Total entering ADT distribution

4.4.3. Geometric Data Distribution

Section 4.1 demonstrated geometric features that might influence the safety performance of roundabouts. The author measured important features such as quantitative data and illustrated their distributions. Figure 4.13 shows the distribution of the inscribed circle diameter. Figure 4.14 provides the distribution of central island diameter. Figure 4.15 illustrates the distribution of truck apron width. Figure 4.16 demonstrates the distribution of circle lane width. Figure 4.17 shows the distribution of the number of approach curve.

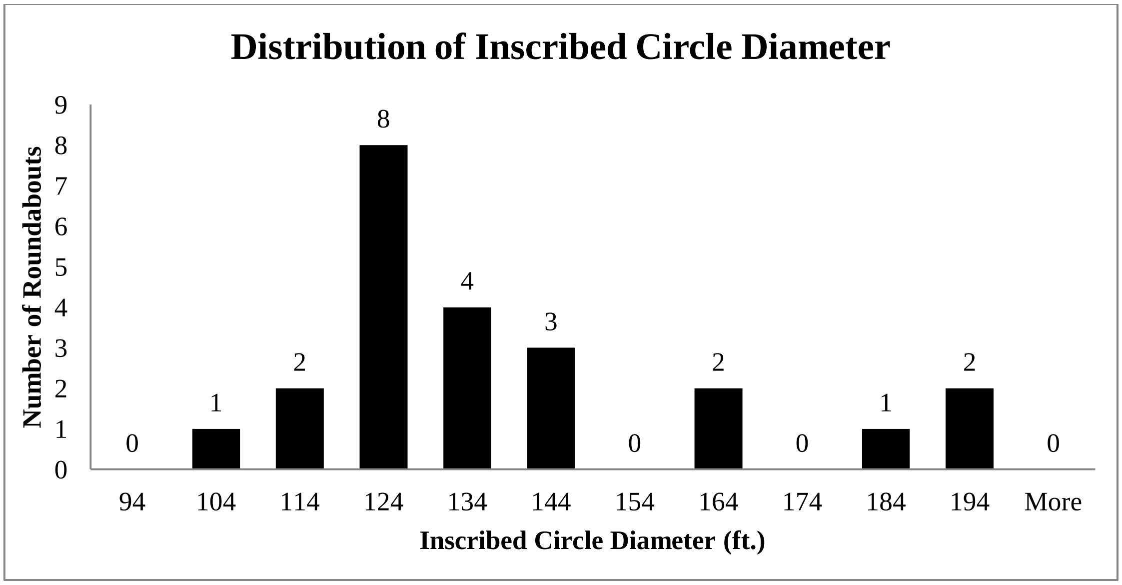


Figure 4.13: Distribution of inscribed circle diameter

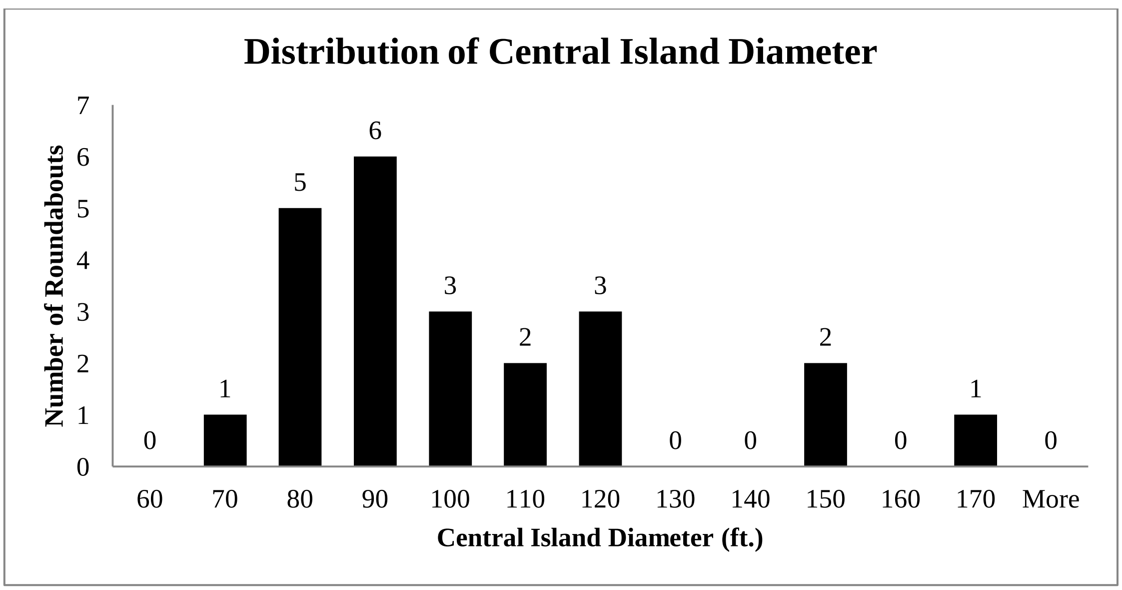


Figure 4.14: Distribution of central island diameter

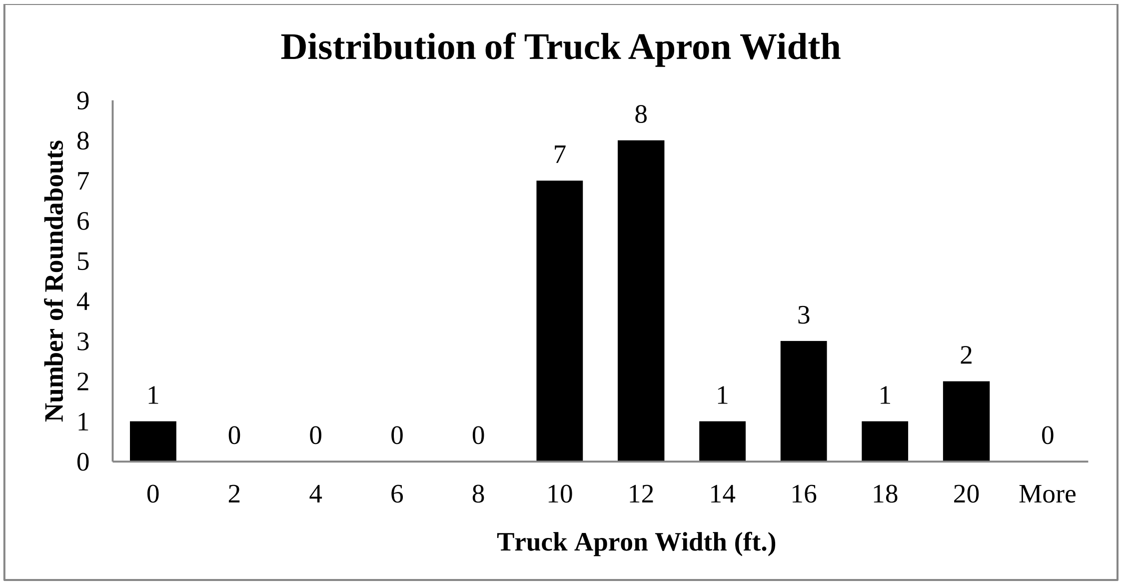


Figure 4.15: Distribution of truck apron width

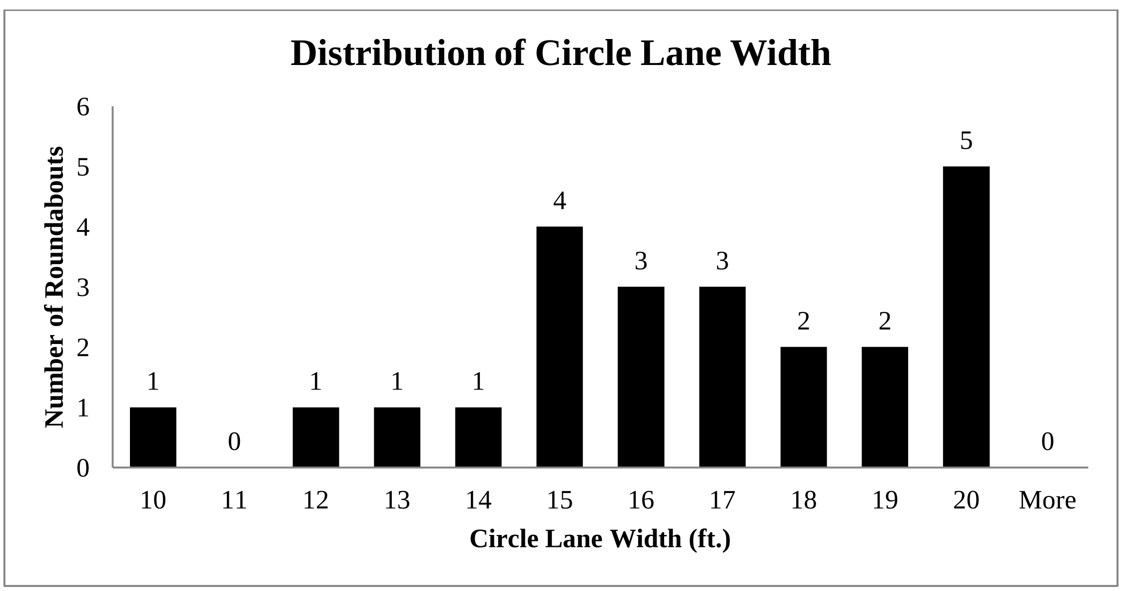


Figure 4.16: Distribution of circle lane width

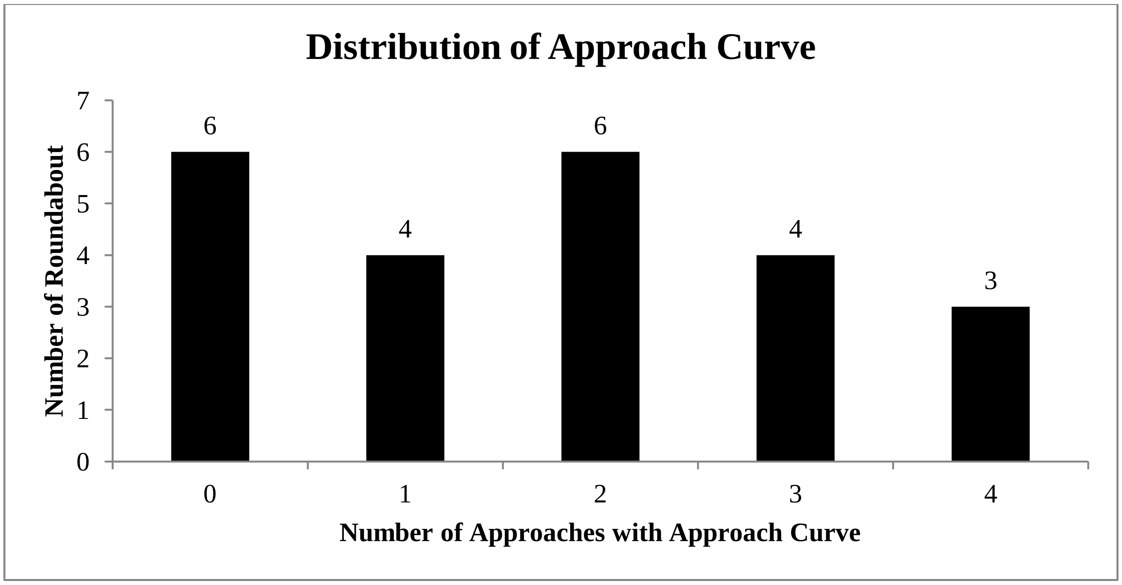


Figure 4.17: Distribution of approach curve

4.4.4. Summary of Variable Description

Table 4.8 includes a descriptive summary of important variables. The geometric features do not have great variations so that they might be grouped as baseline conditions, which the author will discuss in Section 5.

Table 4.8: Variable descriptive summary

Variable	Average	Standard Deviation	Minimum	Maximum
Total Crashes for 5 Years per Roundabout	5.7	5.93	0	19
Total Injury Crashes for 5 Years per Roundabout	2.26	3.02	0	9
Total Property Damage Only Crashes for 5 Years per Roundabout	3.43	3.37	0	10
ADT on Major Street (vpd)	11,697.09	3,837.73	6,430	19,350
ADT on Minor Street (vpd)	6,704.43	3,540.22	1,400	13,285
Inscribed Circle Diameter (ft)	134.39	25.41	104	192
Central Island Diameter (ft)	99.61	26.41	70	165
Truck Apron Width (ft)	11.96	4.06	0	20
Circulating Lane Width (ft)	16.61	2.78	10	20

The quality of a research effort is mainly based on the quality of the data. The cross-sectional study requires three major data sets for developing the safety performance of a traffic facility. A local agency often provides the database of crash information that one can access online. Google Earth and other online map system provide the data and images that one can use to check and measure geometric features. Traffic volume data of local roadways, on the other hand, usually suffered from missing values. One needs to develop a proper strategy that helps to project or estimate traffic volume data for those local roadways.

5. RESULTS

Since the sample size tends to be small and most of roundabouts share similar geometric features, a baseline model serves as a good approach to reveal the relationship between crashes and traffic volume. The HSM derived baseline models as a function between number of crashes and entering traffic volume based on certain pre-defined geometric feature settings. For instance, the HSM baseline model for a rural two-lane, two-way road stop controlled intersection is shown as follows:

$$N_{spf4ST} = \exp\left[-8.56 + 0.6\ln\left(AADT_{Major}\right) + 0.61\ln\left(AADT_{minor}\right)\right]$$

Where:
N_{spf4ST} = Expected number of crashes per year for 4 legs stop controlled intersection, crash/year
$AADT_{Major}$ = AADT from major street, vehicle/day
$AADT_{minor}$ = AADT from minor street, vehicle/day

This safety performance function is derived using on 4 baseline conditions:

- No intersection skew,
- No lighting system,
- No left turn lane, and
- No right turn lane.

This function provides a method to estimate the expected number of annual total crashes based on different traffic volumes for this type of intersection under above baseline conditions. If an intersection has some geometric features that differ from these baseline conditions, CMFs will help to account for the effects that different geometric features have on the expected number of crashes by multiplying CMFs by the corresponding SPF.

Based on the roundabout data, the analysis evaluated geometric features typical for a majority of roundabouts as the baseline conditions. These baseline conditions for roundabouts included:

- Raised central island present,
- Truck apron present,
- No bicycle lane,
- Sidewalk present,
- Splitter island associated with a pedestrian refuge area,
- Lighting system present,
- No bypass lane,
- Center alignment design,
- No oval roundabouts,
- Inscribed circle diameter of approximately 135 ft.,
- Circulating lane width of approximately 16 ft., and
- 15 mph circulating speed limit.

Based on these baseline conditions, the data set is re-filtered including roundabouts with the above desirable baseline features. As a result, 21 out of 23 roundabouts that are associated with baseline features were used in the subsequent modeling process.

Even though the author intended to adopt a similar model as used for the HSM and its development of SPFs for traditional intersections, the roundabout data did not fit the model that has both its dependent variable as the number of crashes, and the explanatory variable as the traffic volume in the logarithm form.

Crash data is frequency data that should be well described by Poisson or Negative Binomial models. These two models then will take the logarithm on the dependent variable in order to rescale the skewness of the crash data. The logarithm operation arbitrarily forces data points to meet the normality assumption. The roundabout data appears to have a concave shape when plotting the dependent variable as the number of crashes against the explanatory variable as the traffic volume. The logarithm operation on dependent variable, based on the default setting of the Poisson and Negative Binomial model, will mitigate this concave vertically. The additional logarithm operation on the explanatory variable will revert the data points shape back the concave configuration.

After fitting the data points to a linear term for the explanatory variable, a quadratic term seems to appear in the data trend. As a result, the author added a quadratic term to the traffic volume in the model so as to see the effects of goodness-of-fit.

The model selection process is based on both the significant level of the variables and the goodness-of-fit of the model. These two characteristics during a model selection process are usually controversy. Keeping more variables in the model will make it fit the data better, which comes at price that the variables may no longer be significant. Excluding important variables will influence the quality of goodness-of-fit. It is optimal then to find the model that has a relatively good fit to the data while keeping only the important explanatory variables.

The important explanatory variables are determined by both the significant level from the regression model and the engineering judgment. The goodness-of-fit, on the other hand, can be evaluated in multiple ways. The AIC index result from each model provides a relative quantitative measurement of the goodness-of-fit of corresponding model. The smaller value of the AIC index is preferred, since the AIC is constructed based on the difference between the number of variables included in a model and the maximized value of the likelihood function. Intuitively, the more variables included in a model, the more goodness-of-fit a model will have for its data, which will increase the maximized value of the likelihood function. However, the AIC will treat the number of variables as a penalty for an over-fitted model. This is an appropriate way to compare models with the same underlying probability assumptions, such as assuming dependent variables following a Poisson distribution.

