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Development of Colorado Specific Safety Performance Functions (SPF's) and Diagnostic Norms for Roundabouts

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16. Abstract

Roundabouts commonly replace intersections to reduce the number of conflict points, with the objective of crash reduction and better operations. They are becoming ever more popular in the United States. Many U.S. based research studies on the topic of roundabouts have focused on evaluating the effectiveness of converting existing intersections to roundabouts. This study was concerned with the development of Safety Performance Functions (SPFs) for Colorado roundabouts as well as diagnostics norms.

Implementation:
SPF models and diagnostic norms to evaluate safety performance using Colorado-specific crash prediction models for three roundabout facility types have been developed: Urban 3-leg 1-lane, 4-leg 1-lane, and 4-leg 2-lane. The models are ready for immediate use on safety projects by CDOT engineers. The products of this research will allow CDOT to more accurately quantify and evaluate the safety performance of Colorado roundabouts in a timely manner, assess design alternatives as part of future projects and overall make better investments of limited funding where maximizing safety is concerned.

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Executive Summary

The aim of this study was to develop Colorado-specific Safety Performance Functions (SPFs) and diagnostic norms for Colorado roundabouts. The research commences with a review of extant literature from within the United States and abroad concerning the development of crash prediction models and safety performance measures for application to roundabouts. It is widely agreed in the literature that it is best when an SPF is developed specifically for the geographic area to which it is to be applied using data directly from that area.

To achieve the ultimate results, all of the Safety Performance Functions (SPFs) in this report were developed using original Colorado data. Crash data over a study period from 1/1/2015 through 12/31/2019 was used to capture safety performance characteristics of Colorado roundabouts.

The greatest challenge as part of this effort was in data collection. Using Vision Zero Suite (VZS), a listing of all crashes at roundabouts in Colorado between 1/1/2015 and 12/31/2019 was made. Locations were then individually assessed for categorization into more specific facility types. This enabled identification of facility types with a sufficient number of locations for model development. The work on this project includes development of the Safety Performance Functions (SPF) and diagnostic norms for the following facilities:

- Urban 3-leg 1 circulating lane,
- Urban 4-leg 1 circulating lane, and
- Urban 4-leg 2 circulating lanes.

Obtaining Annual Average Daily Traffic (AADT) counts on all legs of each facility posed the most difficult challenge. When ‘CDOT MS2’ and local county and town sources of data were exhausted, collaboration with the Colorado Department of Transportation (CDOT) on the use of the STREETLIGHT software tool using connected vehicle and mobile phone location data for AADT collection to supplement and confirm existing AADT data was pursued.

The primary use of SPFs is to assess the magnitude of the safety problem, while diagnostic menus and pattern recognition analysis are used to identify its nature. New roundabout SPFs can be applied statewide to identify locations with potential for crash reductions. Development of roundabout SPFs enables CDOT to evaluate the magnitude of the safety problems using the *Level of Service of Safety* (LOSS) concept. The LOSS concept applied to roundabouts uses quantitative and qualitative measures that characterize the safety performance of a facility in reference to its expected performance. The level of safety predicted by the SPF represents a normal or expected number of crashes at a specific level of exposure, and the degree of deviation from the norm is stratified to represent four specific levels of safety.

LOSS I - Indicates low potential for crash reduction.

LOSS II - Indicates low to moderate potential for crash reduction.

LOSS III - Indicates moderate to high potential for crash reduction.

LOSS IV - Indicates high potential for crash reduction.

Model parameters were estimated by the maximum-likelihood method using Generalized Linear Modeling (GLM) methodology by maximizing log-likelihood function with negative binomial distributional assumptions. The quality of fit was examined with the Cumulative Residuals (CURE) method. Models were independently validated by Craig Lyon, a Canadian safety researcher.

Implementation Strategy

The products of this research effort, Colorado specific roundabout SPF models and diagnostic norms, are ready for immediate use within the VZS platform already employed by CDOT. Application of the LOSS concept to the CDOT roundabouts enables CDOT to do the following:

- Quantitatively assess and qualitatively describe the degree of safety or un-safety of Colorado 3-leg 1-lane, 4-leg 1-lane and 4-leg 2-lane roundabouts,
- Effectively communicate the magnitude of the safety problem to other professionals, traveling public, law enforcement personnel and elected officials,
- Provide a frame of reference for decision making on non-safety motivated projects (operational improvements, resurfacing, reconstruction or widening, for instance)
- Provide a frame of reference from a safety perspective for planning systemic or corridor improvements.

Enabled with SPFs for roundabout facilities CDOT can make better informed project selection in terms of future construction alternatives, assisted by the determination of the LOSS of a roundabout facility. Use of the developed models will enable CDOT to identify and address existing safety problems with greater accuracy and effectiveness. Regarding existing facilities, CDOT will be able to identify any areas for potential safety improvements. Systemic strategies to improve safety at Colorado roundabouts will also be achievable through the use of SPFs and diagnostics. Ultimately, CDOT will be better equipped to optimally invest limited resources, which will result in greater crash reduction.

1. Chapter 1 – Introduction And Literature Review

Roundabouts are a common feature in European cities which replace intersections and reduce the number of intersecting conflict points, with the goal of crash reduction and improved operations. Roundabouts are becoming increasingly more popular in the United States. The purpose of this research is the development of crash prediction models to provide the Colorado Department of Transportation (CDOT) with Colorado specific safety performance functions (SPFs) that can be used to evaluate the safety performance of various roundabout facility classes within the state of Colorado, as well as the development of diagnostic norms for those roundabout facilities.

To better inform the process of SPF development and crash prediction modeling, as related specifically to roundabouts, we undertook a review of extant literature from within the United States and abroad concerning the development of crash prediction models and safety performance measures for application to roundabouts.

The review of literature in chronological order is followed by a brief summary of our findings.

Literature on the Topic of Crash Prediction Models and Safety Performance Measures for Roundabouts

Daniels et al. Explaining Variation in Safety Performance of Roundabouts (2010)

In their 2010 paper, Daniels et al. explore the variation in safety performance of roundabouts through cross-sectional risk modeling of crash, traffic, and geometric data of roundabouts in Belgium. The authors discuss the efforts performed to date of publication (2010) which attempted to reveal a relationship between roundabout geometric and traffic characteristics and level of safety by way of before and after studies. The only commonality identified was a distinct relationship between traffic volume (AADT) and crash frequency and efforts being characterized by before-after studies. At the time of publication cross-sectional risk models based on the parameters outlined above were state-of-the-art. One of the main goals of this study was to investigate variables of a structural nature which might influence variation in crash rates at roundabouts. Another goal was the investigation of crash variability due to characteristics of cycle facilities at roundabouts.

Ninety roundabouts in Belgium were studied, all of which were constructed between 1994 and 2000. Geometric data collection included:

- Raised central island,
- Traversable truck apron,
- An oval shape of the central island,
- A gated roadway through central island to accommodate oversized trucks,
- Right turn by-pass lane,
- Located inside/outside built-up area,
- Number of circulating lanes,
- Road width,
- Central island diameter,
- Inscribed circle diameter, and
- Number of legs

The facilities were divided into four types to describe pedestrian and cyclist facilities:

- Mixed traffic roundabouts (vehicle and bicycle use same road),
- Cycle lanes (cycle lanes close to roadway),
- Cycle paths (dedicated bike paths more than 1 meter from roadway), and
- Grade-separated roundabouts (tunnels for bikes)

Other variables which were considered included the presence of pedestrian sidewalks around the roundabout or "zebra" crosswalk markings on the entry/exit lanes. The ADT was estimated from performing 1-hour traffic counts which comprised traffic volume data for six different traffic modes, of which passenger cars, heavy vehicles and motorcycles were considered motorized, fast traffic. This is notably one limitation of the study. Furthermore, the count was performed in the daytime, as such daytime traffic is unlikely to be representative of a 24-hr traffic volume, although nighttime crashes were included.

Registered injury crash data was obtained from the Belgian Ministry of Mobility and Public Works for 1996-2004. In this study crashes that occurred within 100 meters (approx. 328 ft) of the center of the roundabout were considered applicable roundabout related crashes. Crash history showed around 83% of injury crashes involved light vehicles and 30% involved bicycles. The crash history confirmed the findings of previous reports which were referenced in the study, and which indicated that cyclists and pedestrians, as well as motorcyclists, were more frequently involved in crashes in comparison with their average share in traffic. Furthermore, about 80% of crashes were found to be multi-vehicle crashes.

The study included a chi-squared test of homogeneity of vehicle populations and revealed that mopeds, bicycles, and motorcycles were more frequently involved in single vehicle crashes than would be expected based on their traffic share. Additionally, in 60% of multiple vehicle crashes, a bicyclist or moped was involved. It should be observed that the traffic profiles in terms of roadway users in Belgium is likely different to that of roadway users in the U.S., where the proportion of cyclists is probably much lower.

Both Poisson and gamma modeling were used in this study. The average number of crashes per roundabout was the dependent variable in modeling. In this study over-dispersion of data was not present, and in some circumstances, data was even observed to be under-dispersed. As such Poisson loglinear models were fitted, with exposure variables transformed to their natural logarithms. Interestingly, the relative shares of traffic modes were initially considered as explanatory variables but eventually omitted when they were shown to not bring any improvements to the models. The chosen model form was as is seen below.

$$E(\lambda) = e^{\alpha}.Q_1{}^{\beta_1}.Q_2{}^{\beta_2}.e^{\sum_{i=1}^{n}\gamma_i.x_i}$$

with $E(\lambda)$ = expected annual number of crashes

Q_1 = ADT (motor vehicles)

Q_2 = traffic volume for particular vehicle types (bicyclists, mopeds,...)

x_i = other explanatory variables

$\alpha, \beta_1, \beta_2, \gamma_i$ = model parameters

Figure 1-1: Model Form Implemented by Daniels et al. (Daniels, 2010)

The authors used some additional gamma probability models to account for the observed under-dispersion. Explanatory variables were gradually removed based on an inspection technique involving strength of correlation, variables with well-established grounds of importance and significance values. Goodness of fit of the models was performed using the Akaike Information Criterion (AIC). The authors developed interaction terms to ensure that only variables that were relevant in specific cases were modeled appropriately, e.g., physical elements between roadway and cycle facilities were only recorded in the case of roundabouts with cycle lanes.

The results of the modelling performed by Daniels et al. revealed that ADT and bicyclist volume were two significant exposure variables. In relation to this, the number of bicycle lanes was found to affect a higher number of crashes. Another interesting finding was that where roundabout replaced signalized intersections, there was a correlation with a higher number of crashes, however this was not seen to be consistent across Poisson and gamma models and it was found to not always be strongly significant.

The models further revealed single vehicle crashes to be explained by ADT, the presence of a central road through the roundabout for oversized vehicles and by cases of oval roundabouts. In terms of multi-vehicle crashes, it was found that these were affected by ADT, the presence of bicycles and mopeds, the presence of cycle paths or cycle lanes, cases of 3-leg roundabouts and signals. The authors note the mutual interchangeability of some explanatory variables, for example cycle lane and cycle path.

Daniels et al. found that their gamma models fit systematically better than the Poisson models in terms of AIC values. The former also included more variables than the latter.

The findings indicated that variations in crash rates were small and rooted in differences in traffic exposure, with ADT being a significant predictor of most fitted models. ADT as a predictor was only less significant in models with a low number of observations. Daniels et al. conclude that ADT was "the most important variable in the models, which corresponds with many earlier findings in traffic safety research." The results of the research indicate some ambiguity around the relationship exactly between ADT and crash rate, while most Poisson models indicate a positive but less than proportional relationship (i.e., as ADT increases crash rates increases but not in direct proportion), nearly all gamma models showed that as ADT increases, crash rates increase at an increasing rate.

Furthermore, it was found that vulnerable road users, such as pedestrians and cyclists, may be more likely to be involved in crashes than at traditional intersection facilities, with the volume of each being a significant predictor of crashes, not just across models for bicycles and mopeds but also for light vehicle and multi-vehicle crashes. Due to the limited numbers of certain types of facilities amongst the data which was analyzed, the authors indicate it is unclear as to how exactly roundabouts with cycle lanes versus roundabouts with cycle paths perform when compared to other roundabout facilities. While the findings by Daniels et al. provide interesting results in terms of the influence of roundabouts of bicycle crashes and in terms of the influence of the presence of bicycle lanes on bicycle crashes, it is worth reiterating that the modal traffic profile in the United States likely differs strongly from that in Belgium in terms of the volume of cyclists.

This study asserts that the findings conform with the results of other research efforts which indicate that in cases where roundabouts replace signalized intersections, those roundabouts perform worse than other roundabouts. Daniels et al. offer a plausible explanation for this: locations are not randomly assigned to different treatments in the real world, as an unbiased investigation would dictate. That is when signals are installed or when a roundabout replaces a signalized intersection, those decisions are made on specific locations and as such there may be other confounding variables present which are less well understood, and for which the variable of "signals" may be acting as a proxy and masking the true underlying relationships.

Another interesting finding of the research was that the 3-leg roundabouts which were studied performed worse than roundabouts with 4 or more legs. The authors spend some time discussing variables which were found to not carry importance, those turned out to be specifically geometric features, e.g., central island diameter, inscribed circle diameter, number of lanes etc. They recognize that this is a departure from the results of previous research performed by others and also by Daniels et al. in an earlier study, in particular regarding the number of lanes which was previously found to be an important variable in terms of worse performance. Daniels et al. hypothesis is that the number of lanes could be acting as proxy for traffic volume, i.e., more lanes mean higher ADT. This is a point which merits further research and investigation.

A final point to note regarding the reliability of this research is that the under-dispersion witnessed by Daniels et al. in their data is not typical of crash data and it is unclear if it is due to the data itself or a due to a large degree of similarity structurally across the locations which were examined. On the topic of data quality, the report itself admits data quality issues due to incomplete reporting of crash data and possible biases in crash data reporting. Additionally, the study was based on a small number of samples from a single European country, and as such may not have a large degree of transferability to the United States.

Montella, A. et al. International Overview of Roundabout Design Practices and Insights for Improvement of the Italian Standard (2013)

An article published in 2013 by the Canadian Journal of Civil Engineering reviewed roundabout design standards and guidelines across several international locations including the USA, UK, Australasia, Switzerland, France, and Italy, in order to identify differences across procedures and potential areas of improvement in the Italian methods specifically. While the research was not directly concerned with the development of SPFs, the article serves to highlight some worthwhile aspects of current roundabout design and guidelines which may relate to SPF development.

As discussed in more detail in other articles which were consulted as part of the literature review, there are several geometric parameters involved in roundabout design which can impact the operational performance in terms of safety. The article points out that, although guidelines and standards may differ globally, all locations which were studied "agree that achieving appropriate vehicular speeds through the roundabout is the most critical design objective" (Montella A., 2013) and from the point of view of SPF development could have an important effect on the safety performance of a facility. Montella et al. indicate that previous research has shown that high entering speeds is associated with broadside crashes and rear-ends, when entering vehicles do not give way to circulating vehicles.