The likelihood ratio test then provides an approach to compare models with different underlying probability assumptions, allowing a comparison between models assuming a Poisson distribution and models assuming a Negative Binomial distribution. The Poisson regression model is a special case of the Negative Binomial regression model by setting the over dispersion parameter of a Negative Binomial distribution to be 1. As a result, the mean is equal to the variance for a Poisson distribution while there is no such restriction to the Negative Binomial distribution. The latter distribution then has more flexibility in modeling crash data that is usually observed to be over dispersed. Since the author evaluated the same data using both the Poisson and the Negative Binomial model, the likelihood ratio test then tested the null hypothesis of the over dispersion parameter is equal to 1. The small p-value will indicate that the crash data is over dispersed. In this event, the Negative Binomial regression model is assumed to be more appropriate for modeling the data.

The cumulative residual plot, recommended by Hauer et al. (15), visualizes the random walk of the cumulative residuals between data and the fitted model along explanatory variables. This approach gives a graphical description of the goodness-of-fit of a model. The underlying idea of the cumulative residual is intuitive. The cumulative residuals from a regression line along explanatory variables should oscillate around the value of zero if a model fits the data well. This oscillation characteristic of cumulative residuals is usually described as the random walk or random path. This random path of cumulative residuals goes up if corresponding data points are above the regression line, otherwise the random path goes down. Thus, a good fitting regression line should be located in such a way that data points scatter around it randomly in order to have its cumulative residuals' path oscillate around the horizontal line of zero.

After fitting different models to the data, the author noted an outlier in the data set that had an unusually large number of crashes with relatively low traffic volume. The author excluded this data point from the data set for modeling only based on the engineering judgment. Ultimately the modeling results based on the original data set and the data set that does not include the outlier were quite similar.

5.1. Baseline Model of the Number of Total Crashes against Total Traffic Volume

The baseline model for the number of total crashes is developed against the total entering traffic volume. Figure 5.1 shows the scatter plot for their relationship including labels on data points that meet all baseline conditions. Table 5.1 provides the final model fitting results from both the Poisson and the Negative Binomial regression based on the data set without the outlier. The Negative Binomial model is an appropriate model to describe the relationship based on the results from AIC and likelihood ratio test. Figure 5.2 shows the scatter plot overridden with the Negative Binomial regression line and Figure 5.3 displays corresponding cumulative residual plot.

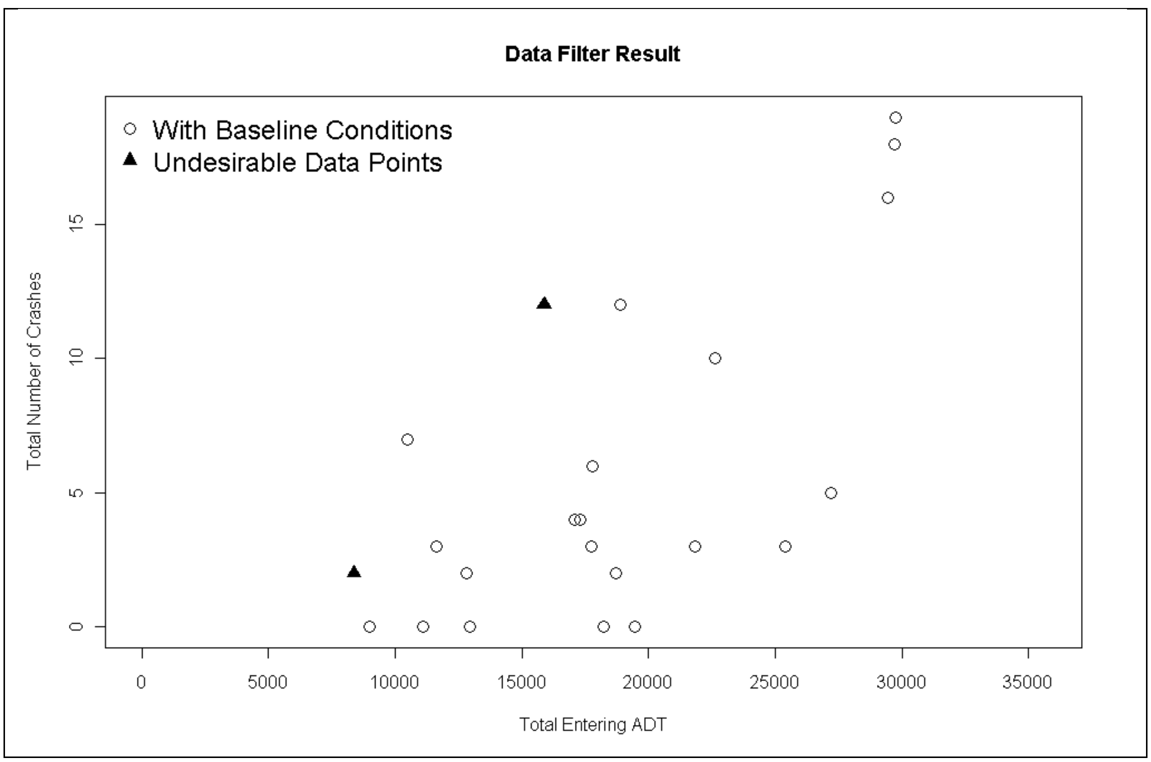


Figure 5.1: Scatter plot of total crashes against total entering volume

Table 5.1: Modeling process results for total crashes

5-year Total Crash Model (without outlier)						
Model:	Poisson Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \mathrm{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	1.292e-01	2.488e-01	0.519	0.604	
β_2	TOT_ADT^2	2.967e-09	3.635e-10	8.161	3.31e-16	***
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \mathrm{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	2.447e-01	3.577e-01	0.684	0.494	
β_2	TOT_ADT^2	2.744e-09	6.536e-10	4.198	2.69e-05	***
θ		2.74	1.98			
Over dispersion 1/θ		0.365				
		Poisson Regression		Negative Binomial Regression		
AIC		107.25		103.47		
Likelihood Ratio Test (p-valve = 0.000355)		Null Hypothesis		Alternative Hypothesis		

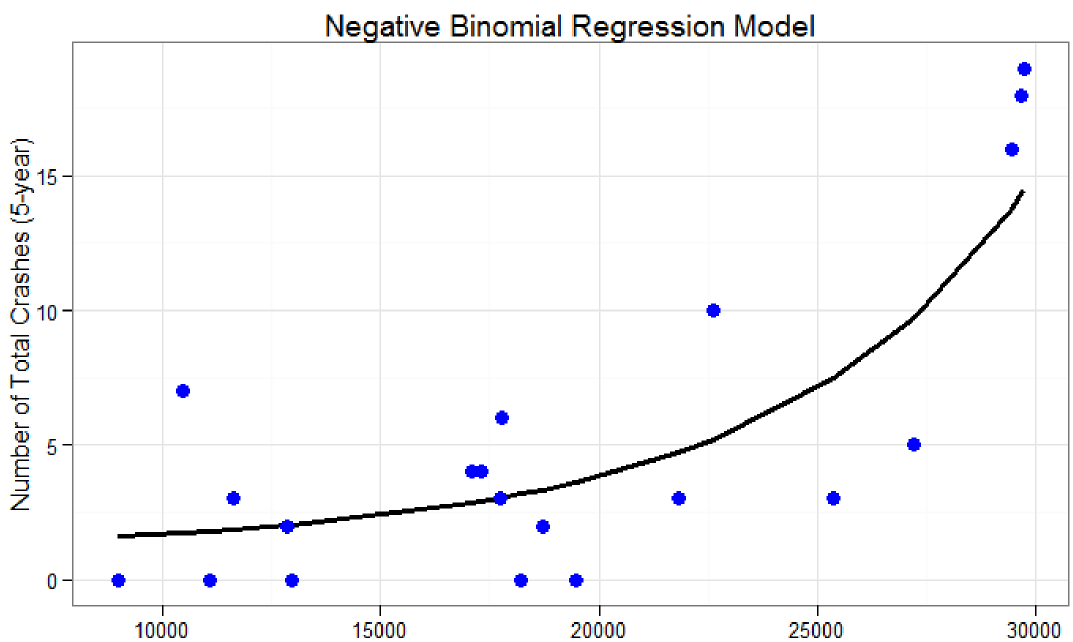


Figure 5.2: Negative Binomial regression model of total crashes

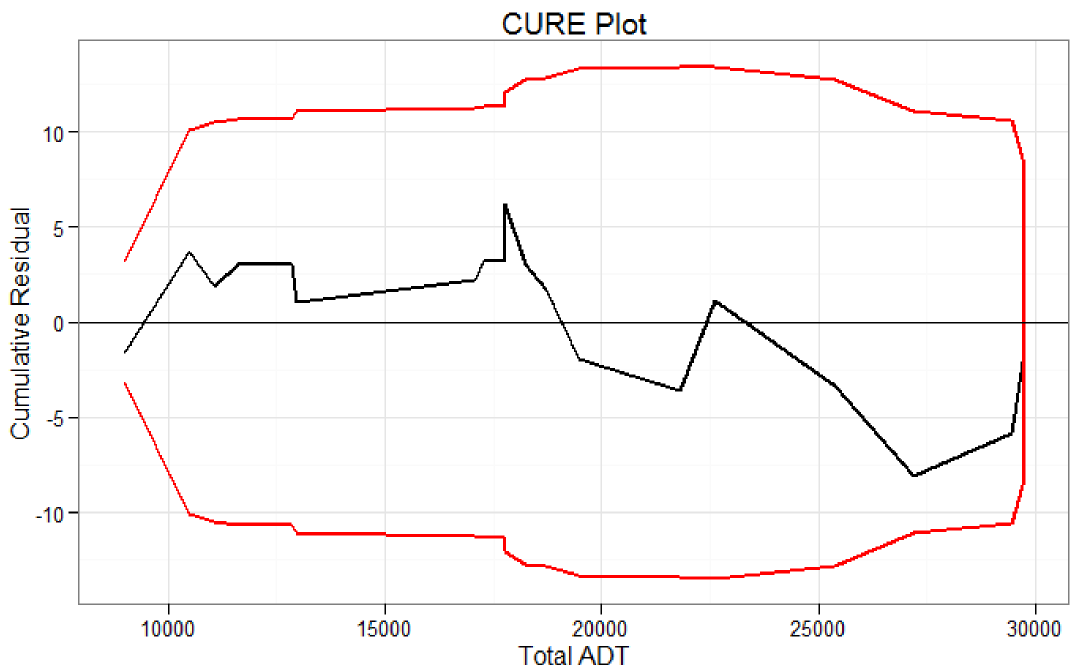


Figure 5.3: Cumulative residual plot for total crashes' model

The model for the 5-year total crash includes only the square of total traffic as an explanatory variable. A high significance level for this explanatory variable based on both regression models indicates that this variable does a good job of explaining the variation in the crash data. Both the AIC index and the likelihood ratio test give the same model selection result in favor of the Negative Binomial model. The cumulative residual plot for the Negative Binomial regression model shows a random walk that oscillates around 0. All indicators, therefore, suggest that the Negative Binomial regression model is an appropriate model for describing total crashes. The resulting regression equation is shown as follow:

$$Total\ Number\ of\ Crash\ (5\ years) = Exp[0.24 + 2.7 \times 10^{-9}(Total\ Entering\ ADT)^2]$$

Where:
Total Number of Crash (5 years) = The expected total number of crashes that will occur at a roundabout during five years, crashes
Total Entering ADT = The total entering taffic volume, vehicle/day

Valid total entering ADT range is from 8975 veh/day to 29732 veh/day

The model for estimating the annual total number of crashes can be derived from this 5-year model by dividing by 5.

$$Annual\ Total\ Number\ of\ Crash$$
$$= \frac{1}{5} Exp[0.24 + 2.7 \times 10^{-9} (Total\ Entering\ ADT)^2]$$

Where:
Annual Total Number of Crash = The expected total number of crashes per year that will occur at a roundabout, crashes/year
Total Entering ADT = The total entering taffic volume, vehicle/day
Valid total entering ADT range is from 8975 veh/day to 29732 veh/day

The author then examined models derived from data including and excluding the outlier. Figure 5.4 shows the difference between these two models is negligible.

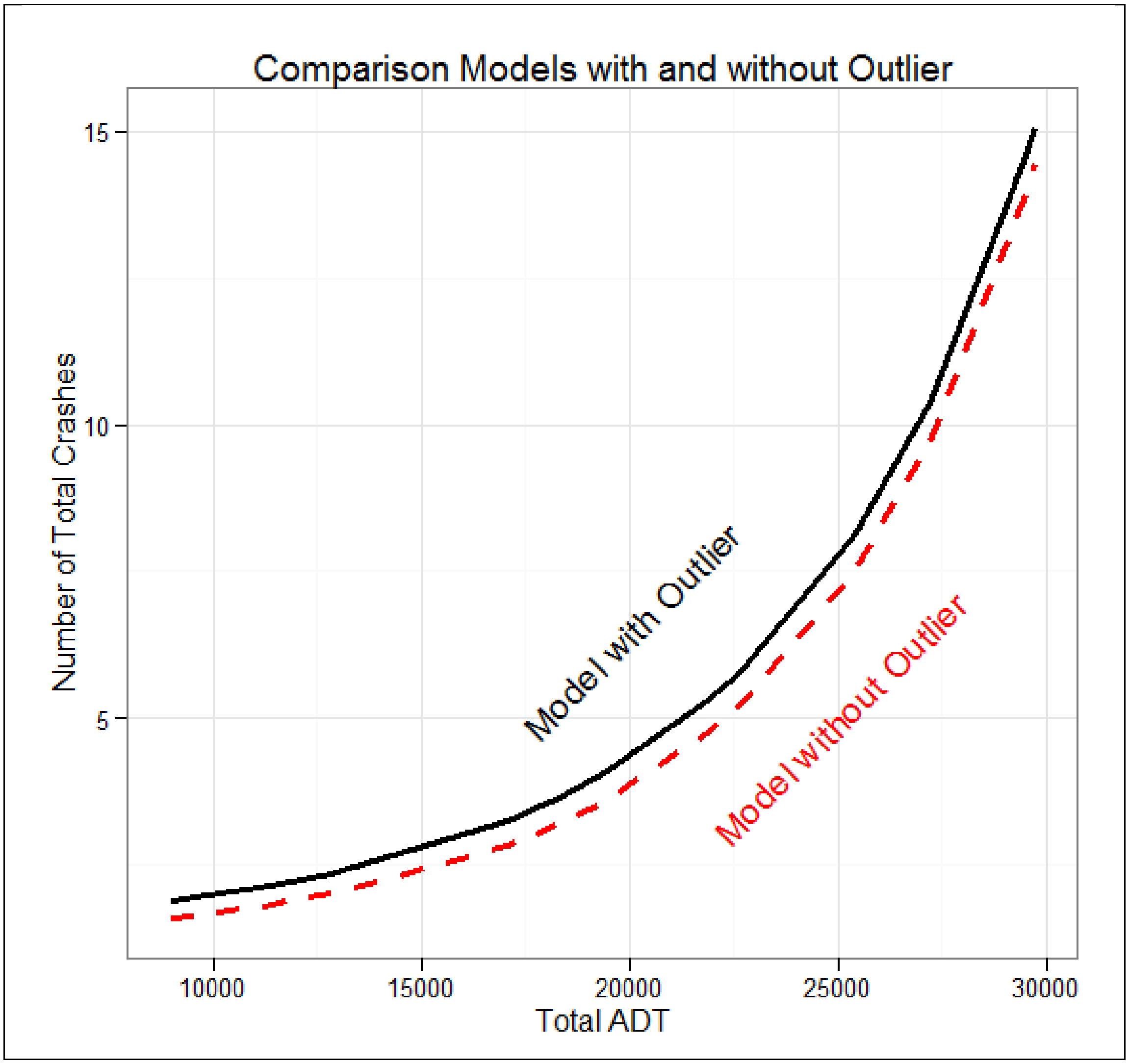


Figure 5.4: Outlier effect on model development

5.2. Baseline Model of the Number of Injury Crashes VS Total Traffic Volume

The baseline model for the number of injury crashes is developed against the total entering traffic volume. Figure 5.5 shows the scatter plot for their relationship including labels on data points that meet all baseline conditions.