The authors assess how several geometric parameters are dealt with across the locations outlined previously, including: radius of deflection, entry path radius, sight distance, entry width, entry angle and circulatory roadway width. The authors conclude that rather than the individual impact of each geometric design element, it is their interaction with each other that is more important in terms of capacity and safety.

The article ends with the recommendation of further research on the relationship between geometric design, driver behavior and safety, and suggest one aspect of research should include the calibration of safety performance functions by incorporating geometric design parameters.

Dixon, K. and Zheng, J. Developing Safety Performance Measures for Roundabout Applications in the State of Oregon (2013)

A 2013 report published by Oregon State University details the research efforts undertaken by Dixon and Zheng in order to develop SPFs for Oregon Department of Transportation (ODOT) to evaluate single-lane four-leg roundabouts within the state. Dixon and Zheng highlight the wide variability in Crash Modification Factors (CMFs) in use for roundabout implementation and reason that this is due to “little consideration of detailed information for explaining how geometric design features and other characteristics of the roundabout directly affect the safety performance” (Dixon, 2013). This research focused on empirical investigation of the relationship between crash frequency and severity and geometric features of roundabouts.

The report recognizes that most safety assessment studies of roundabouts include AADT as a key variable. Dixon and Zheng list the following geometric features as potentially influencing safety performance at roundabouts:

- 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 approaches with bypass for right turn, and
- Entry curve

From their assessment of extant literature regarding roundabout CMFs, Dixon and Zheng found that conversion of a traditional intersection to a roundabout can yield 35-40% crash reduction in total crashes and 52% crash reduction at high-speed rural locations. In a review of CMFs for the conversion of STOP-controlled intersections to a roundabout, the report hypothesizes that the wide variability seen across CMFs suggests site specific features are critical to resulting safety benefits after conversion. The report then draws attention to the findings of international research which indicate that crashes involving pedestrians and cyclists appear to increase when roundabouts replace traditional intersections.

The report critiques two common assessment techniques for road safety modeling: the before-after study and the cross-sectional study. Dixon and Zheng argue the former has a flaw in that it does not directly assess cause and effect, because other influential factors such as changes in traffic volumes through the study period, are difficult to separate, but suggest the use of a comparison group (i.e., a control group) with the treatment group, be assessed in both the before and the after period, so that any differences observed between analysis periods could be attributed to the treatment. The authors refer to a paper by Hauer (Hauer E. , 2010) which points out another detractor of the before-after study, which is that one treatment may introduce multiple changes at the same time, with the result being that the safety effects cannot be measured by one change. For these reasons the authors assert a before-after study can only give us a "general interpretation that the difference in crash frequency is associated with the construction of a roundabout" (Dixon, 2013). On the other hand, the authors are proponents of the cross-sectional study and regard it as a reliable way to evaluate the expected safety performance of a facility. The cross-sectional study uses statistical regression to relate crash frequency to facility features. The report discusses how the nature of crash data as being over-dispersed (variance is greater that mean), means it lends itself well to use of a negative binomial regression or alternatively Poisson regression.

For their study, Dixon and Zheng used available and observational data for geometric features, traffic volume and crash history to assess the safety performance of single-lane four-leg roundabouts in Oregon. **Figure 1-2** provides an example of the geometric data used to develop SPFs which was expected to influence operational and safety performance. In their study, Dixon and Zheng presumed widths and turning radii to have the most direct impact on safety due to their direct impact on speed within the roundabout. **Table 1-1** shows the average roundabout geometric characteristics for features such as circulating width. The authors indicate that "circulating width" and "truck apron width" may be amalgamated and considered as "total traversable width."

Source: Google Maps

Basic Information	
Intersecting Approaches	Mt. Washington Dr.
	NW Shevlin Park Rd.
County	Deschutes
State	OR
Type	Single
Number of Legs	4
Year of Completion	2000

Inventory of Presence (1=presence; 0=absence)			
Raised Central Island	1	Marked Crosswalk	1
Truck Apron	1	Pedestrian Refuge Area	1
Bicycle Lane	0	Splitter Island	1
Bicycle Path	1	Signal Control	0
Sidewalk	1	Lighting	1
Combination of Sidewalk and Bicycle Path	1		

Geometric Design Information			
Inscribed Circle Diameter (ft)	127	Minimum Distance between Sidewalk and	8
Central Island Diameter (ft)	106	Entry Alignment	Center
Truck Apron Width (ft)	10	Offset Alignment	0
Minimum Lane Width (ft)	10	Minimum Angle between Legs (degrees)	75
Bicycle Lane/Path Width (ft)	6	Number of Crosswalks	4
Sidewalk Width (ft)	6	Number of Approach Curves	2
Number of Approach with Bypass for Right	0		

Figure 3.1: Example Geometric Feature Summary (Site #4 -- OR-S4-4)

Figure 1-2: Geometric Features Assessed by Dixon & Zheng (Dixon, 2013)

Table 1-1: Geometric Characteristics of Roundabouts Assessed by Dixon & Zheng (Dixon, 2013)

Table 3.2: Description of Roundabout Geometric Characteristics

Geometric Feature	Minimum	Maximum	Average	Standard Deviation
Inscribed Circle Diameter (ft)	104	192	134.4	25.41
Central Island Diameter (ft)	70	165	99.6	26.41
Truck Apron Width (ft)	0	20	12.0	4.06
Circulating Lane Width (ft)	10	20	16.6	2.78
Truck Apron + Lane Width (ft)	18	38	28.6	5.01

This report recognizes entering traffic volume as a key parameter for base condition safety performance functions and expects the same degree of influence for roundabouts. Dixon and Zheng populated gaps in the available ADT data using supplemental counting, volume estimation and projection techniques. For existing data, the authors used changes in regional population over 10 years as a predictor for annual traffic growth rate. For data collection, the authors obtained peak hour traffic volume, a proportion of the daily traffic occurring during the peak hour. **Table 1-2** shows the traffic volume characteristics encountered as part of the research. The authors stress that their findings should only be applied to facilities of similar volumes.

Table 1-2: Roundabout Traffic Volume Characteristics Seen by Dixon & Zheng (Dixon, 2013)

Table 3.8: Description of Roundabout Traffic Volume Characteristics

Representative Traffic Volume	Minimum	Maximum	Average	Standard Deviation
ADT on Major Street (vpd)	6,430	19,350	11,697.1	3,837.73
ADT on Minor Street (vpd)	1,400	13,285	6,704.4	3,540.22
Total ADT (Major plus Minor) (vpd)	8,371	29,732	18,401.5	6,597.25

The report describes the process used to decide upon a "functional area" within which crashes are considered to be roundabout related crashes, similar to the limitations placed on intersection facilities. The approach involved an assumption of a four-vehicle storage area with an average distance of 100 feet beyond the inscribed circle, combined with the stopping sight distance which was calculated according to the AASHTO guidance for perception-reaction time and deceleration rate. In this case a conservative estimate of 10 mph above the average posted speed limit was utilized, resulting in an assumed speed of 50 mph for all facilities. The authors used a rounded estimate of 800 ft to define the upstream boundary for inclusion in roundabout related crashes.