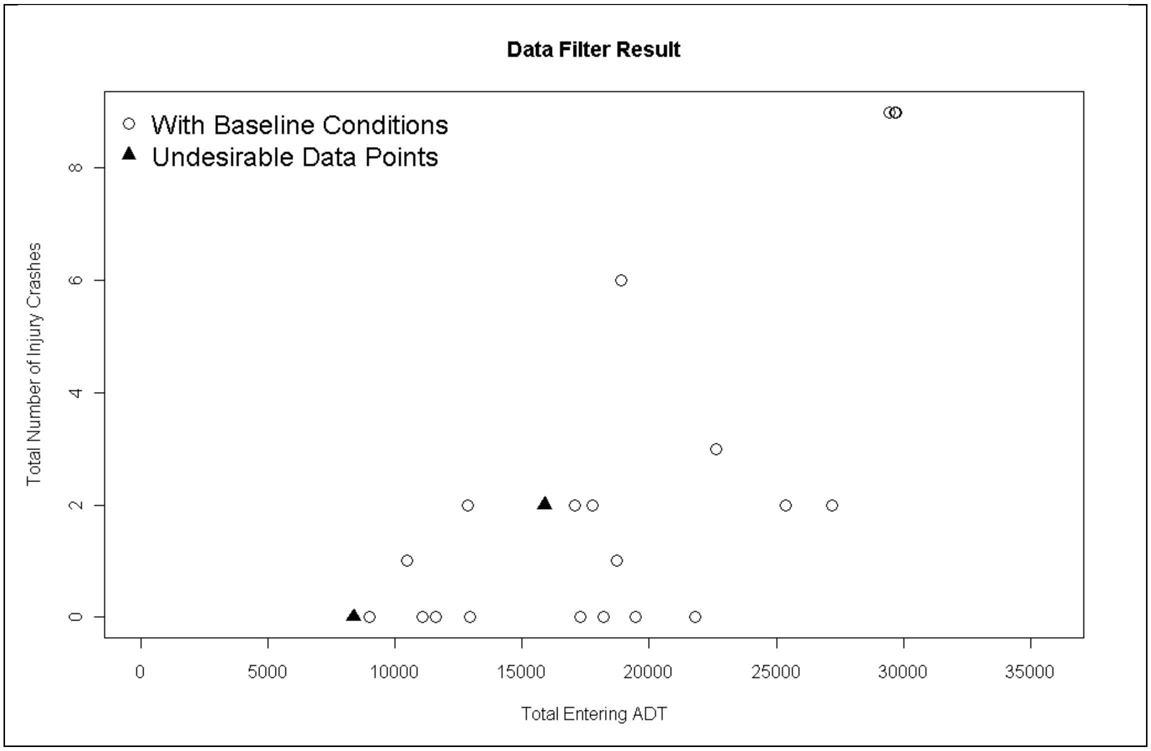


Figure 5.5: Scatter plot of injury crashes against total entering volume

When modeling the total injury crashes using the Negative Binomial regression, the model reached its iteration limit as modeling the data without the outlier. Since Negative Binomial regression has an additional parameter, the over dispersion parameter, the associated degrees of freedom is reduced for a data size that is already small. However, it is appropriate to assume the model selection process will yield analog conclusions for both data sets with or without outlier. Table 5.2 shows the modeling results based on data with the outlier. Figure 5.6 and Figure 5.7 show the

Poisson regression line and corresponding cumulative residual plot for injury crashes with the outlier, respectively.

Table 5.2: Modeling process results for injury crashes with outlier

5-year Total Injury Crash Model (with outlier)						
Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = \mathrm{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-9.558e-01	3.855e-01	-2.479	0.0132	*
β_2	TOT_ADT^2	3.456e-09	5.473e-10	6.314	2.72e-10	***
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \mathrm{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-9.219e-01	4.095e-01	-2.251	0.0244	*
β_2	TOT_ADT^2	3.395e-09	6.223e-10	5.455	4.9e-08	***
θ		11.1	36.8			
Over dispersion 1/θ		0.09				
		Poisson Regression		Negative Binomial Regression		
AIC		74.98		76.901		
Likelihood Ratio Test (p-valve = 0.778)		Null Hypothesis		Alternative Hypothesis		

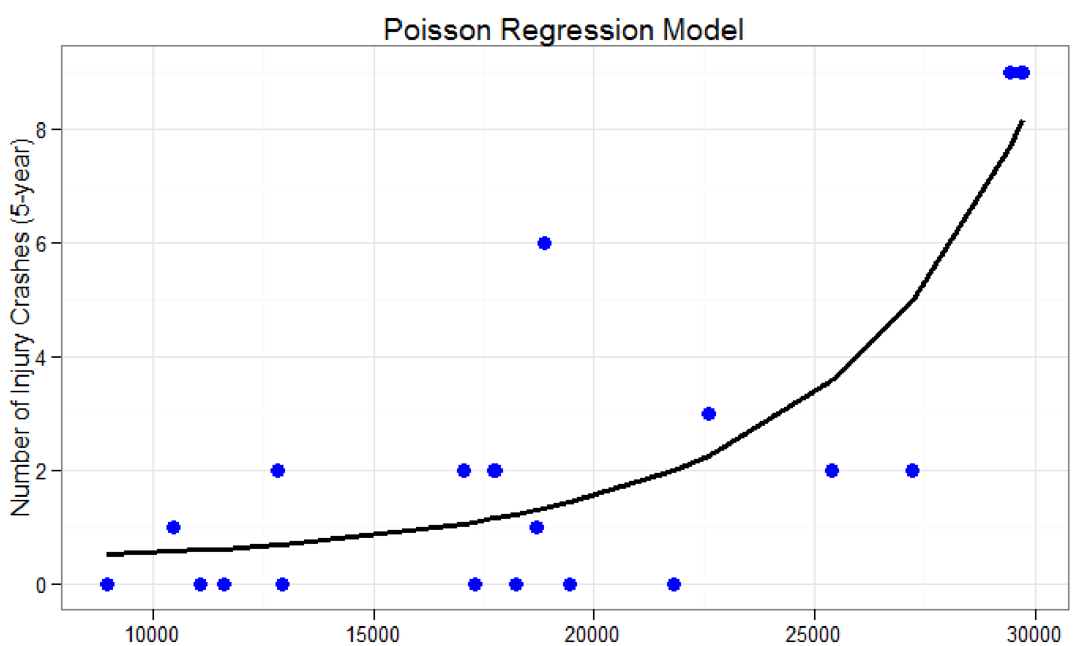


Figure 5.6: Poisson regression model for injury crashes

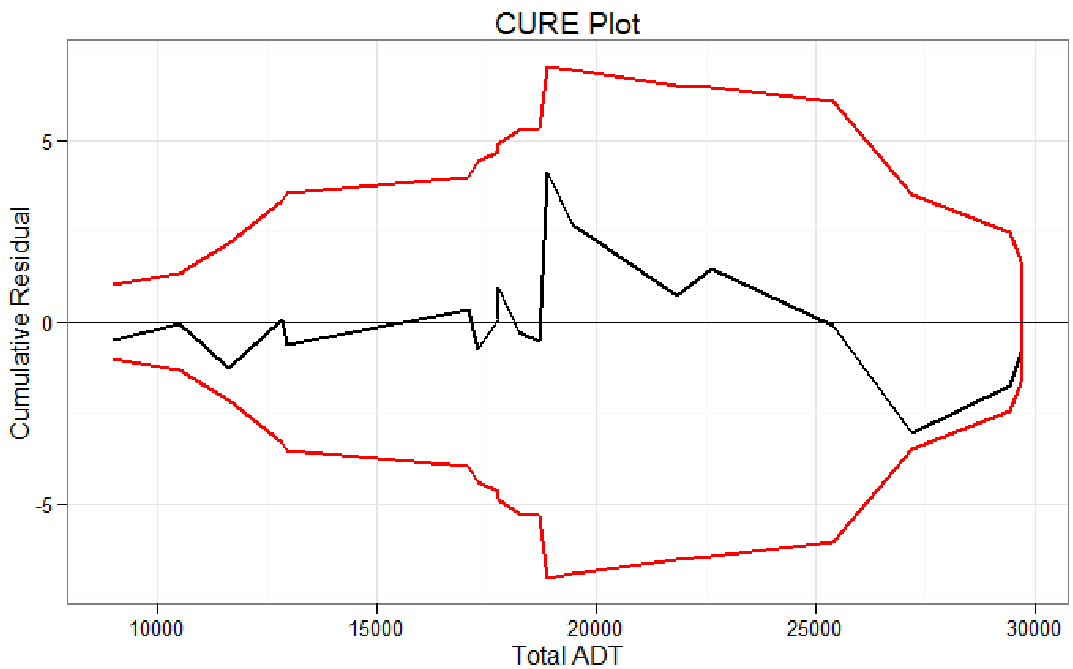


Figure 5.7: Cumulative resdual plot for injury crashes' model

The same analysis strategy applies to the model selection process for the 5-year total injury crashes. Both the AIC index and likelihood ratio test provide the same model selection preference in favor of the Poisson regression model. Even though the author could not successfully develop a Negative Binomial regression model for injury crashes without the outlier data point, it is likely that the model selection has the same result in favor of the Poisson model. The resulting Poisson regression model that is based on the data excluding the outlier point is shown in Table 5.3. Figure 5.8 and Figure 5.9 show the Poisson regression line and corresponding cumulative residual plot for injury crashes without the outlier, respectively.

Table 5.3: Modeling process results for injury crashes without outlier

5-year Total Injury Crash Model (without outlier)						
Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = \mathrm{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-1.41e+00	4.584e-01	-3.080	0.00207	**
β_2	TOT_ADT^2	3.978e-09	6.221e-10	6.395	1.61e-10	***

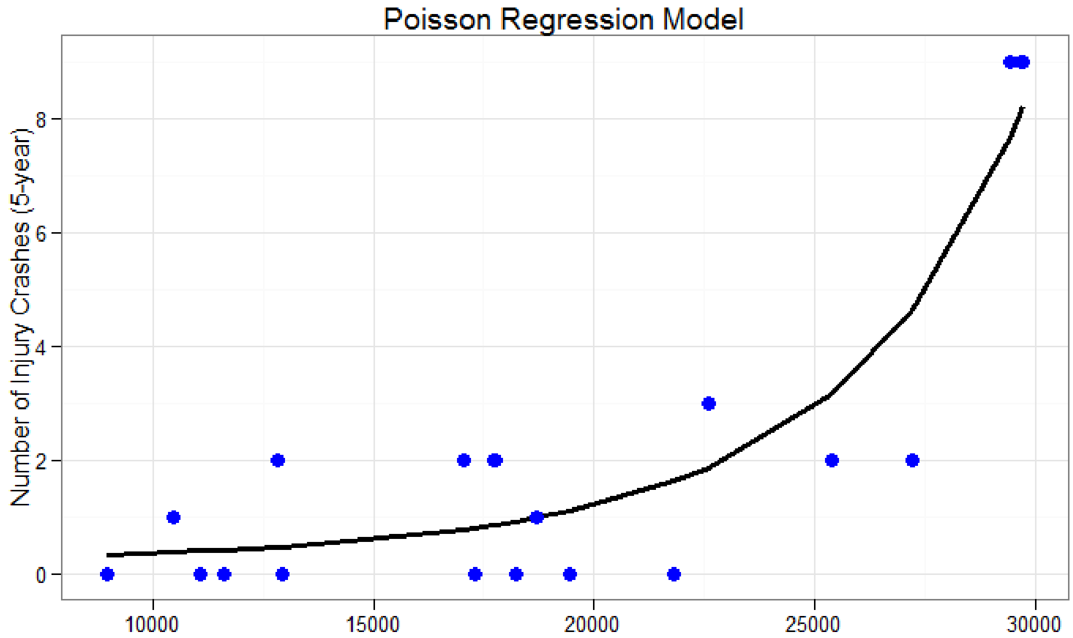


Figure 5.8: Poisson regression model for injury crashes

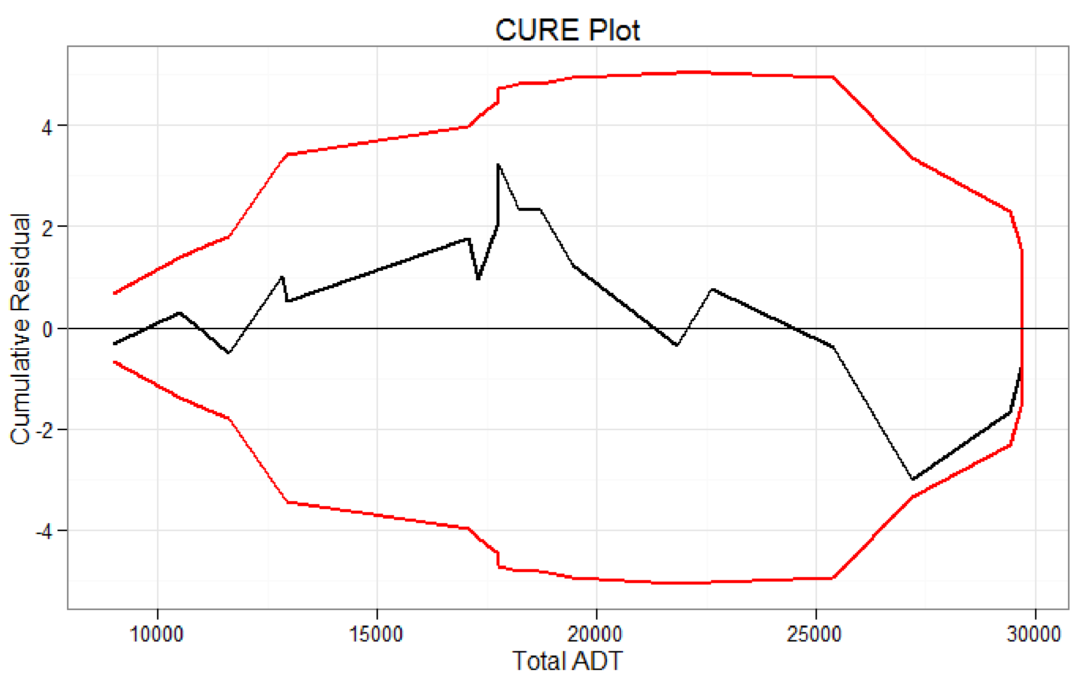


Figure 5.9: Cumulative residual plot for injury crashes' model

The final resulting Poisson regression equation is depicted as follows:

$$Total\ Number\ of\ Injury\ Crash\ (5\ years) = Exp[-1.41 + 4.0 \times 10^{-9}(Total\ Entering\ ADT)^2]$$

Where:
Total Number of Injury Crash (5 years) = The expected total number of injury crashes that will occur at a roundabout during five years, crashes
Total Entering ADT = The total entering taffic volume, vehicle/day
Valid total entering ADT range is from 8975 veh/day to 29732 veh/day

The model for estimating the total number of injury crashes for one year can be derived from this 5-year model by dividing by 5.

$$Annual\ Total\ Number\ of\ Injury\ Crash = \frac{1}{5} Exp[-1.41 + 4.0 \times 10^{-9}(Total\ Entering\ ADT)^2]$$

Where:
Annual Total Number of Injury Crash = The expected total number of crashes per year that will occur at a roundabout, crashes/year
Total Entering ADT = The total entering taffic volume, vehicle/day
Valid total entering ADT range is from 8975 veh/day to 29732 veh/day

5.3. Comparison of Models

The comparison of roundabouts model with traditional intersections model from the HSM will give an insight into the relationship of safety performance between these facilities. 4-leg Single-lane roundabouts in this study have similar baseline settings as that of traditional intersections of rural two-lane two-way road in the HSM.

The HSM provides baseline model for two types of rural intersections: stop controlled intersection and signalized intersection. Both of these two models are derived from a Negative Binomial regression process and are represented as follows:

$$N_{spf4ST} = \exp\left[-8.56 + 0.6\ln\left(AADT_{Major}\right) + 0.61\ln\left(AADT_{minor}\right)\right]$$

$$N_{spf4SG} = \exp\left[-5.13 + 0.6\ln\left(AADT_{Major}\right) + 0.2\ln\left(AADT_{minor}\right)\right]$$

N_{spf4ST} represents the predicted number of annual total crashes at a stop controlled intersection under baseline conditions. N_{spf4SG} represents the predicted number of annual total crashes at a signalized intersection under baseline conditions. $AADT_{Major}$ and $AADT_{minor}$ represent major traffic volume and minor volume, respectively, in units of vehicles per day.

The baseline conditions on which these two models are developed include no skewed intersections, no lighting systems and no left and right turn lanes. In order to make fair comparisons, the baseline settings need to be consistent between these traditional intersection models and the roundabout model.

Since all roundabouts in the data set had street lights, a CMF of the lighting system should be applied to the baseline model for the traditional intersections so as to adjust the predicted number of crashes to a value representative of the presence of street lights. The CMF for lighting is shown as follow:

$$CMF_{lighting} = \begin{cases} 4ST: 1 - 0.38 \times 0.244 = 0.90728 \\ 4SG: 1 - 0.38 \times 0.286 = 0.89132 \end{cases}$$

Basically, the presence of street lights will reduce the predicted number of total crashes due to the fact that this corresponding CMF is always less than one. Then the predicted number of crashes is adjusted by multiplying this CMF by the baseline models.

The intersection skew does not directly apply to roundabouts. The traditional intersection models were developed under the condition of no intersection skew. The HSM provides CMFs for both models in order to account for the variation from the baseline condition of no intersection skew.

$$CMF_{skew}\ for\ 4ST = \begin{cases} e^{0.0054 \times skew}, presence\ of\ skew\ (skew = 1) \\ 1 \qquad\qquad\quad , absence\ of\ skew\ (skew = 0) \end{cases}$$

$$CMF_{skew}\ for\ 4SG = 1, presence\ or\ absence\ of\ skew$$

The CMFs for intersection skew are always equal to or larger than one, which indicates that the intersection skew feature will be associated with more crashes. Since one of the objectives of this comparison is to see how well the roundabouts improve safety performance of an intersection, setting the CMF of intersection skew to be 1 will result in lower crash numbers at traditional intersection, resulting in a conservative comparison evaluation.

Thus, the author compared the two groups of safety performance models between traditional intersections under rural two-lane two-way road settings with roundabouts.

Based on different traffic volume thresholds, the author calculated the predicted number of annual total crashes for different intersection characteristics under similar baseline conditions. The aim of this calculation is to visualize the difference in trends for the predicted number of crashes for different models so as to see how well roundabouts improve safety performance for an intersection when compared to traditional intersections. As shown in Figure 5.10, circle dots represent observations of annual total crashes for roundabouts in the data set. Triangles represent the predicted number of annual total crashes for 4-leg stop controlled intersections with the same traffic volumes as the corresponding roundabouts. Squares represent the predicted number of annual total crashes for 4-leg signalized intersections with the same traffic volumes as the corresponding roundabouts. The regression line represents the predicted trend of number of annual total crashes for roundabouts. As shown in Figure 5.10, the overall predicted numbers of roundabout crashes are less than the overall predicted numbers of crashes for traditional intersections under similar settings. This figure provides evidence that roundabouts actually improve safety performance of an intersection for the ADT thresholds considered in this study.

Table 5.4: Comparison groups' settings

<table>
<tr><td rowspan="4">Traditional Intersections</td><td colspan="2">$N_{spf4ST} = CMF_{lighting} \times CMF_{skew} \times \exp\left[-8.56 + 0.6\ln\left(AADT_{Major}\right) + 0.61\ln\left(AADT_{minor}\right)\right]$</td></tr>
<tr><td>$Over\ dispersion = 0.24$</td><td>Input Range:
$AADT_{Major} = [0, 14700]$
$AADT_{minor} = [0, 3500]$</td></tr>
<tr><td colspan="2">$N_{spf4SG} = CMF_{lighting} \times CMF_{skew} \times \exp\left[-5.13 + 0.6\ln\left(AADT_{Major}\right) + 0.2\ln\left(AADT_{minor}\right)\right]$</td></tr>
<tr><td>$Over\ dispersion = 0.11$</td><td>$AADT_{Major} = [0, 25200]$
$AADT_{minor} = [0, 12500]$</td></tr>
<tr><td rowspan="2">Roundabouts</td><td colspan="2">$Annual\ Total\ Number\ of\ Crash = \frac{1}{5} Exp[0.24 + 2.7 \times 10^{-9}(Total\ Entering\ ADT)^2]$</td></tr>
<tr><td>$Over\ dispersion = 0.34$</td><td>$AADT_{Total} = [8975, 29732]$</td></tr>
</table>

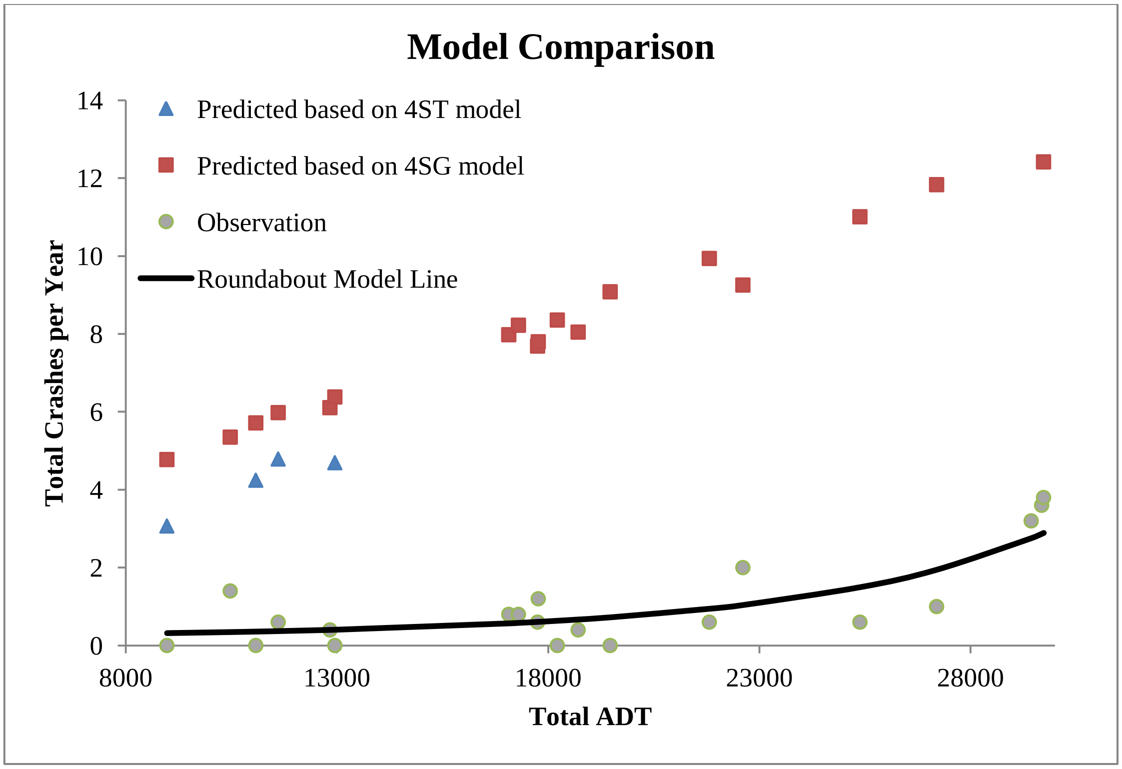


Figure 5.10: Model comparison between roundabouts and traditional intersections

The modeling results indicate that the number of crashes has a strong positive relationship with corresponding traffic volumes as the increase in traffic volume will result in the increase for the number of crashes at a roundabout. The Poisson and the Negative Binomial regression models are developed for modeling total crashes and injury crashes. The final models are selected based on the results of AIC index and likelihood ratio test. Model comparison results provide evidence that roundabouts, based on this study, are involved with fewer crashes than traditional intersections under similar baseline conditions. One example for applying the results of this study is provided next.

5.4. Roundabout Model Application Procedure

1. Check baseline conditional settings for roundabouts to which the model is applied:

    - Raised central island present,
    - Truck apron present,
    - No bicycle lane,
    - Sidewalk present,
    - Splitter island associated with a pedestrian refuge area,
    - Lighting system present,
    - No bypass lane,
    - Center alignment design,
    - No oval roundabouts,
    - Inscribed circle diameter of approximately 135 ft.,
    - Circulating lane width of approximately 16 ft., and
    - 15 mph circulating speed limit.

2. Identify the traffic volumes from both Major and Minor Streets. Compare traffic volume values from Table 5.5.

Table 5.5: Valid traffic volumes range

	Traffic Volume Range (Average Daily Traffic)	
	Minimum	Maximum
Major Street ADT	6430	19350
Minor Street ADT	1400	13285
Total Entering ADT	8975	29732

3. Estimate the number of annual total crashes or injury crashes through roundabout models provided in Table 5.6 if all baseline conditions and volume criteria are met. Figure 5.11 shows the regression lines for these two model.

Table 5.6: Roundabout models

Estimate Value	Model	Over Dispersion Parameter
Annual total crashes	$N = \frac{1}{5}\mathrm{e}^{[0.245+2.7\times10^{-9}(Total\ Entering\ ADT)^2]}$	0.365
Annual total injury crashes	$N = \frac{1}{5}\mathrm{e}^{[-1.41+4.0\times10^{-9}(Total\ Entering\ ADT)^2]}$	1

4. Report the results in terms of annual total crashes or annual total injury crashes.

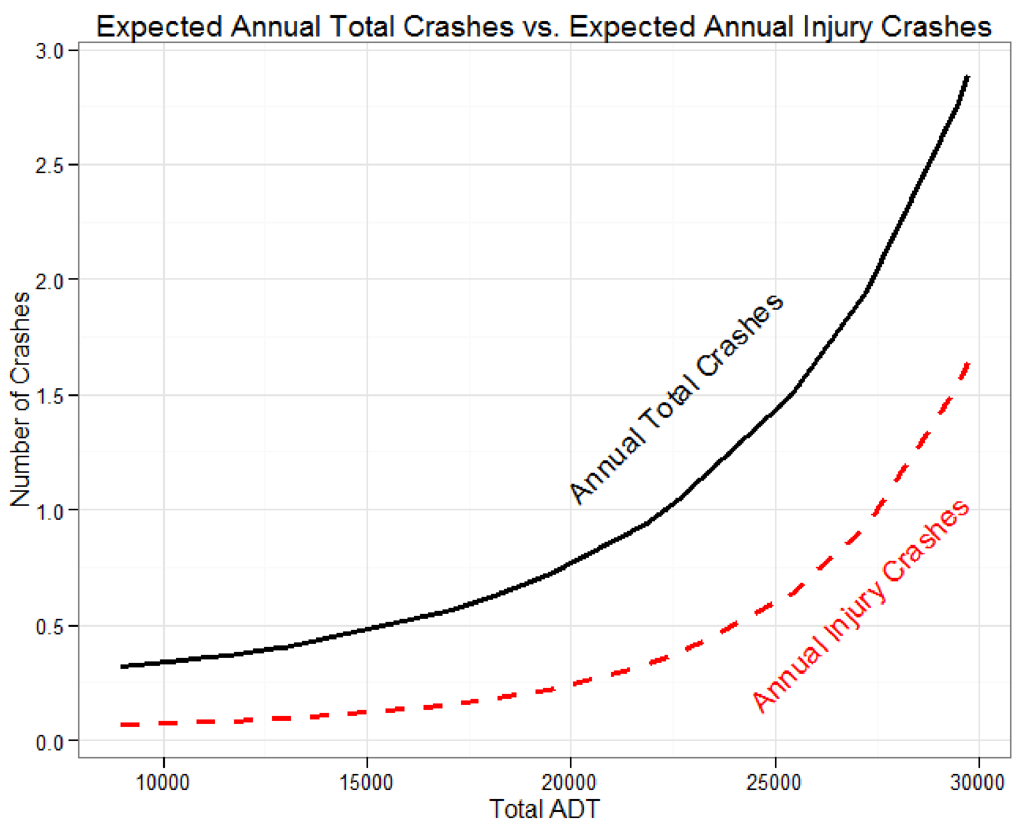


Figure 5.11: Annual total crashes and annual injury crashes regression lines

5.5. Application Example

Example:

Department of Transportation wants to evaluate the safety performance of the site shown in Figure 5.12. This site locates in Bend, Oregon.

Figure 5.12: Sample Site OR-S4-16, Bend, Oregon

The important quantitative features of this roundabout are listed in:

Table 5.7: Sample input for roundabout example from Bend, Oregon

Important Quantitative Feature	Value
Inscribed Circle Diameter	157 ft.
Circulating Lane Width	20 ft.
Major Traffic Volume	18748 vehicle/day
Minor Traffic Volume	10984 vehicle/day
Total Entering Volume	29732 vehicle/day

Step 1: Check this roundabout meets all baseline conditions.

- ✓ Raised central island present,
- ✓ Truck apron present,
- ✓ No bicycle lane,
- ✓ Sidewalk present,
- ✓ Splitter island associated with a pedestrian refuge area,
- ✓ Lighting system present,
- ✓ No bypass lane,
- ✓ Center alignment design,
- ✓ No oval roundabouts,
- ✓ Inscribed circle diameter of approximately 135 ft.,
- ✓ Circulating lane width of approximately 16 ft., and
- ✓ 15 mph circulating speed limit.

Step 2: Check traffic volume within the volume range based on Table 5.5**.**
The Major ADT range is from 6430 to 19350 vehicle/day. The Major ADT that this site has is 18748 vehicle/day, which is within the range. The Minor ADT range is from 1400 to 13285 vehicle/day. The Minor ADT that this site has is 10984 vehicle/day, which is within the range. The total entering volume range is from 8975 to 29732 vehicle/day. The total entering volume that this site has is 29732 vehicle/day, which is within the range.

Step 3: Calculate the predicted annual total crashes using Table 5.6**.**

$$\text{Annual total crashes} = \frac{1}{5}\mathrm{e}^{[0.245+2.7\times10^{-9}(Total\ Entering\ ADT)^2]}$$

$$\text{Annual total crashes} = \frac{1}{5}\mathrm{e}^{[0.245+2.7\times10^{-9}(29732)^2]} = 2.78 \text{ crashes}$$

Step 4: Calculate the predicted annual injury crashes using Table 5.6**.**

$$\text{Annual injury crashes} = \frac{1}{5}\mathrm{e}^{[-1.41+4.0\times10^{-9}(Total\ Entering\ ADT)^2]}$$

$$\text{Annual injury crashes} = \frac{1}{5}\mathrm{e}^{[-1.41+4.0\times10^{-9}(29732)^2]} = 1.68 \text{ crashes}$$

Step 5: Report the results.
It predicts that totally 3 roundabout related crashes (round from 2.78) will occur on this site. It also predicts that 2 injury crashes (round from 1.68) will occur on this site.

6. CONCLUSION

The simple before-after study is a commonly used method to address safety performance issues. The idea of a before-after study is straightforward as it compares the safety performance of two groups of facilities. This study is similar to research in the medical field where patients are usually separated into two groups. Patients who are in the treatment group receive medicine. On the other hand, the control group receives the same amount of pseudo medicine. The researcher then compares recover times of these two groups so as to test the effect of that medicine.

Extending this example to transportation, the treatments would be the change of geometric features. The aim of the before-after study is to attribute the difference in number of crashes occurred from these two groups to these corresponding geometric changes. Similar to medicine research in which two groups of patients are usually selected to be of similar age and condition, the researcher has to make sure that the two groups of traffic facilities have similar traffic exposure. Since the traffic exposure significantly influences the safety performance, it will be difficult to attribute the effects on safety performance to either geometric changes or the change of traffic exposure.

The before-after study of the conversion of traditional intersections to roundabouts compares safety performance between a group of traditional intersections and a group of roundabouts. Both groups of facilities are supposed to have similar traffic exposures or traffic volumes in both pre and post roundabout construction periods so as to exclude the effect of traffic volume on safety performance. Since this conversion involves the change of the nature of an intersection, the treatment that this study tests on safety performance is the construction of the roundabout rather than a specific change of feature. This test results would then reveal the overall effect of a roundabout on its pre-roundabout intersection. It is usually difficult to find groups of sites that have similar traffic volumes during both pre and post roundabout construction periods.

This deficiency of a before-after study leads researchers to conduct cross-sectional studies for evaluating the safety performance of roundabouts. The cross-sectional study basically uses statistical regression techniques to address safety performance of roundabouts. There are not as many restrictions on data collection for this study as that for a before-after study. The cross-sectional statistical analysis provides a regression line that represents the relationship between crash occurrences, traffic exposures, and geometric features. Since the HSM includes models for traditional intersections, comparing the predicted number of crashes based on different models serves as an alternative approach to reveal the effect of roundabouts on safety performance. The baseline condition for each model plays an important role in the comparison process. Since the goal of such an analysis is to see the safety effect of a roundabout, it is important to have models based on similar settings so as to yield sound comparison results.

Based on the results of baseline models from this thesis, the safety performance of a roundabout has a strong relationship with its associated traffic exposure. As a summary, the baseline conditions and statistical relationships are illustrated in Table 6.1.

The result of comparing annual total crash models for roundabouts to models of traditional intersections based on the HSM procedures provides strong graphical evidence that roundabouts reduce the total number of crashes.

The author could not develop a multivariate full model for roundabout safety performance due to the relatively small sample size. The author did not analyze safety performance of roundabouts on pedestrians since crash data that related to pedestrians at roundabouts was insufficient for developing sound statistical analysis (shown in Table 4.7). As previously indicated, most of the roundabouts in the data set were located in rural areas or suburban areas where pedestrian related crashes are minimal. Section 4.4.4 provides the range of features for the data set, including the statistically significant traffic volume. The results from this thesis can only be applied to roundabout locations with similar ranges. As there are only a limited number of 4-leg, one-lane roundabouts in Oregon, it is not feasible at this time to evaluate the safety performance of roundabouts for high traffic exposures.

Table 6.1: Summary of roundabout models

Baseline Models for Roundabouts	
Baseline Conditions: • Raised central island present, • Truck apron present, • No bicycle lane, • Sidewalk present, • Splitter island associated with a pedestrian refuge area, • Lighting system present, • No bypass lane, • Center alignment design, • No oval roundabouts, • Inscribed circle diameter of approximately 135 ft., • Circulating lane width of approximately 16 ft., and • 15 mph circulating speed limit.	
Total Crashes VS Total Traffic Volume	$Total\ Number\ of\ Crash\ (5\ years) = Exp[0.24 + 2.7 \times 10^{-9}(Total\ Entering\ ADT)^2]$
Annual Total Crashes VS Total Traffic Volume	$Annual\ Total\ Number\ of\ Crash = \frac{1}{5}Exp[0.24 + 2.7 \times 10^{-9}(Total\ Entering\ ADT)^2]$
Injury Crashes VS Total Traffic Volume	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = Exp[-1.41 + 4.0 \times 10^{-9}(Total\ Entering\ ADT)^2]$
Annual Injury Crashes VS Total Traffic Volume	$Annual\ Total\ Number\ of\ Injury\ Crash = \frac{1}{5}Exp[-1.41 + 4.0 \times 10^{-9}(Total\ Entering\ ADT)^2]$
Valid Total Entering ADT Range	Minimum: 8975 veh/day Maximum: 29732 veh/day

In conclusion, the cross-sectional study actually provides a way to summarize previous before-after studies. The underlying traffic conditions influence the safety performance substantially.