In terms of crash history used for this research, it should be noted that total crashes were very low for the five-year crash period (131) and averaged only 1.1 crash per roundabout annually. This was a limiting factor in the development of severity models as part of this research effort. Furthermore, property-damage-only (PDO) crashes in Oregon are self-reported crashes and as such this further affected the reliability of the crash data used in terms of being a true reflection of expected crash frequency. The most common crash types encountered in the research were rear-end collisions, followed by fixed or other object collisions, followed by angle collisions, and turning movements.

Data Analysis

This research effort developed a base model grounded on the following baseline conditions:

- Single lane roundabout,
- Four approach legs,
- 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,
- Circular roundabouts (no ovals),
- Inscribed circle diameter of approximately 135 feet
- Circulating lane width of approximately 16 to 17 feet, and
- A 15-mph circulating speed limit.

The authors recognized a poor fit between their data and the models for traditional intersections used the Highway Safety Manual SPFs, as such to account for the concave shape they added a quadratic term to improve the fit.

The authors used a cross-sectional model approach to develop Poisson and negative binomial regression statistical models that represent predicted number of crashes at a roundabout in Oregon in terms of both total crashes and injury crashes. A cumulative residual plot (CURE) was used to assess the model. The Total Crashes baseline model developed from a negative binomial model was described as an appropriate model, and CURE plots showed a random walk oscillating around zero. The authors used total traffic volume as an explanatory variable as part of their regression equation. A resulting high significance level for total traffic volume as a variable indicated it is an appropriate variable in explaining variation in crash data. An Injury Crashes baseline model was also produced. Both models are explicitly valid only for entering volumes of 8,975 to 29,732 vpd.

The report used the Empirical Bayes (EB) procedure to predict the safety of similar roundabouts. Dixon and Zheng identified that the procedure could be enhanced with the development of CMFs for non-baseline condition configurations, at the time of publication there were not enough of these configurations within the state to extend the procedure. The report outlines the multi-step procedure for roundabout safety assessment in Oregon, summarized as follows:

1. Check baseline conditions for target roundabouts (i.e., geometric, and operational configurations),
2. Identify traffic volumes for major and minor streets and compare to the minimum and maximum ranges for model application,
3. If baseline and volume criteria are met, estimate the annual total crashes or injury crashes using the roundabout models,
4. Report the results in terms of annual total crashes or annual total injury crashes.

The modeling results showed a strong positive relationship between traffic volumes and number of crashes. A limitation of the procedure developed by Dixon and Zheng is that the user must estimate the number of PDO crashes by subtracting the number of injury crashes from the number of total crashes. Comparison of the roundabout models with traditional rural 4-leg STOP-controlled and rural 4-leg signalized controlled intersection models available in the Highway Safety Manual (HSM) indicated the overall predicted crashes were fewer at roundabouts than for traditional intersections under similar settings.

Data from roundabouts in Washington state was used to assess the transferability of the Oregon model. While data were similar between groups, they were not identical, which presented another limitation. However, the report demonstrated that the SPFs when expanded to site-specific applications using the EB procedure, had reasonable transferability to sites in the state of Washington.

Geometric features such as the width of the circulating lane and the inscribed circle radius were ultimately found to not be statistically significant factors for the model, however this may be attributable to the similarity of the roundabouts used to develop the model.

In general, the research performed was a credible effort in the development of roundabout SPFs for the state of Oregon. However, it is not without its limitations, particularly in terms of data breadth and depth. The models developed as part of this research are limited in application to low-volume (< 30,000 vehicles per day) facilities with single circulatory lanes.

Chiu, L. The Development of Safety Performance Functions for Roundabouts in Wisconsin (2014)

In a 2014 master's thesis submitted to the University of Wisconsin, Chiu reviews the benefits of replacing intersections with roundabouts and provides a literature review of findings on the associated effects on safety performance. Chiu states that research shows that roundabouts, in general, perform better in terms of safety than conventional intersections, and experience different crash types due to their geometric characteristics.

The research performed by Chiu focused on the development of Wisconsin-specific safety performance functions (SPFs) for roundabouts which could build on the generic models found in the 2010 AASHTO Highway Safety Manual. The author reminds us that the reliability of SPFs rests on the goodness of fit of the model with local characteristics and features. The wide use of the Empirical Bayes method to estimate crash frequency is pointed out in this paper, as is the benefit in accounting for overdispersion of data by use of the negative binomial distribution for modeling.

A sample of 25 roundabouts in Wisconsin were used in conducting this research, and all were previously signalized or stop-controlled intersections. Roundabout configurations varied from typical four-leg to three-leg to ramp interchange roundabouts. The specific geometric features of all 25 roundabouts fed the model development as part of this research. Features were either obtained from plans or manually measured and included:

- AADT
- Inscribed circle diameter
- Center island radius
- Minimum circulating lane width,
- Number of circulating lanes
- Number of approaches and
- Crash frequency

In addition to developing SPFs for the 25 roundabouts sampled statewide, Chiu also developed a SPF for single approaches based on characteristics such as geometry and entering volume. Some limitations of the latter are that the roundabouts selected varied in geometry across different sectors of the same roundabout, while other roundabouts had a varying number of circulatory lanes. Features included as part of this model were:

- Entry angle,
- Entry width,
- Flare length,
- Turning radius,
- Circulatory AADT,
- Entering AADT and
- Crash frequency

Crash data employed as part of this research covered four years following construction of each roundabout and included crashes within 250 feet of the roundabout. Similar to other literature reviewed as part of this report, Chiu considered the total entering volume of traffic for model development.

The author used the forward step selection method to determine which variables were suitable for inclusion in the model, adding one variable at a time to the model, choosing the next variable based on the likelihood ratios test, which Chiu describes as "a statistical method that provides an objective standard for selecting better models" (Chiu, 2014). This was combined with Cook's Distance Leverage, which examines the result that removal or inclusion of a data point has on the regression model in order to determine its influential significance.

Another limitation of this research was that relatively low levels of injury crashes were found in the crash data history, such that the general SPF model developed was limited to total crash frequency only. Chiu's SPF models were developed using the negative binomial regression model. The form of the model as depicted in the paper published by the University of Wisconsin, is below in **Figure 1-3**.

$$4\ year\ crashes = \exp(Intercept) \cdot AADT^{b_1} \exp(c_1X_1 + c_2X_2 + \cdots + c_nX_n)$$

Where

$AADT$: annual average daily traffic entering the intersection

$X_1 + \cdots X_n$: other geometric features that affect the crash frequency

$b_1 \ldots b_n, c_1 \ldots c_n$: calibration coefficient

Figure 1-3: SPF Model Used by Chiu (Chiu, 2014)

Interestingly, the research performed by Chiu found that only AADT, in this case, was a significant variable to the model. The model developed to analyze single approaches took the same format and was implemented on 8 of the 25 locations, with results showing that a wider entry lane width was associated with decreased crashes, in comparison when the number of entering and exiting lanes increased the number of crashes was found to increase. While the single approach model did not find AADT to be a significant predictor of crashes, Chiu did note that entry lane width and the number of entering/exiting lanes, which were significant factors, are often directly related to volume.

This paper supports general assertions in the field of research regarding the negative binomial regression model being a highly suitable model for crash data and roundabout SPF development.

Giuffrè et al. An Italian Experience on Crash Modeling for Roundabouts (2015)

In a 2015 paper published in the Journal of Engineering and Applied Sciences, Giuffrè et al. concern themselves with the transferability of a SPF to sites outside of the geographic region for which it was developed. They investigate the calibration of an urban roundabout SPF in the Italian context for comparison with other SPFs available in literature to test transferability.