The SPFs that the author developed include a quadratic term for the traffic volume as the explanatory variable, thereby suggesting that the safety performance of a roundabout is sensitive to its traffic exposure. As shown in Figure 5.10, there seems to be a turning point where high traffic exposure at the study roundabouts tends to start performing worse and involving with more crashes. The quadratic term makes roundabout model appear to be a convex function whereas model for signalized intersections has a concave curve. This observation makes sense, since signalized intersections are traffic controlled using traffic signal devices and these signals help to control vehicles as the traffic exposure increases. Figure 5.10 suggests that there might be a higher traffic volume value where roundabouts eventually perform worse than signalized intersections in safety.

The author would recommend that it is suitable to construct roundabouts in places that have low and moderate traffic exposure levels. Caution should be exercised when putting sing-lane roundabouts in conjunction with high traffic volume locations such like intersections in dense urban areas. High traffic exposures might make roundabout inefficient according to evidence that the author observed during the data collection process.

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8. APPENDIX A ABBREVIATIONS AND ACRONYMS

Table 8.1: Abbreviations and acronyms

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
CMF	Crash Modification Factors
HSM	Highway Safety Manual
ODOT	Oregon Department of Transportation
SPF	Safety Performance Function

9. APPENDIX B BRIEF SUMMARY OF INVENTORY DATA

Table 9.1: Some Important Inventory Data

SITE ID	SITE ID LOGIC	PRESENCE RAISED CENTRAL ISLAND	PRESENCE TRUCK APRON	PRESENCE SIDEWALK	PRESENCE PRA	PRESENCE LIGHTING
123	OR-S4-1	X	X	X	X	X
145	OR-S4-2	X	X	X	X	X
250	OR-S4-3	X	X	X	X	X
252	OR-S4-4	X	X	X	X	X
253	OR-S4-5	X	X	X	X	X
254	OR-S4-6	X	X	X	X	X
255	OR-S4-7	X	X	X	X	X
256	OR-S4-8	X	X	X	X	X
257	OR-S4-9	X	X	X	X	X
258	OR-S4-10	X	X	X	X	X
261	OR-S4-11	X	X	X	X	X
426	OR-S4-13	X	X	X	X	X
427	OR-S4-14	X	X	X	X	X
463	OR-S4-15	X	X	X	X	X
465	OR-S4-16	X	X	X	X	X
466	OR-S4-17	X	X	X	X	X
470	OR-S4-18	X	X	X	X	X
540	OR-S4-19	X	X	X	X	X
637	OR-S4-21	X	X	X	X	X
710	OR-S4-22	X	X	X	X	X
938	OR-S4-24	X		X		X
975	OR-S4-25	X	X	X	X	X
1621	OR-S4-26	X	X	X	X	X

10. APPENDIX C TRAFFIC VOLUME DATA

Table 10.1: Raw Traffic Volume Data

Site ID	Site No.	Street	Location of Leg	Volume Type	AADT/ADT
OR-S4-1	123	Stevens RD	N	ADT	6250
OR-S4-1	123	Monterey Ave	E	ADT	1400
OR-S4-1	123	Stevens RD	S	ADT	7575
OR-S4-1	123	Monterey Ave	W	ADT	412
OR-S4-2	145	SW Century DR	N	ADT	8982
OR-S4-2	145	SW Colorado Ave	E	ADT	9730
OR-S4-2	145	SW Century DR	S	ADT	8654
OR-S4-2	145	SW Colorado Ave	W	ADT	6325
OR-S4-3	250	Mt Washington	N	ADT	9088
OR-S4-3	250	Skyliners	E	ADT	2272
OR-S4-3	250	Mt Washington	S	ADT	9215
OR-S4-3	250	Skyliners	W	ADT	2395
OR-S4-4	252	Mt Washington	N	ADT	5379
OR-S4-4	252	Shevlin Park	E	ADT	7160
OR-S4-4	252	Mt Washington	S	ADT	7150
OR-S4-4	252	Shevlin Park	W	ADT	5675
OR-S4-5	253	Mt Washington	N	ADT	7150
OR-S4-5	253	Crossing	E	ADT	843
OR-S4-5	253	Mt Washington	S	ADT	9088
OR-S4-5	253	Crossing	W	ADT	1992
OR-S4-6	254	Century	N	ADT	8654
OR-S4-6	254	Mt Washington	E	ADT	10837
OR-S4-6	254	Century	S	ADT	8054
OR-S4-6	254	Mt Washington	W	ADT	6628
OR-S4-7	255	14th	N	ADT	16402
OR-S4-7	255	Simpson	E	ADT	10604
OR-S4-7	255	Century	S	ADT	8982
OR-S4-7	255	Simpson	W	ADT	3908
OR-S4-8	256	14th	N	ADT	13285
OR-S4-8	256	Galveston	E	ADT	16402
OR-S4-8	256	17th	S	ADT	13261
OR-S4-8	256	Galveston	W	ADT	4980
OR-S4-9	257	14th	N	ADT	215
OR-S4-9	257	Newport	E	ADT	13410
OR-S4-9	257	14th	S	ADT	13156

Site ID	Site No.	Street	Location of Leg	Volume Type	AADT/ADT
OR-S4-9	257	Newport	W	ADT	16283
OR-S4-10	258	9th	N	ADT	7850
OR-S4-10	258	Newport	E	ADT	16014
OR-S4-10	258	Nashville	S	ADT	
OR-S4-10	258	Newport	W	ADT	19350
OR-S4-11	261	Terwilling Blvd	N	ADT	12125
OR-S4-11	261		E	ADT	5863
OR-S4-11	261	Terwilling Blvd	S	ADT	5174
OR-S4-11	261	Palater Rd	W	ADT	3611
OR-S4-13	426	Carman Dr	N	ADT	9150
OR-S4-13	426	Quarry	E	ADT	4885
OR-S4-13	426	Carman Dr	S	ADT	8790
OR-S4-13	426	Meadow	W	ADT	8602
OR-S4-14	427	Colorado	N	ADT	15869
OR-S4-14	427	Simpson	E	ADT	1673
OR-S4-14	427	Colorado	S	ADT	5949
OR-S4-14	427	Simpson	W	ADT	9625
OR-S4-15	463	8th	N	ADT	11266
OR-S4-15	463	Franklin	E	ADT	9077
OR-S4-15	463	9th	S	ADT	11412
OR-S4-15	463	Franklin	W	ADT	11201
OR-S4-16	465	Bond	N	ADT	11041
OR-S4-16	465	Reed Mkt	E	ADT	18748
OR-S4-16	465	Blakely	S	ADT	10984
OR-S4-16	465	Reed Mkt	W	ADT	10837
OR-S4-17	466	Century Dr	N	ADT	6233
OR-S4-17	466	Reed Mkt	E	ADT	10837
OR-S4-17	466	Century Dr	S	ADT	3800
OR-S4-17	466	Reed Mkt	W	ADT	10837
OR-S4-18	470	58th	N	ADT	6430
OR-S4-18	470	Thruston	E	ADT	5863
OR-S4-18	470	58th	S	ADT	4045
OR-S4-18	470	Thruston	W	ADT	
OR-S4-19	540	Stafford	N	ADT	10570
OR-S4-19	540	Rosemont	E	ADT	6914
OR-S4-19	540	Stafford	S	ADT	11305
OR-S4-19	540	Atherton	W	ADT	333
OR-S4-21	637	Marsh	N	ADT	204

Site ID	Site No.	Street	Location of Leg	Volume Type	AADT/ADT
OR-S4-21	637	Verboort	E	ADT	14488
OR-S4-21	637	Martin	S	ADT	6333
OR-S4-21	637	Verboort	W	ADT	4982
OR-S4-22	710	15th	N	ADT	8859
OR-S4-22	710	Bear Creek	E	ADT	8281
OR-S4-22	710	15th	S	ADT	9487
OR-S4-22	710	Bear Creek	W	ADT	4922
OR-S4-24	938	Juniper Terrace	N	ADT	1525
OR-S4-24	938	Sorrento Rd	E	ADT	6846
OR-S4-24	938	Juniper Terrace	S	ADT	6846
OR-S4-24	938	Sorrento Rd	W	ADT	1000
OR-S4-25	975	Highland	N	ADT	6595
OR-S4-25	975	Siskiyou	E	ADT	5268
OR-S4-25	975	Highland	S	ADT	9288
OR-S4-25	975	Siskiyou	W	ADT	7537
OR-S4-26	1621	Roshak Rd	N	ADT	1531
OR-S4-26	1621	Barrows Rd	E	ADT	11006
OR-S4-26	1621	Roshak Rd	S	ADT	1946
OR-S4-26	1621	Barrows Rd	W	ADT	11006

Table 10.2: Traffic Volume Data for Modeling

SITE_ID	SITE_ID_LOGIC	MAJ_ADT	MIN_ADT	TOT_ADT
123	OR-S4-1	7575	1400	8975
145	OR-S4-2	9730	8982	18712
250	OR-S4-3	9215	2395	11610
252	OR-S4-4	7160	5675	12835
253	OR-S4-5	9088	1992	11080
254	OR-S4-6	10837	8054	18891
255	OR-S4-7	16402	8982	25384
256	OR-S4-8	16402	13285	29687
257	OR-S4-9	16283	13156	29439
258	OR-S4-10	19350	7850	27200
261	OR-S4-11	12125	5174	17299
426	OR-S4-13	9150	8602	17752
427	OR-S4-14	15869	5949	21818
463	OR-S4-15	11412	11201	22613
465	OR-S4-16	18748	10984	29732
466	OR-S4-17	10837	6233	17070
470	OR-S4-18	6430	4045	10475
540	OR-S4-19	11305	6914	18219
637	OR-S4-21	14488	4982	19470
710	OR-S4-22	9487	8281	17768
938	OR-S4-24	6846	1525	8371
975	OR-S4-25	9288	6595	15883
1621	OR-S4-26	11006	1946	12952

11. APPENDIX D MODELING TRIAL SUMMARY

This section shows efforts that the author made for model comparison and selection process. The goal of these efforts is to finalize models for total crashes and total injury crashes. Four different candidate model configurations based on two different data sets have been combined for developing models.

Table 11.1: Attempts for modeling total crashes

Models of Total Crash		
Model	Data	
	Include outlier	Exclude outlier
$ln(crash) \sim TOT\_ADT$	***Section 1***	***Section 4***
$ln(crash) \sim TOT\_ADT + TOT\_ADT^2$	***Section 2***	***Section 5***
$ln(crash) \sim TOT\_ADT^2$	***Section 3***	***Section 6***
Reference Model		
$ln(crash) \sim ln(TOT\_ADT)$	***Section 7***	***Section 8***

Table 11.2: Attempts for modeling injury crashes

Models of Injury Crash		
Model	Data	
	Include outlier	Exclude outlier
$ln(inj\ crash) \sim TOT\_ADT$	***Section 9***	***Section 12***
$ln(inj\ crash) \sim TOT\_ADT + TOT\_ADT^2$	***Section 10***	***Section 13***
$ln(inj\ crash) \sim TOT\_ADT^2$	***Section 11***	***Section 14***
Reference Model		
$ln(inj\ crash) \sim ln(TOT\_ADT)$	***Section 15***	***Section 16***

1. Total Crash Model with Explanatory Variable of TOT_ADT (Include outlier)

Table 11.3: Summary of total crash model with explanatory variable of TOT_ADT (include outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = Exp(\beta_1 + \beta_2 Total\ Entering\ ADT)$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-7.649e-01	3.752e-01	-2.039	0.0415	*
β_2	TOT_ADT	1.162e-04	1.536e-05	7.560	4.02e-14	***
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ of\ Crash\ (5\ years) = Exp(\beta_1 + \beta_2 Total\ Entering\ ADT)$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-5.474e-01	6.460e-01	-0.847	0.396781	
β_2	TOT_ADT	1.060e-04	3.048e-05	3.479	0.000503	***
θ		1.90	1.05			
Over dispersion 1/θ		0.526				

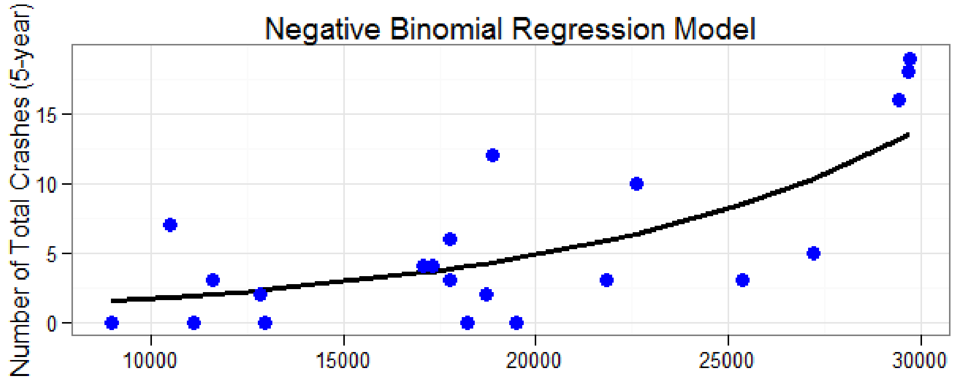

Figure 11.1: Regression model

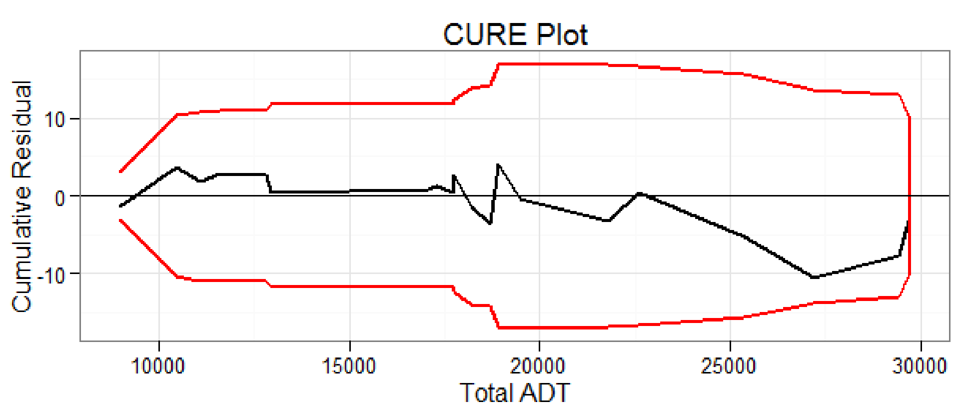

Figure 11.2: Cumulative residual plot

2. Total Crash Model with Explanatory Variable of TOT_ADT+TOT_ADT^2 (Include outlier)

Table 11.4: Summary of total crash model with explanatory variable of TOT_ADT+TOT_ADT^2 (include outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \text{Exp}[\beta_1 + \beta_2 Total\ Entering\ ADT + \beta_3 (Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	1.152e+00	1.156e+00	0.996	0.3190	
β_2	TOT_ADT	-7.840e-05	1.149e-04	-0.682	0.4950	
β_3	TOT_ADT^2	4.487e-09	2.654e-09	1.691	0.0909	.
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \text{Exp}[\beta_1 + \beta_2 Total\ Entering\ ADT + \beta_3 (Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	6.131e-01	1.907e+00	0.321	0.748	
β_2	TOT_ADT	-1.901e-05	1.983e-04	-0.096	0.924	
β_3	TOT_ADT^2	3.030e-09	4.805e-09	0.631	0.528	
θ		2.00	1.14			
Over dispersion 1/θ		0.5				