Giuffrè et al. begin by emphasizing the importance and value of SPFs in highway safety analysis and the question of transferability of SPFs outside of the geographic area within which they were developed. The latter being called into question due to parameters such as crash history, traffic volume, geometric characteristics, differences in driver population, crash reporting and climate etc. varying across geographic areas. The authors describe the two traditional options for procuring an SPF for a particular area: calibration of an existing SPF for conditions within the area of interest using CMFs, or development of an area specific SPF. This study is concerned with calibration of an Italian SPF for transferability to other available SPFs.

The paper highlights the differences seen in urban/suburban roundabout SPFs used across various countries including Italy which were developed between 2007 and 2011. As seen in **Figure 1-4** there are similarities between Canada and Trento, and between New Zealand and

Sweden, but the U.S. models are concave downwards which the others are concave upward. The authors assert that differences are due to specific geographic characteristics such as geometry, speed, climate etc., as well as crash reporting characteristics (e.g., PDO crashes are under reported in Italy) and small sample sized across the Italian models.

The study expanded the sample size of Italian roundabouts to 177 from 36 in order to develop an Italian SPF roundabout model which extended the original Trento model seen in **Figure 1-4**, with crashes observed from 1997 to 2020. The authors used GenStat software to produce a "flow-only" model using a Poisson distribution. This was supplemented by performing tests for overdispersion and ordinary least-squares regressions, which confirmed that a Poisson distribution was the most appropriate for the new extended model.

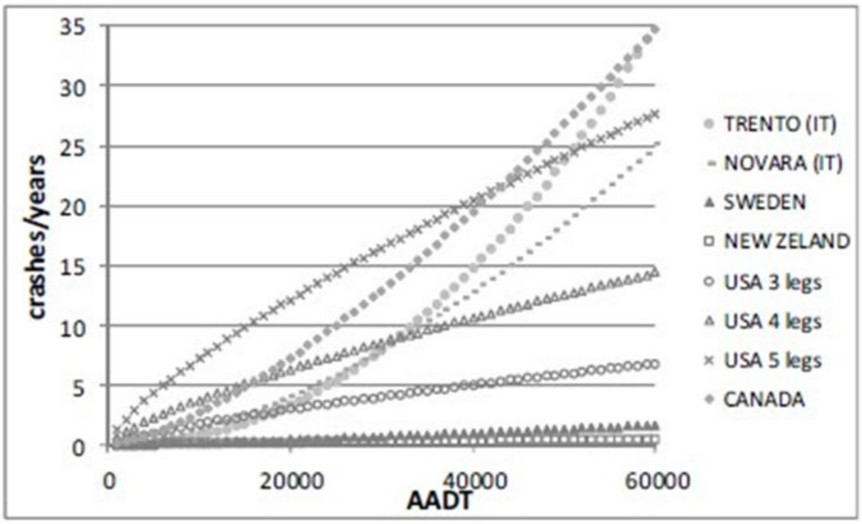

Figure-1. Comparison of safety performance functions for roundabouts from around the world.

Figure 1-4: Comparison of SPFs for Roundabouts from Various Countries by Giuffrè et al. (Giuffre, 2015)

To compare the Trento model and the new model for goodness of fit (GOF), the indicator of Mean Prediction Bias (whether the model over or under predicts crashes), Mean Absolute Deviance (the average misprediction of the model) and Mean Squared Predictive Error (assesses the error associated with external data sets) were used. The results of the analysis showed that the new model had a better GOF, that is estimated crashes well and that it has better prediction capacity.

The new extended model used by Giuffrè et al. was similar to the U.S. model seen in **Figure 1-4** found in literature. When both models were compared, the results showed that the differences in models increased as AADT increased, and as the number of legs increased. The study followed this comparison up with using the HSM calibration procedure to test the transferability of the USA model in an Italian context. The study used the CURE method to determine the GOF of the USA model and the extended Italian model to the observed data, to assess if calibration of a model from outside their jurisdiction performed as well as development of a jurisdiction specific model. Results indicated that both models oscillate around zero, indicating a good fit, however the Italian extended model had a lower standard deviation boundary width (see **Figure 1-5**).

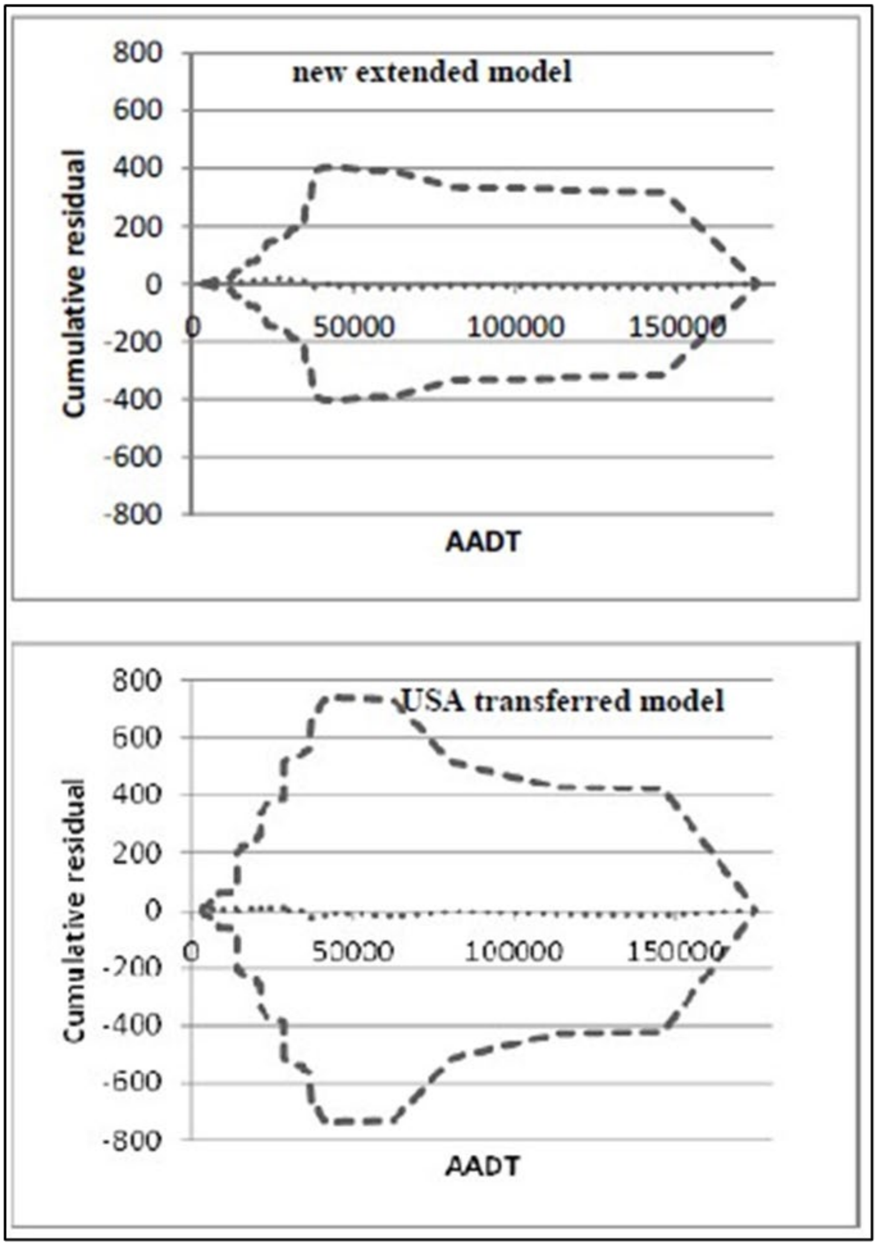

Figure 1-5: CURE Plots for Italian Extended Model and U.S. Model by Giuffrè et al.