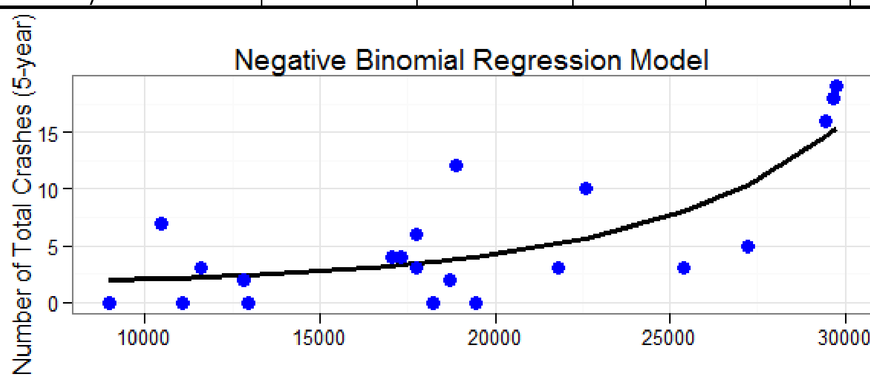

Figure 11.3: Regression model

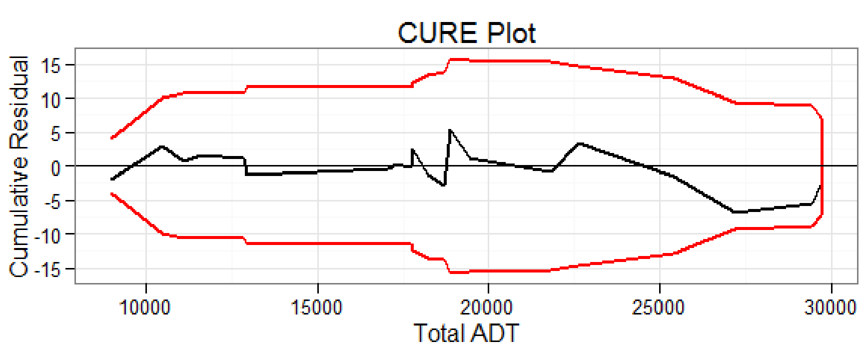

Figure 11.4: Cumulative residual plot

3. Total Crash Model with Explanatory Variable of TOT_ADT^2 (Include outlier)

Table 11.5: Summary of total crash model with explanatory variable of TOT_ADT^2 (include outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \text{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	3.712e-01	2.239e-01	1.657	0.0975	.
β_2	TOT_ADT^2	2.698e-09	3.391e-10	7.957	1.76e-15	***
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \text{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	4.320e-01	3.720e-01	1.161	0.245483	
β_2	TOT_ADT^2	2.579e-09	7.135e-10	3.614	0.000301	***
θ		2.00	1.14			
Over dispersion 1/θ		0.5				

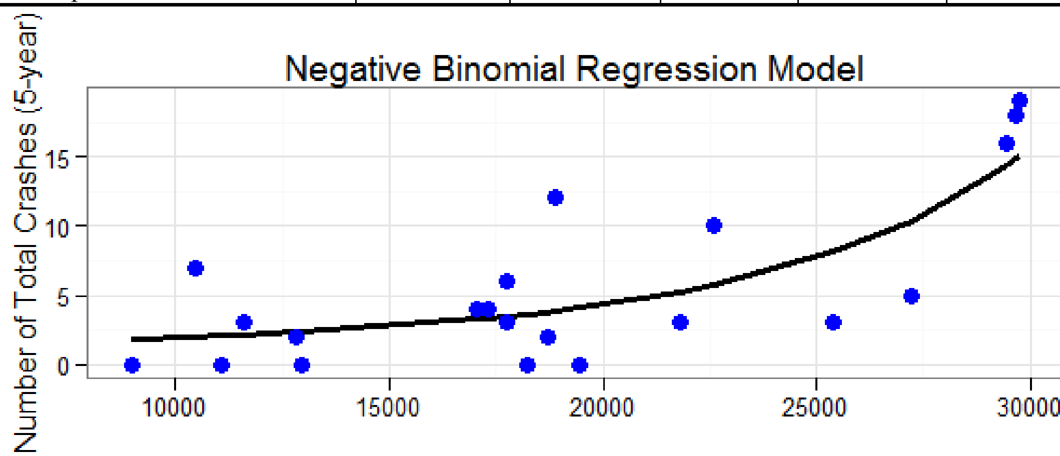

Figure 11.5: Regression model

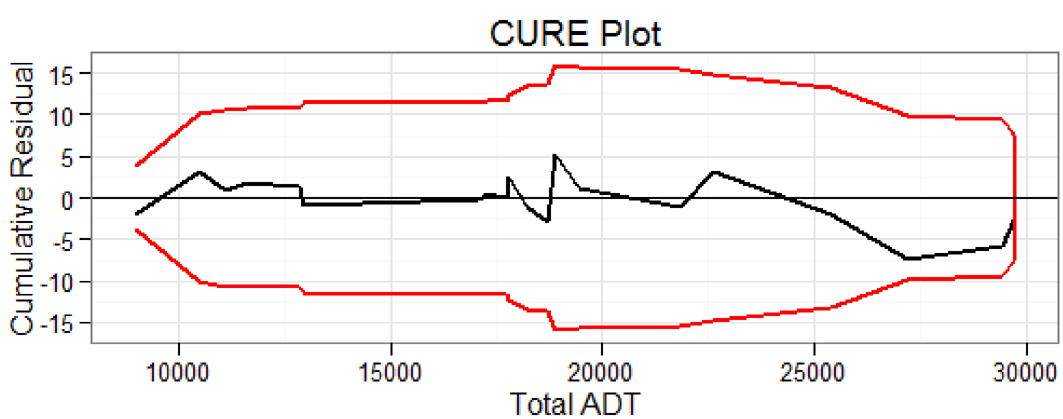

Figure 11.6: Cumulative residual plot

4. Total Crash Model with Explanatory Variable of TOT_ADT (Exclude outlier)

Table 11.6: Summary of total crash model with explanatory variable of TOT_ADT (exclude outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = Exp(\beta_1 + \beta_2 Total\ Entering\ ADT)$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-1.08e+00	4.107e-01	-2.639	0.00831	**
β_2	TOT_ADT	1.264e-04	1.647e-05	7.675	1.66e-14	***
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ of\ Crash\ (5\ years) = Exp(\beta_1 + \beta_2 Total\ Entering\ ADT)$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-7.314e-01	6.323e-01	-1.157	0.247419	
β_2	TOT_ADT	1.102e-04	2.927e-05	3.765	0.000167	***
θ		2.28	1.47			
Over dispersion 1/θ		0.439				

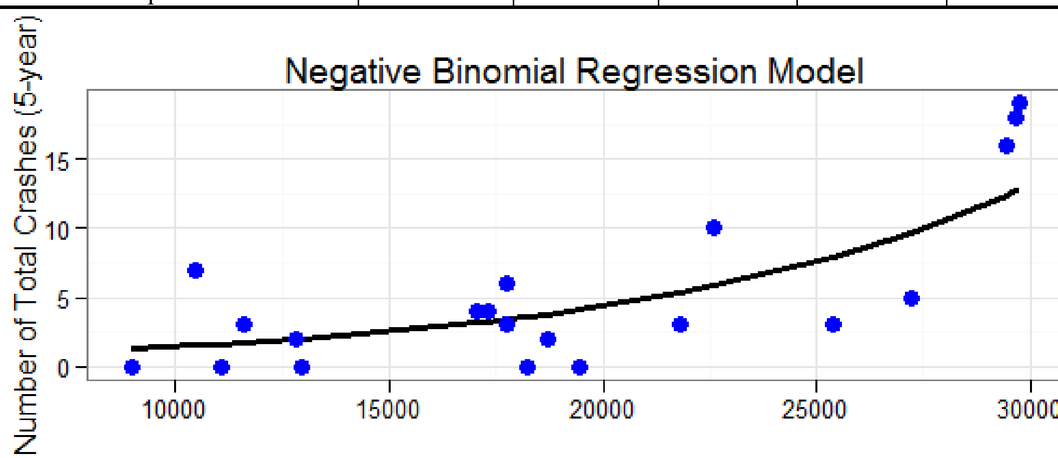

Figure 11.7: Regression model

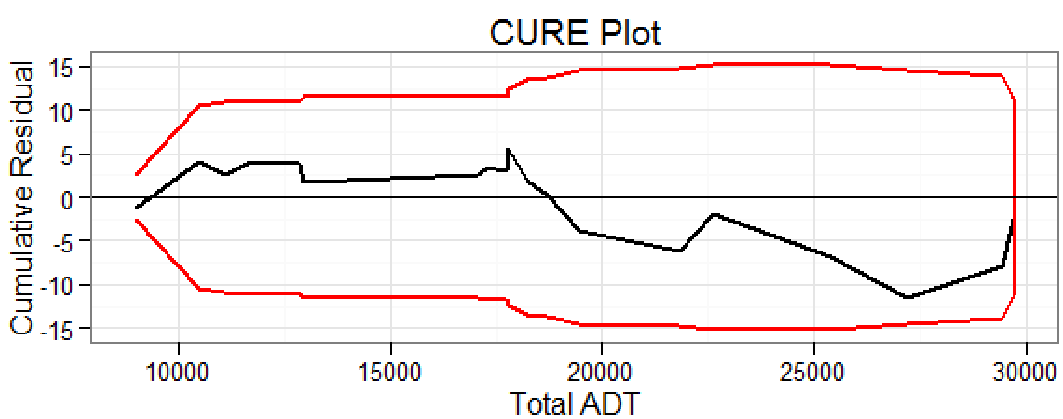

Figure 11.8: Cumulative residual plot

5. Total Crash Model with Explanatory Variable of TOT_ADT+TOT_ADT^2 (Exclude outlier)

Table 11.7: Summary total crash model with explanatory variable of TOT_ADT+TOT_ADT^2 (exclude outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \text{Exp}[\beta_1 + \beta_2 Total\ Entering\ ADT + \beta_3 (Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	2.002e+00	1.202e+00	1.666	0.0956	.
β_2	TOT_ADT	-1.901e-04	1.221e-04	-1.558	0.1193	
β_3	TOT_ADT^2	7.323e-09	2.846e-09	2.573	0.0101	*
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \text{Exp}[\beta_1 + \beta_2 Total\ Entering\ ADT + \beta_3 (Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	1.628e+00	1.732e+00	0.940	0.347	
β_2	TOT_ADT	-1.468e-04	1.815e-04	-0.809	0.419	
β_3	TOT_ADT^2	6.232e-09	4.386e-09	1.421	0.155	
θ		3.09	2.42			
Over dispersion 1/θ		0.324				

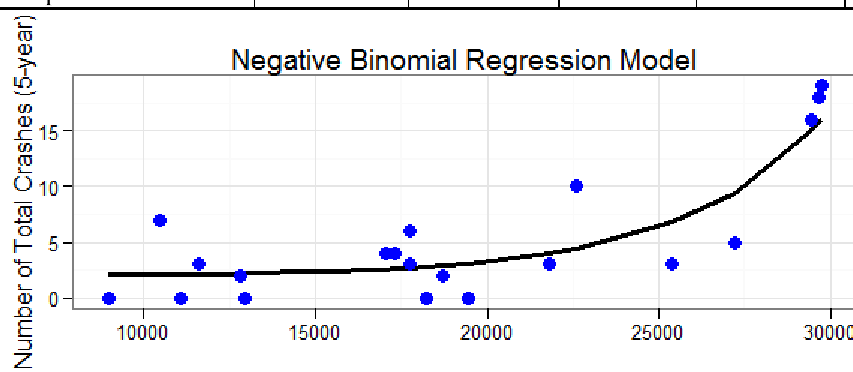

Figure 11.9: Regression model

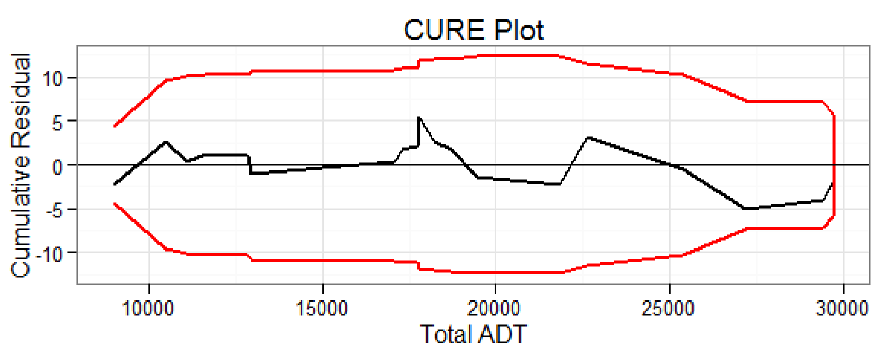

Figure 11.10: Cumulative residual plot

6. Total Crash Model with Explanatory Variable of TOT_ADT^2 (Exclude outlier)

Table 11.8: Summary of total crash model with explanatory variable of TOT_ADT^2 (exclude outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \mathrm{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	1.292e-01	2.488e-01	0.519	0.604	
β_2	TOT_ADT^2	2.967e-09	3.635e-10	8.161	3.31e-16	***
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = \mathrm{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	2.447e-01	3.577e-01	0.684	0.494	
β_2	TOT_ADT^2	2.744e-09	6.536e-10	4.198	2.69e-05	***
θ		2.74	1.98			
Over dispersion 1/θ		0.365				

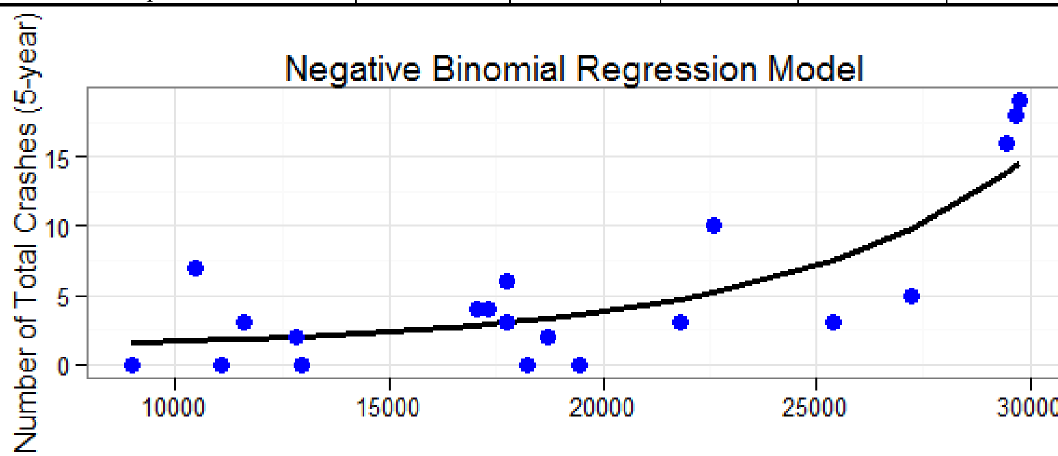

Figure 11.11: Regression model

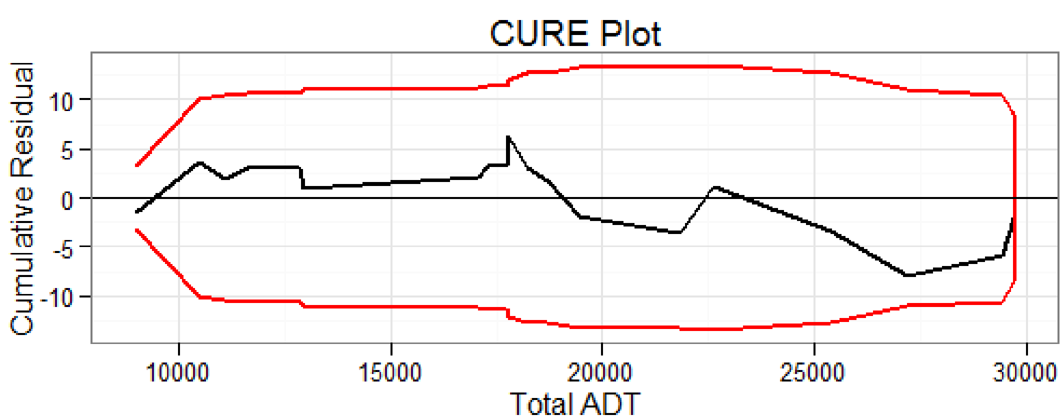

Figure 11.12: Cumulative residual plot

7. Total Crash Reference Model with Explanatory Variable of ln(TOT_ADT)]

(Include outlier)

Table 11.9: Summary of total crash reference model with explanatory variable of ln(TOT_ADT)] (include outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = Exp(\beta_1) \times (Total\ Entering\ ADT)^{\beta_2}$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-20.9527	3.3096	-6.331	2.44e-10	***
β_2	log(cd$TOT_ADT)	2.2856	0.3299	6.927	4.29e-12	***
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ of\ Crash\ (5\ years) = Exp(\beta_1) \times (Total\ Entering\ ADT)^{\beta_2}$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-17.434	5.969	-2.921	0.00349	**
β_2	log(cd$TOT_ADT)	1.931	0.605	3.192	0.00141	**
θ		1.709	0.893			
Over dispersion 1/θ		0.585				

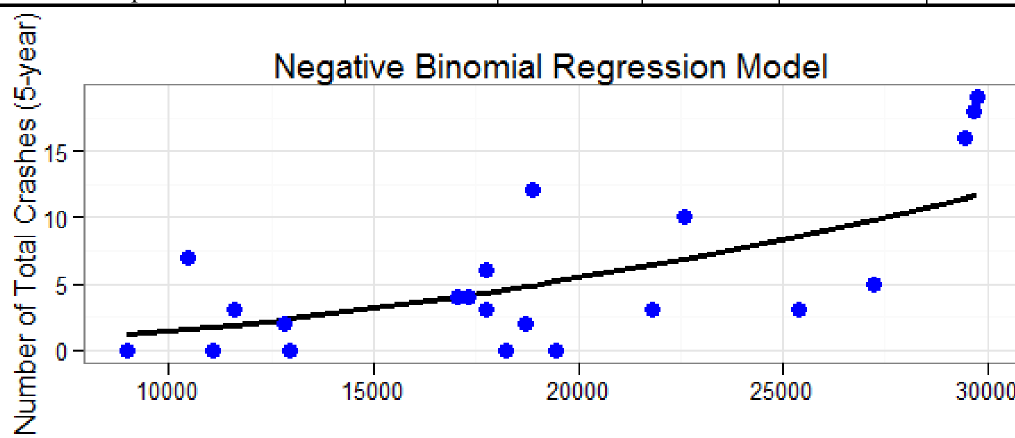

Figure 11.13: Regression model

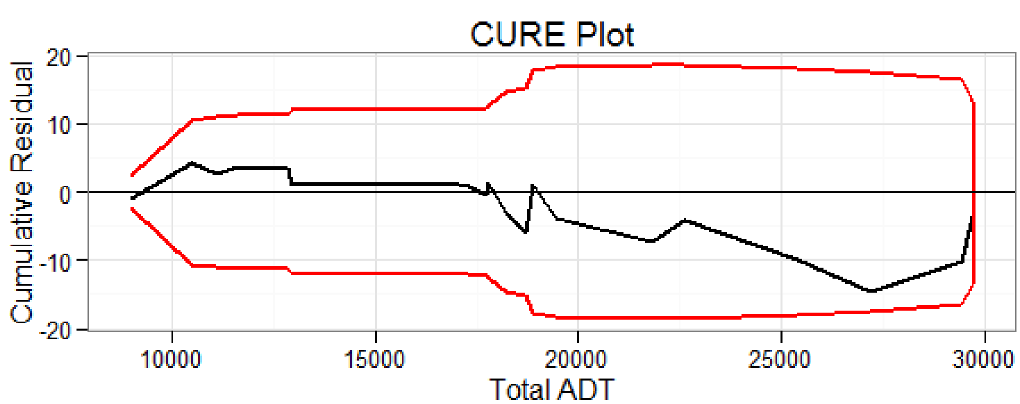

Figure 11.14: Cumulative residual plot

8. Total Crash Reference Model with Explanatory Variable of ln(TOT_ADT) (Exclude outlier)

Table 11.10: Summary of total crash reference model with explanatory variable of ln(TOT_ADT) (exclude outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ Crash\ (5\ years) = Exp(\beta_1) \times (Total\ Entering\ ADT)^{\beta_2}$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-22.6864	3.5453	-6.399	1.56e-10	***
β_2	log(cd$TOT_ADT)	2.4516	0.3527	6.951	3.64e-12	***
Model:	Negative Binomial Regression Model					
Equation:	$Total\ Number\ of\ Crash\ (5\ years) = Exp(\beta_1) \times (Total\ Entering\ ADT)^{\beta_2}$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-17.7570	5.9565	-2.981	0.00287	**
β_2	log(cd$TOT_ADT)	1.9555	0.6032	3.242	0.00119	**
θ		1.82	1.03			
Over dispersion 1/θ		0.549				

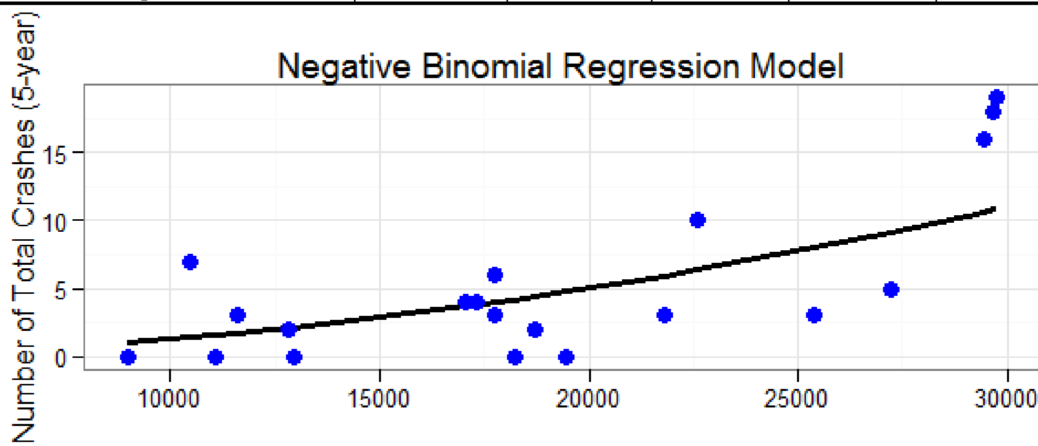

Figure 11.15: Regression model

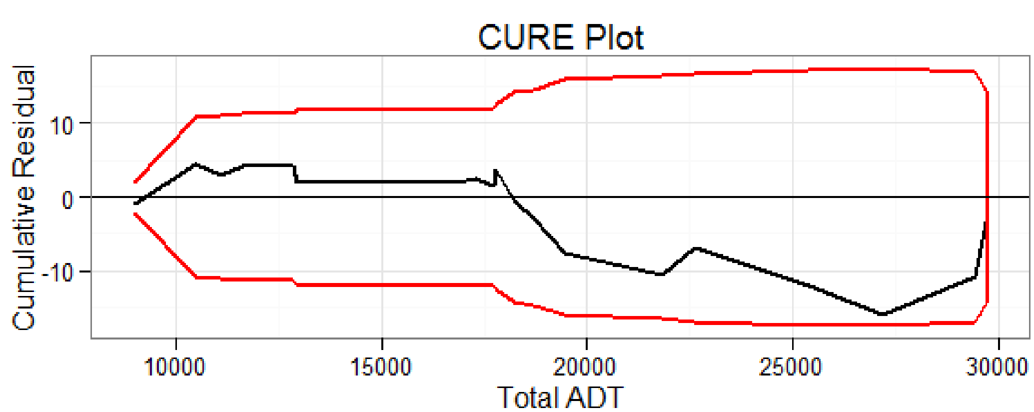

Figure 11.16: Cumulative residual plot

9. Injury Crash Model with Explanatory Variable of TOT_ADT (Include outlier)

Table 11.11: Summary of injury crash model with explanatory variable of TOT_ADT (include outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = Exp(\beta_1 + \beta_2 Total\ Entering\ ADT)$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-2.52e+00	6.504e-01	-3.877	0.000106	***
β_2	TOT_ADT	1.534e-04	2.547e-05	6.024	1.7e-09	***

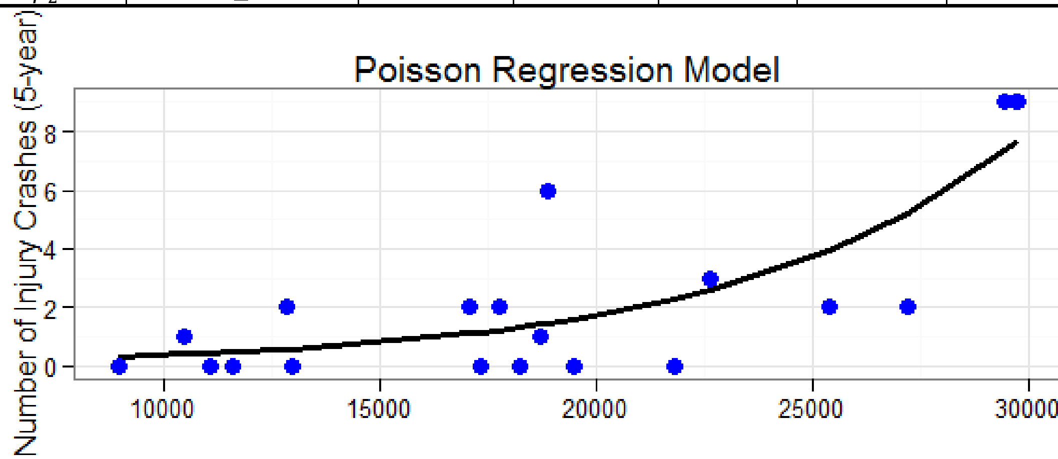

Figure 11.17: Regression model

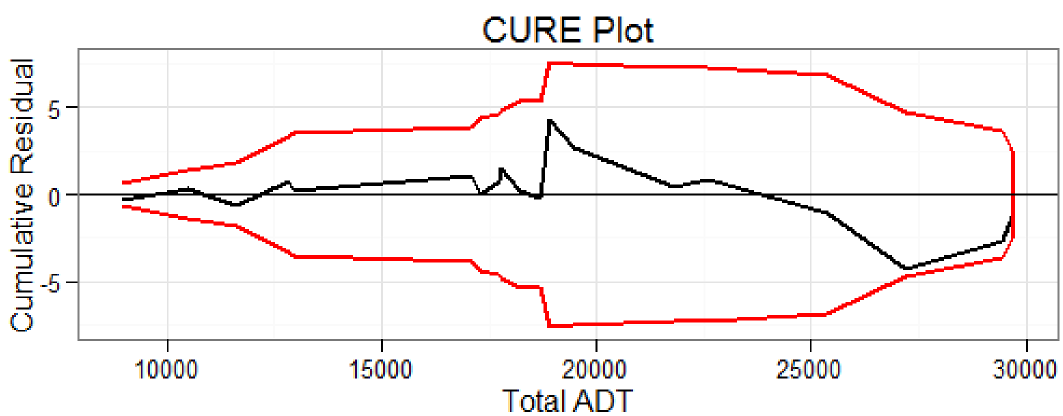

Figure 11.18: Cumulative residual plot

10. Injury Crash Model with Explanatory Variable of TOT_ADT+TOT_ADT^2 (Include outlier)

Table 11.12: Summary of injury crash model with explanatory variable of TOT_ADT+TOT_ADT^2 (include outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = \text{Exp}[\beta_1 + \beta_2 Total\ Entering\ ADT + \beta_3 (Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-8.054e-01	2.120e+00	-0.380	0.704	
β_2	TOT_ADT	-1.464e-05	2.034e-04	-0.072	0.943	
β_3	TOT_ADT2	3.784e-09	4.587e-09	0.825	0.410	

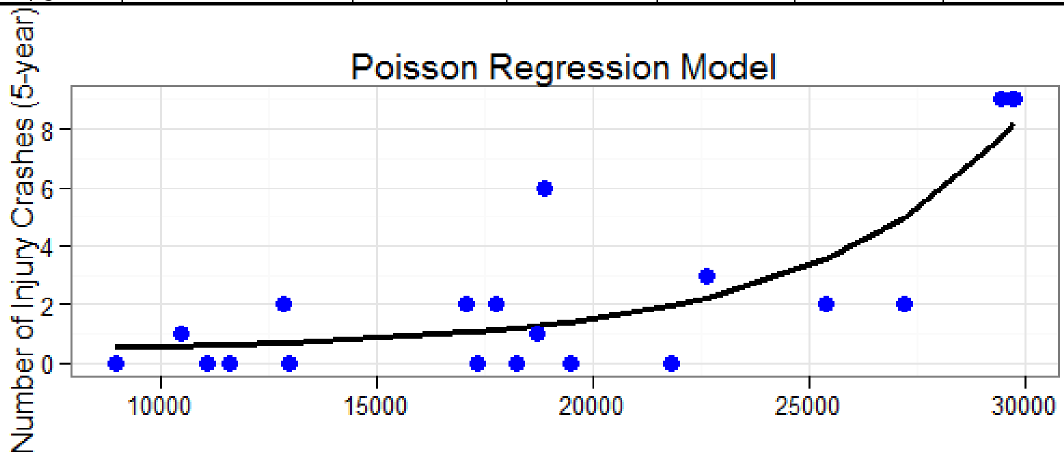

Figure 11.19: Regression model

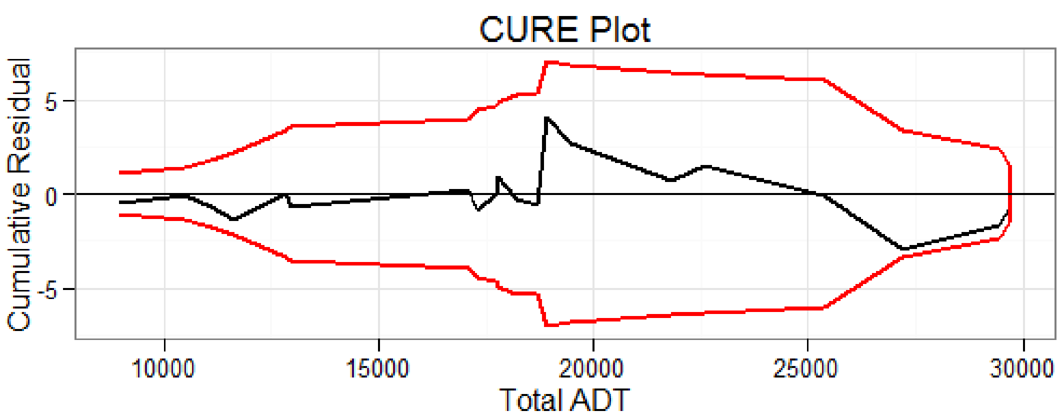

Figure 11.20: Cumulative residual plot

11. Injury Crash Model with Explanatory Variable of TOT_ADT^2 (Include outlier)

Table 11.13: Summary of injury crash model with explanatory variable of TOT_ADT^2 (include outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = \text{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-9.558e-01	3.855e-01	-2.479	0.0132	*
β_2	TOT_ADT^2	3.456e-09	5.473e-10	6.314	2.72e-10	***

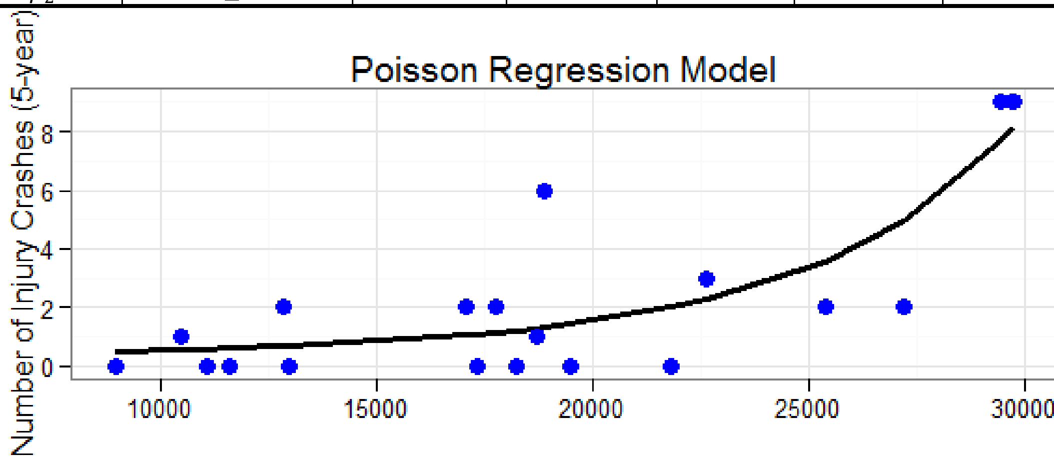

Figure 11.21: Regression model

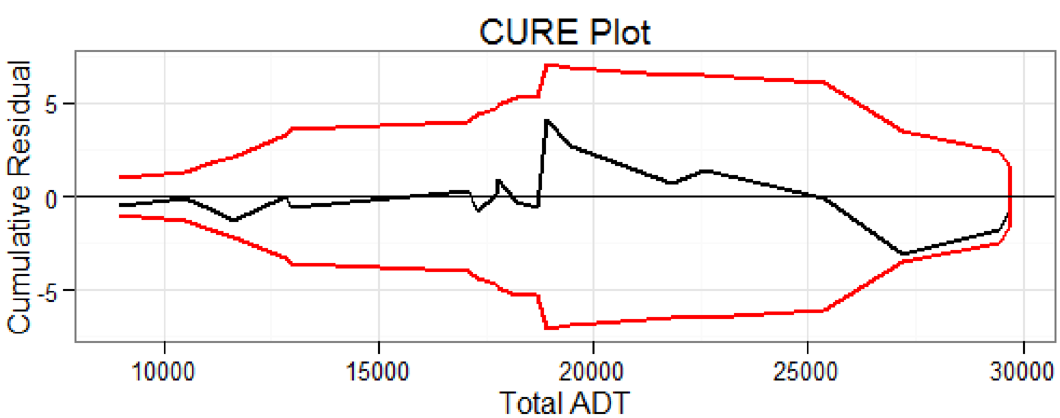

Figure 11.22: Cumulative residual plot

12. Injury Crash Model with Explanatory Variable of TOT_ADT (Exclude outlier)

Table 11.14: Summary of injury crash model with explanatory variable of TOT_ADT (exclude outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = Exp(\beta_1 + \beta_2 Total\ Entering\ ADT)$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-3.187729	0.7641033	-4.172	3.02e-05	***
β_2	TOT_ADT	0.0001758	0.0000291	6.041	1.53e-09	***