Further GOF indicators were employed, such as Mean Prediction Bias, Mean Absolute Deviance and Mean Squared Predictive Error, which further confirmed that the Italian extended model was a better fit than the calibrated U.S. model.

The results of this study suggested that there is good transferability of SPF models between jurisdictions using the HSM calibration procedure, however, there is a better GOF when a SPF is developed specifically for the geographic area to which it is to be applied using data directly from that area. Giuffrè et al. conclude a jurisdiction specific SPF gives more reliable parameter estimates.

Gbologah, F.E. The Impacts of Illumination Levels on Nighttime Safety at Roundabouts (2016)

In his 2016 doctoral dissertation Gbologah evaluates the impact of illumination on nighttime safety at roundabouts, wherein he also develops a rapid measurement protocol for intersection illumination and applies the method to case studies in the state of Georgia. While Gbologah extols the more obvious benefit in terms of safety that roundabouts offer in comparison to intersections, that is the reduced number of conflict points, his review of literature regarding the specific degree of total and severe crash reduction that can be expected reveals that studies vary widely in their results. Gbologah's research was undertaken to address contemporary U.S. guidelines for the systematic illumination of all roundabouts to allow drivers to comprehend the layout and operation of the roundabout in enough time to maneuver appropriately. Gbologah argues this may not be a cost-effective policy and ignores the effects of ambient lighting.

The paper highlights several key reasons to consider illumination of roundabouts which include: the presence of pedestrian crossing in advance of the yield line for entering traffic and beyond the intersection point for exiting traffic, the necessity to see traffic approaching from the left and the necessity to negotiate the roundabout in dark conditions when headlights are tangential to the path, adequate lighting reduces delays and aids progression, lack of familiarity with geometrics is improved upon by adequate lighting. Gbologah argues that the geometric characteristics of roundabouts, that is deflected travel paths and sometimes raised splitter island with aprons, mean roundabouts require "visibility enhancing treatments…(…)...to ensure they can be safely negotiated, especially during nighttime conditions" (Gbologah, 2016).

An evaluation of contemporary literature by Gbologah along with a survey led to the assertion that most countries do not have a policy of systemic illumination of all roundabouts, that most rural roundabouts remain unlit, with that decision being largely left up to the local authorities. He goes on to highlight studies which have indicated reduced illumination may be equally effective in terms of nighttime safety. The author reviewed literature on both before-and-after studies and on cross-sectional studies regarding intersection illumination, his findings show that there is not conformity across studies in regard to the effects of intersection illumination on crash rates.

This paper asserts that the negative binomial regression is the traditional means of assessing the impact of illumination on safety because it does not require data to be split into before and after data, but into illuminated and unilluminated sets of data and accounts for overdispersion. Gbologah points to a paper by Bhagavathula et al. (Bhagavathula, 2015) which argues that using only nighttime crashes as a dependent measure in the model discounts day crashes and results in over or underestimation of other explanatory variables, and as such the number of day crashes should be incorporated as an offset variable in any model.

This paper highlights the wide variability across both studies and states in terms of selection of a "safety influence area" for intersection crashes, i.e., up to what extent do we consider crashes to have occurred at the intersection or to be related to the intersection on each approach. Studies reviewed by the author showed ranges from approximately 65 feet up to 500 feet, depending on the approach speed, while state practices outlined by the author indicate a range of 50 feet to 1320 feet.

Using qualitative intersection illumination data and crash data between 2003-2010 from Minnesota, Gbologah found that nighttime crash rates were approximately 61% lower in the presence of lighting compared to unlit conditions. Furthermore, findings indicated the most benefit in terms of nighttime crash reduction was found from the illumination of the roundabout circle alone when illumination of the circle and the approaches are considered. Empirical Bayes (EB) procedure could not be applied however, as data limitations in the date of illumination meant a before and after period could not be established. Another limitation was that all locations were on state or U.S. routes. Gbologah's method however showed only a 3.6% difference in estimated illumination between his method and existing methods.

Nighttime crash rates at roundabouts in Minnesota were observed to fall over the study period, however this may have been due to improvements in roundabout design over time, with many locations having "NONE" for illumination data being amongst the oldest data and those having "FULL" for illumination data being amongst the most recent. Nighttime and daytime adjustment factors were used to normalize crash rates. A limitation of the data set used by Gbologah is that it is unknown if there was bias in the lighting policy, that is some locations may have been chosen to be illuminated based on high crash history, while another limitation is a lack of information on any design or operational differences between the lighted and unlighted roundabouts. A further limitation of the analysis was that data could not be split into urban versus rural locations.

Roundabouts studied by the author had 'no,' 'partial' or 'full' illumination. It was observed that the crash rate for nighttime crashes at unlit roundabouts was about 2.5 times as high as the crash rate at lighted roundabouts. Gbologah's analysis led him to infer that nighttime crashes are reduced by 55% with partial illumination compared to no illumination and by 66% by full illumination compared to no illumination, although the degree of illumination is not quantified. An important finding by Gbologah was that about 80% of the benefits achieved from full illumination can be achieved by only partial illumination (central circle), which contradicts other studies which recommended increasing the length of the illumination zone. The findings of this paper regarding severe crashes stated that illumination can "significantly reduce or eliminate the occurrence of fatal and severe crashes" at roundabouts. However, this should not be over emphasized as the author's dataset included only one fatal crash over the study period.

The author, seeking an efficient quantitative method of measuring intersection illumination developed a protocol with a view to the development of an illumination level crash modification factor. The protocol involved a photographic method and two digital cameras for measurement of nighttime luminescence at intersections. The new protocol was applied to measure intersection illumination at 100 intersections and roundabouts in Georgia, with crash data from 2009-2014, to provide an initial estimate for a roundabout illumination crash modification factor. Limitations in this study included a small sample size and potential selection biases. Nonetheless, the application of quantifying illumination using the newly developed protocol showed a relationship between illuminance and nighttime crash rate, whereby a higher level of illuminance saw a reduction in nighttime crash rate.

The CMF developed by Gbologah used negative binomial regression to model changes in expected number of nighttime crashes and the associated illumination CMF for roundabouts with greater than 10,000 AADT. His findings showed that increasing luminance by 1 lux, implementing a 4-leg rather than a 3-leg roundabout configuration and locating the roundabout on a state road, decreased the expected number of nighttime crashes. It was also found that approach speeds greater than 45 mph or skew angles of 20 degrees or more had the effect of increasing the expected number of crashes. Gbologah's CMF indicated a 4.72% reduction in expected nighttime crashes when illumination is increased by 1 lux, with the results being very statistically significant ($p = 0.000915$).

The paper makes note of some findings which might be considered expected, being that facilities found to have a higher level of illumination were those that had higher volumes, higher approach speeds and a bigger skew angle. This paper further iterates a point which has been made in other papers regarding vulnerable road users: where roundabouts replace previously signalized intersections crashes involving vulnerable road users, e.g., pedestrians, can be seen to increase.

Gbologah makes the point that the unique geometric nature of roundabouts means that a change in one geometric parameter which positively affects one crash type may negatively affect another crash type. This is an interesting point to consider regarding the development of roundabout SPFs in general.