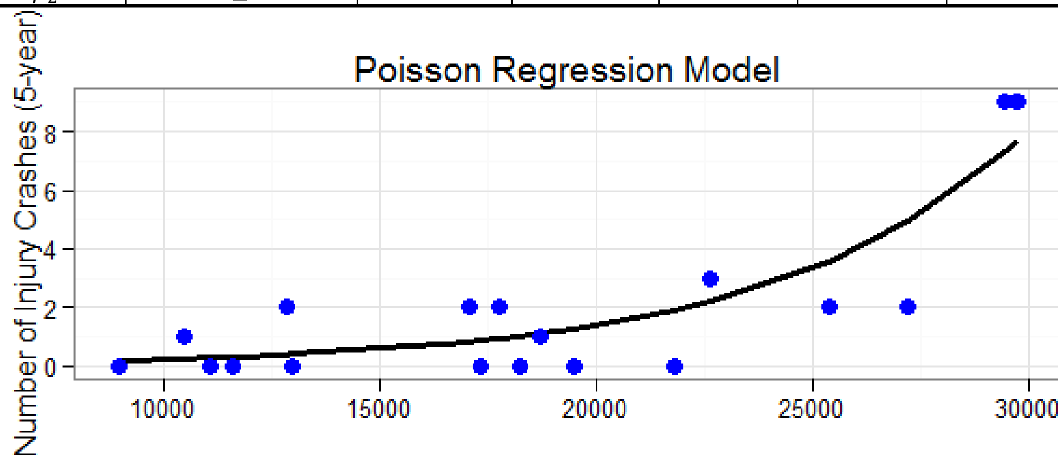

Figure 11.23: Regression model

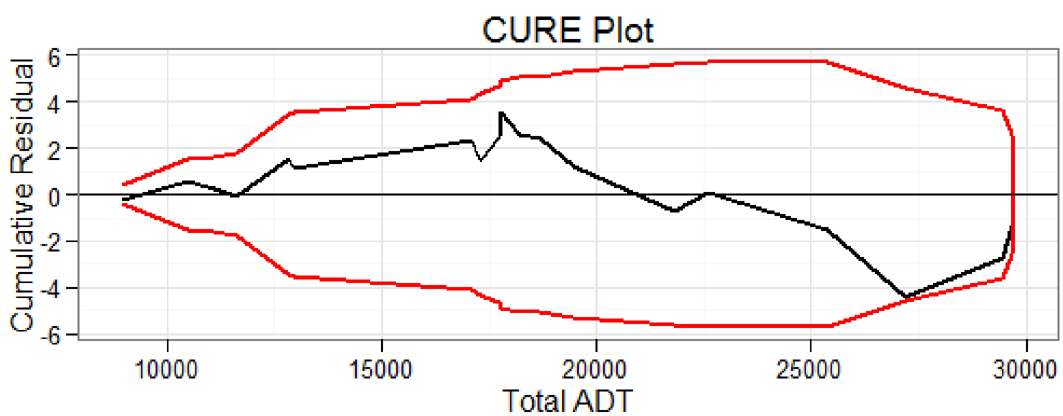

Figure 11.24: Cumulative residual plot

13. Injury Crash Model with Explanatory Variable of TOT_ADT+TOT_ADT^2 (Exclude outlier)

Table 11.15: Summary of injury crash model with explanatory variable of TOT_ADT+TOT_ADT^2 (exclude outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = \mathrm{Exp}[\beta_1 + \beta_2 Total\ Entering\ ADT + \beta_3 (Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	3.769e-01	2.252e+00	0.167	0.867	
β_2	TOT_ADT	-1.756e-04	2.212e-04	-0.794	0.427	
β_3	TOT_ADT^2	7.914e-09	5.044e-09	1.569	0.117	

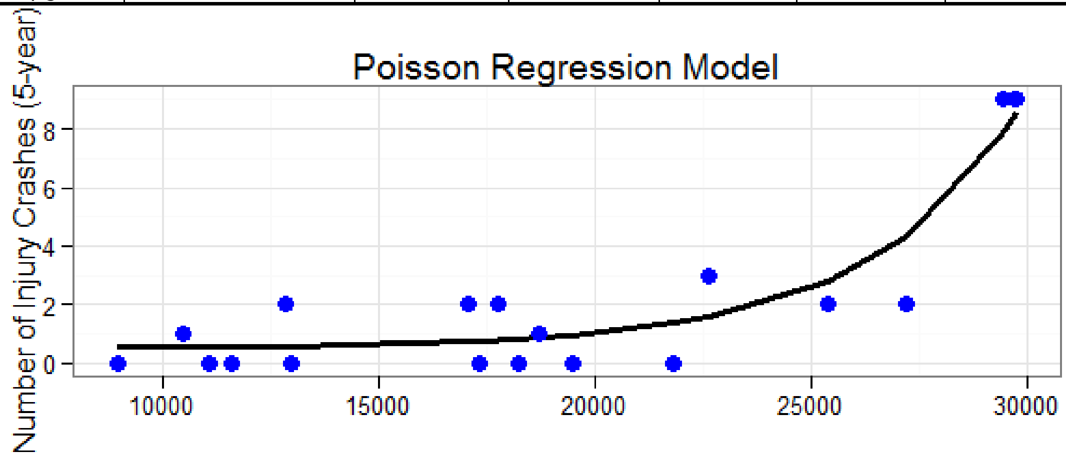

Figure 11.25: Regression model

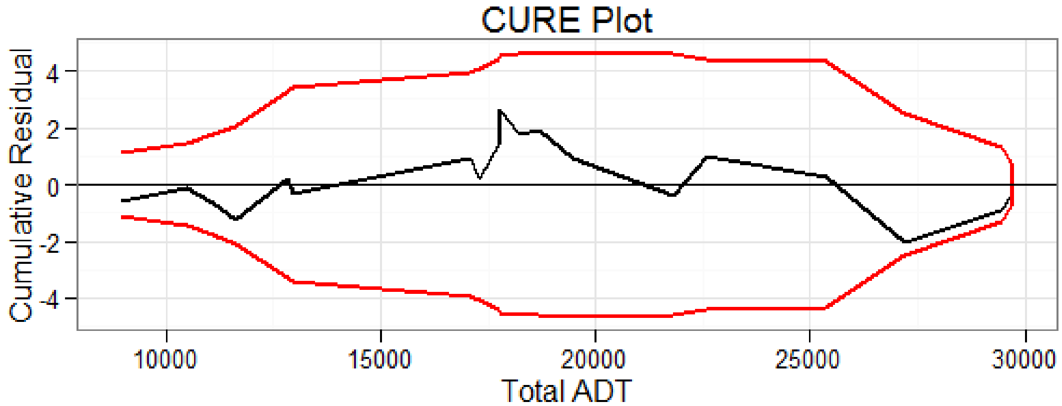

Figure 11.26: Cumulative residual plot

14. Injury Crash Model with Explanatory Variable of TOT_ADT^2 (Exclude outlier)

Table 11.16: Summary of injury crash model with explanatory variable of TOT_ADT^2 (exclude outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = \mathrm{Exp}[\beta_1 + \beta_2(Total\ Entering\ ADT)^2]$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-1.41e+00	4.584e-01	-3.080	0.00207	**
β_2	TOT_ADT^2	3.978e-09	6.221e-10	6.395	1.61e-10	***

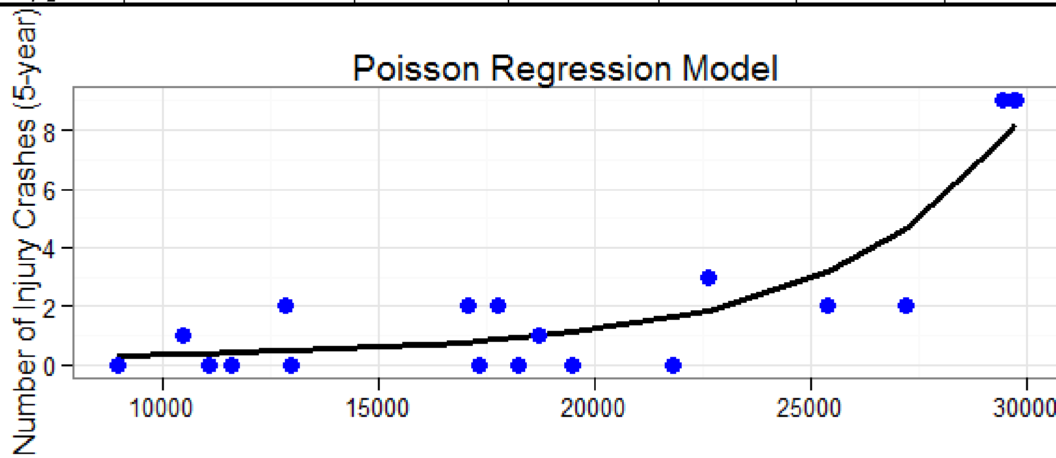

Figure 11.27: Regression model

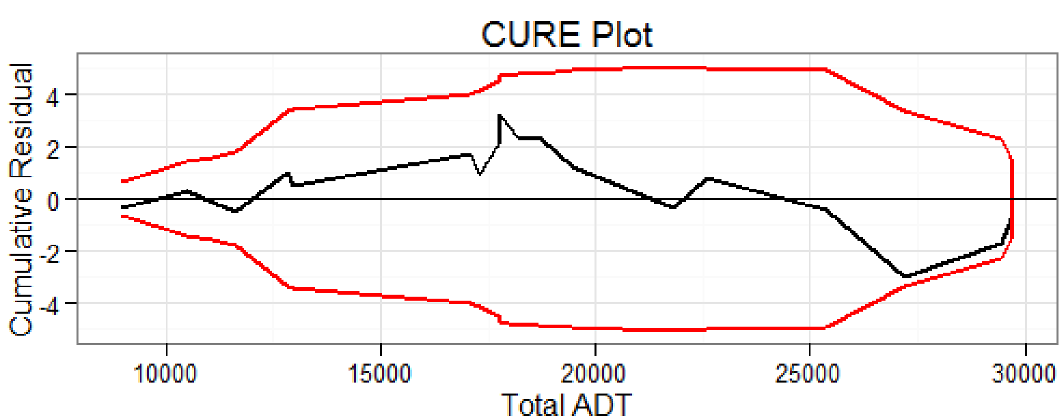

Figure 11.28: Cumulative residual plot

15. Injury Crash Reference Model with Explanatory Variable of ln(TOT_ADT) (Include outlier)

Table 11.17: Summary of injury crash reference model with explanatory variable of ln(TOT_ADT) (include outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = Exp(\beta_1) \times (Total\ Entering\ ADT)^{\beta_2}$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-30.979	5.793	-5.347	8.93e-08	***
β_2	log(cd$TOT_ADT)	3.198	0.574	5.571	2.53e-08	***

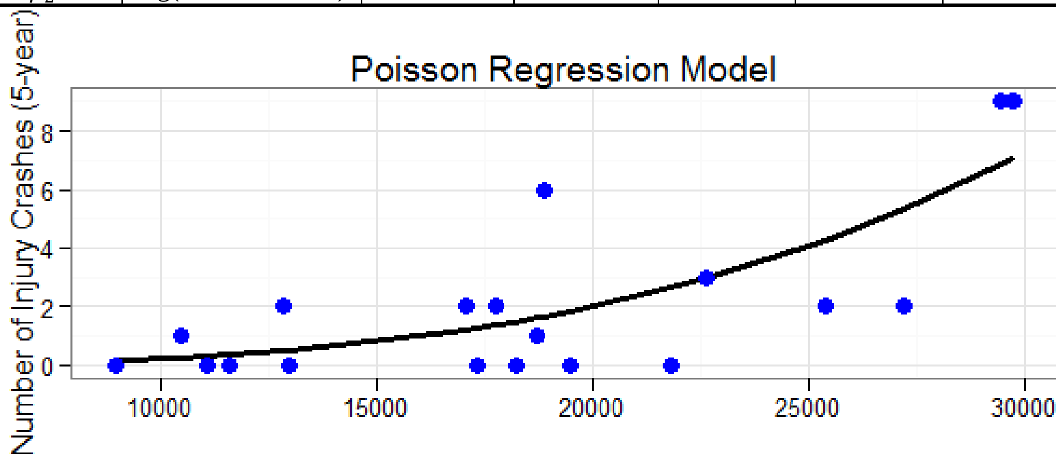

Figure 11.29: Regression model

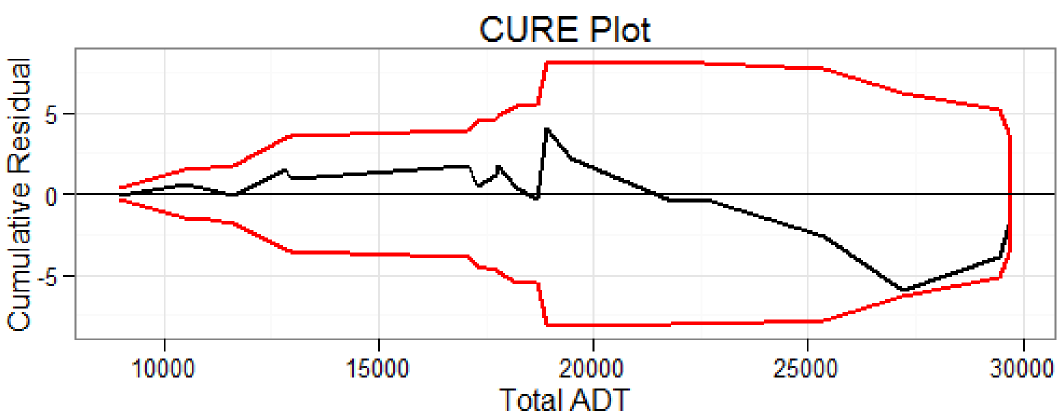

Figure 11.30: Cumulative residual plot

16. Injury Crash Reference Model with Explanatory of ln(TOT_ADT) (Exclude outlier)

Table 11.18: Summary of injury crash reference model with explanatory of ln(TOT_ADT) (exclude outlier)

Model:	Poisson Regression Model					
Equation:	$Total\ Number\ of\ Injury\ Crash\ (5\ years) = Exp(\beta_1) \times (Total\ Entering\ ADT)^{\beta_2}$					
Coefficients	Input Variable	Estimate	Std. Error	z value	Pr(>|z|)	Significance
β_1	(Intercept)	-35.5153	6.6570	-5.335	9.55e-08	***
β_2	log(cd$TOT_ADT)	3.6371	0.6574	5.532	3.16e-08	***

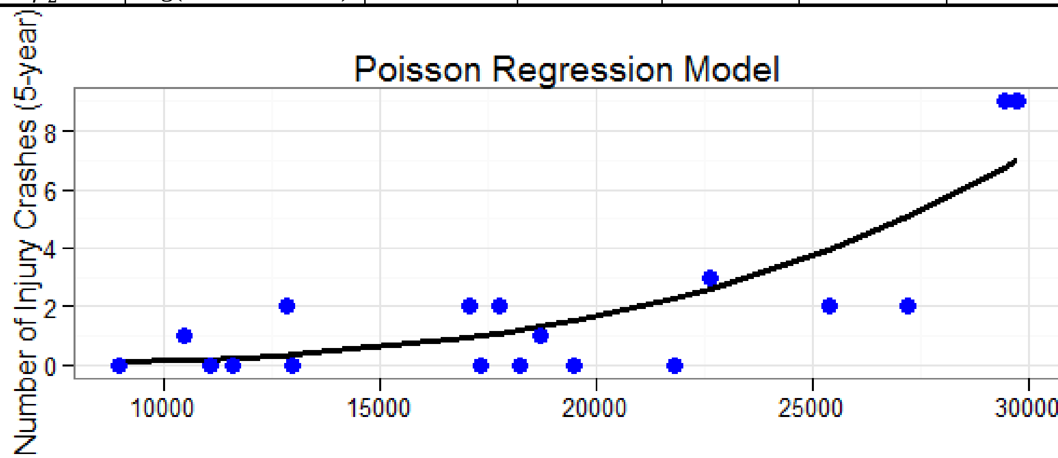

Figure 11.31: Regression model

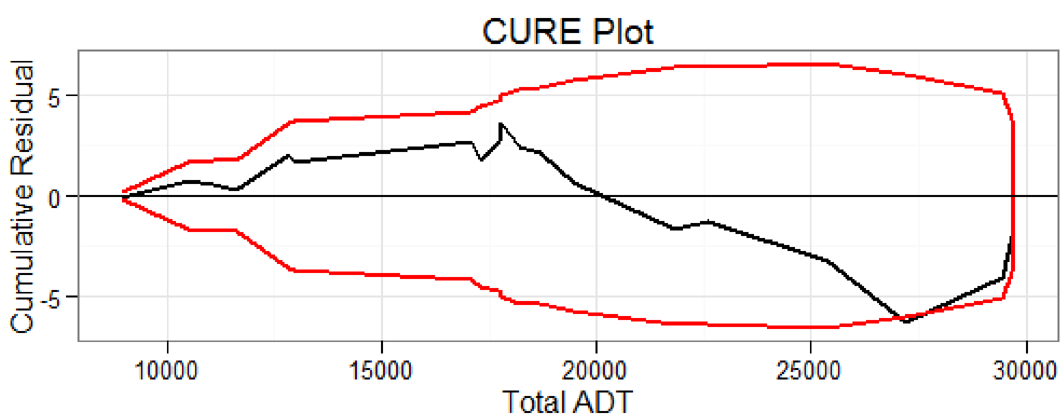

Figure 11.32: Cumulative residual plot