Despite limitations to the analysis performed by Gbologah, the findings provide evidence that direct safety benefits that are not insignificant can be achieved by roundabout illumination regarding nighttime crashes. The research also confirms findings made by other researchers regarding the effects of intersection replacement on vulnerable road users.

National Academies of Sciences, Engineering and Medicine. Development of Roundabout Crash Prediction Models and Methods (TRB Report 888) (2019)

The NCHRP Research Report 888 (National Academies of Sciences, Engineering and Medicine, 2019) presented the findings of a team which developed crash prediction models for urban/suburban and rural single lane and multilane roundabouts. Data was gathered from 350 U.S. roundabouts and the results produced three crash prediction models: planning level, intersection level, and leg-level. The crash prediction models provide Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs) to estimate frequency and severity of crashes expected to occur at roundabouts.

The primary objective was to discern how geometric and operational features of roundabouts affect crash frequency, severity, and type, in order to develop SPFs and CMFs. Other goals of this research effort included the evaluation of the effects of driver learning curves on crash frequency and severity at roundabouts and to fill in the gap in the Highway Safety Manual (HSM) first edition, which contained SPFs for traditional intersections but lacked any SPFs for roundabouts.

In their literature review the authors reiterate the widely accepted view that the negative binomial regression model is the dominant statistical modeling technique for SPFs because it accounts well for overdispersion of data which is typical with crash events. All crash prediction models which were developed by the team were developed using binomial regression modeling. The authors refer to the usefulness of the Empirical Bayes (EB) method which can be employed by use of the overdispersion factor, k, to adjust expected crash frequencies by accounting for observed crash counts also. This is presented in concert with a cautionary warning that the overdispersion parameter might vary as a function of site characteristics and any roundabout modeling should consider this. In terms of CMF development, because of limited before and after data due to the relative newness of roundabouts as a feature in the U.S., the cross-sectional method was used.

The review of U.S. and international literature which the team performed as part of this research effort found that the following roundabout features are commonly considered to be influential on crash frequency and severity:

- Volume Characteristics
  - Vehicle AADT
  - Pedestrian, bicycle, and motorcycle volume data
- Configuration Characteristics
  - Number of approaching or entering lanes and
  - Number of circulating lanes.
- Geometric Characteristics
  - Entry width,
  - Central island diameter,
  - Angle between approach legs,
  - Inscribed circle diameter,
  - Circulating width, and
  - Approach lane width.
- Speed-Related Characteristics
  - Entering, exiting, and circulating vehicle speed
  - Variation in vehicle speed (e.g., between vehicles, and for a single vehicle traveling through).
- Other Characteristics
  - Sight distance of approaching vehicle.

From the SPF models identified within their literature review (**Figure 1-6**) the authors observed that predicted crash frequency increases with an increasing entering volume and with two-circulating lanes, observations which were echoed in their own research which followed.

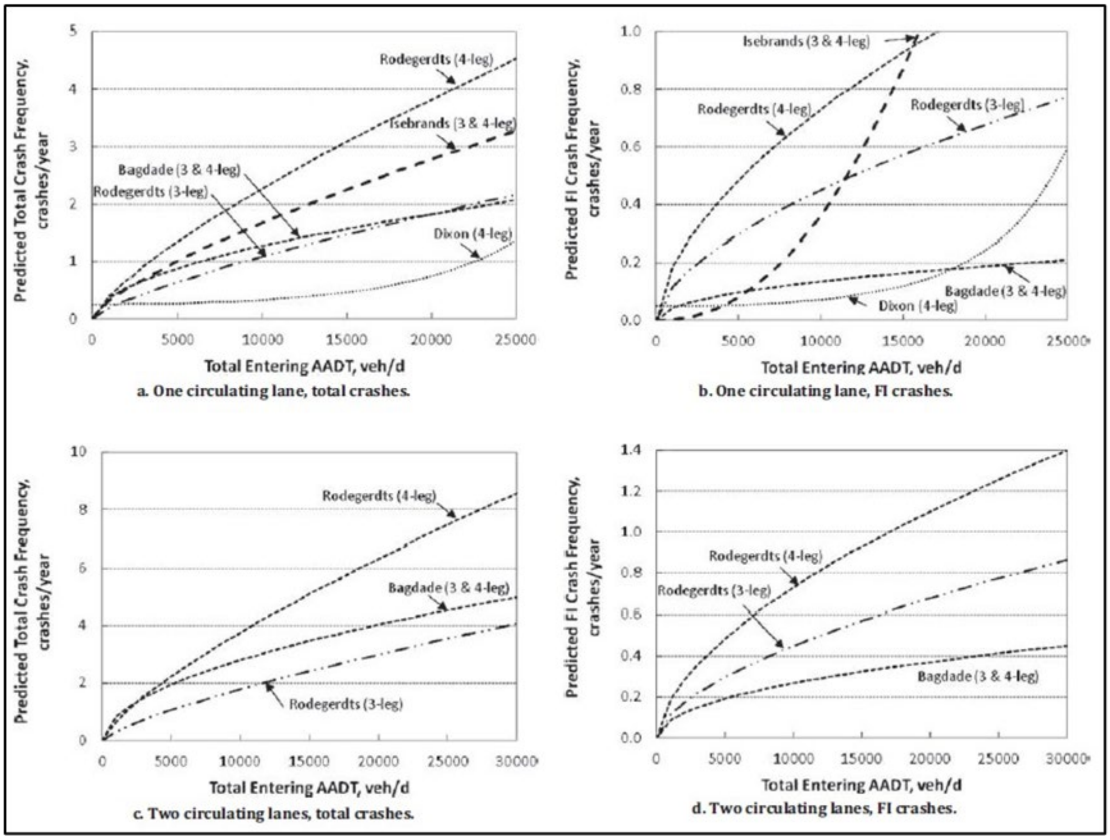

Figure 1-6: Figure 2-2 from NCHRP Report 888 (TRB 2019)

Like Gbologah (Gbologah, 2016), the authors outline the different approaches to SPF development: on the one hand developing SPFs with AADT-only variables and using CMFs to adjust the predictions when site-specific conditions differ from the base condition; and on the other hand, developing SPFs which are fully specified to site conditions.

The models developed here follow the former process which is also the process described in the HSM. Roundabout crashes were defined in a similar manner to HSM criteria and broadly used reporting practices, such that a roundabout crash is a crash which occurred at the intersection or is intersection-related within 250 feet. The intersection-level crash prediction models which were developed as part of this research used traditional crash-type definitions observed in U.S. databases (e.g., sideswipe, rear-end etc.), while leg-level crash prediction models which were developed used crash-type definitions unique to roundabouts (e.g., entering-circulating, exiting-circulating etc.).

The database which was assembled included roadway inventory, speed, traffic volume and crash data (3 or more years) from U.S. databases and local agencies. The data collection process itself appears to have been underpinned by a robust quality control and quality assurance procedure developed by the authors, which involved frequent checks for consistency and re-examination of data elements. A “Data Reduction Procedures Guide” was developed to ensure consistency in the method of data collection during the project, for example a step-by-step procedure for taking measurements from aerial imagery.

Figure 1-7 shows the number of sites used by state in the database, which suggests good diversity of conditions across sites used.

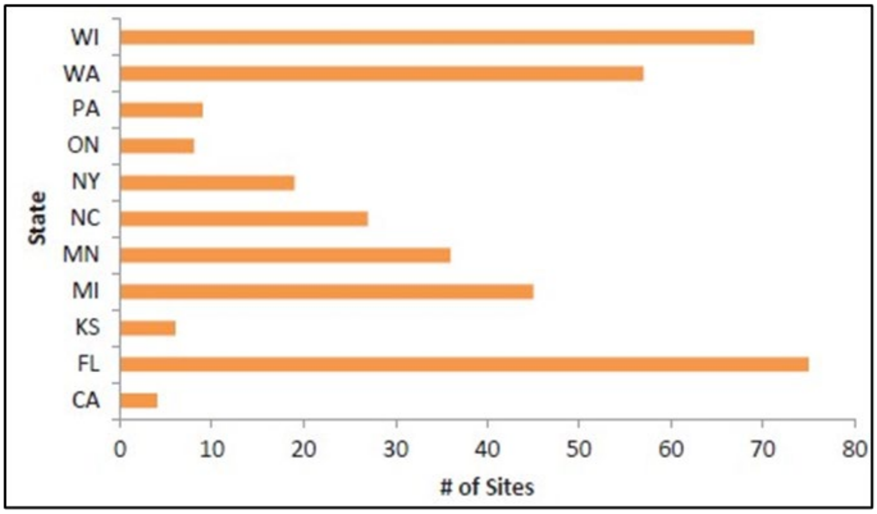

Figure 1-7: Figure 4-1 from NCHRP Report 888 (TRB 2019)

The geometric characteristics of the final database used by the authors shows most roundabouts were single lane in an urban/suburban setting and predominantly 4-leg (**Table 1-3**).

Table 1-3: Table 4-4 from NCHRP Report 888 (TRB 2019)

Data Attributes (Geometry, Area Type, Opening Year)	Number of Sites
Total Number of Single-Lane Roundabout Sites	235
Total Number of Multilane Roundabout Sites	120
Area Type (urban/suburban, rural)	Urban/Suburban = 250 Rural = 105
Ramp Terminal Intersection	Yes = 30 No = 325
Number of Roundabouts with Three Legs	104
Number of Roundabouts with Four Legs	251
Presence of Right-Turn Bypass Lane	Yes = 44 No = 311

Traffic volume data for sites used in the database indicate that the median AADT per leg for single-lane roundabouts was 5,100 vehicles per day (vpd) and 7,900 vpd for multilane sites.

The authors did not consider driveways which entered onto the roundabout to be “legs” because they had no splitter islands and considered one-way outbound legs which directed traffic onto a freeway to be freeway ramps. There are multiple examples of the latter in Colorado, and this presents an interesting point to note in the development of Colorado specific roundabout SPFs.

Planning-Level Crash Prediction Models

Planning level models have fewer data requirements and are intended for use in the early project stages for the comparison of the safety performance of one type of control with another. Models in this category were developed using only AADT as a predictor variable, with a few cases using additional variables which may be known at planning stages. The predicted crash frequency includes crashes both circulating the roundabout and those on the approach leg. The authors developed SPFs at the intersection-level for rural, urban single lane and urban multilane roundabouts.

The model form seen in **Figure 1-8**, which is taken directly from Chapter 6 of the report, was used for rural roundabouts. 'a' through 'e' are parameter estimates and k is the negative binomial overdispersion parameter. Due to the small number of rural multilane sites, these were combined with rural single lane sites for model development.

$$N = exp^{a+STATE} MAJAADT^{b} MINAADT^{c} exp^{(d \times NUMBERLEGS + e \times CIRCLANES)} \qquad \text{Equation 6-1}$$

where

N = predicted average crash frequency, crashes/yr;
STATE = an additive intercept term dependent on state;
MAJAADT = total entering AADT on major road;
MINAADT = total entering AADT on minor road;
NUMBERLEGS = 1 if a 3-leg roundabout; 0 if 4-legs;
CIRCLANES = 1 if a single-lane roundabout; 0 if more than 1 circulating lane; and
MAJSPD = posted speed on the major road (mph).

Figure 1-8: Equation 6-1 from NCHRP Report 888 (TRB 2019)

The model forms seen in **Figure 1-9** and **Figure 1-10**, which were both taken directly from chapter 6 of the report, were used for urban single lane roundabouts and urban multilane roundabouts, respectively. Again, 'a' through 'e' are parameter estimates and k is the negative binomial overdispersion parameter.

$$N = exp^{a} MAJAADT^{b} MINAADT^{c} exp^{(d \times NUMBERLEGS)}$$

Equation 6-2

where

N = predicted average crash frequency, crashes/yr;
MAJAADT = total entering AADT on major road;
MINAADT = total entering AADT on minor road; and
NUMBERLEGS = 1 if a 3-leg roundabout; 0 if 4-legs.

Figure 1-9: Equation 6-2 from NCHRP Report 888 (TRB 2019)

$$N = exp^{a} MAJAADT^{b} MINAADT^{c} exp^{(d \times NUMBERLEGS)}$$

Equation 6-3

where

N = predicted average crash frequency, crashes/yr;
MAJAADT = total entering AADT on major road;
MINAADT = total entering AADT on minor road; and
NUMBERLEGS = 1 if a 3-leg roundabout; 0 if 4-legs.

Figure 1-10: Equation 6-3 from NCHRP Report 888 (TRB 2019)

The models developed in these categories included total crashes, PDO crashes and 'Fatal+Injury' (FI) level crashes, as follows (KABC refers to the KABCO injury scale where K is Fatal, A is Severe injury, B is Moderate injury and C is Minor injury):

- Rural single lane, total.
- Rural single lane, KABC.
- Rural single lane, (PDO).
- Rural multilane, total.
- Rural multilane, KABC.
- Rural multilane, PDO.
- Urban single lane, total.
- Urban single lane, KABC.
- Urban single lane, PDO.

- Urban multilane, total.
- Urban multilane, KABC; and
- Urban multilane, PDO.

The models omitted bicycle and pedestrian crashes due to relative rarity of those events and insufficient data.

Intersection-Level Crash Prediction Models

Intersection level models are intended to assist with design decisions, similar to the way crash prediction models for signal and stop controlled intersections in the HSM do. These models are intended to predict total crash frequency and crash severity at a roundabout, with subsets of models used to achieve this. The models were intended to be used in the evaluation of alternative features or designs during the preliminary and final design stages. Crashes of all types were calibrated for, except those involving vehicle crashes with pedestrians or bicycles, due to insufficient crash history. Crash frequency models follow the HSM procedure, whereby a baseline SPF is adjusted using a CMF which accounts for individual site characteristics. Applicability is for at intersection or intersection-related crashes with an approach length of 250 feet from the back of the yield line.

The authors used the KABCO injury level scale to categorize crash severity. For the crash frequency subset, one group of models was calibrated to predict FI crashes while another was used to predict PDO crash frequency. For the crash severity subset, models were calibrated to predict the distribution of all FI crashes (K, A, B, and C). Both subsets can be used together to predict the frequency and severity of all crash levels.

This paper asserts that models estimating total crash frequency by developing a single model for predicting total (FI and PDO) crash frequency, have potential limitations when a less-than-optimal function is used as a crash model, and that they could lead to biased estimates and misleading conclusions. They further assert that the better approach is to calibrate a predictive model for the PDO category, and the FI category separately and then combine the two. The following subsets of models were developed as part of the intersection-level crash prediction modeling:

1. FI Crash Frequency Prediction Model - 1 Circulating Lane.
2. FI Crash Frequency Prediction Model - 2 Circulating Lanes.
3. PDO Crash Frequency Prediction Model - 1 Circulating Lane; and
4. PDO Crash Frequency Prediction Model - 2 Circulating Lanes.

The report presents baseline SPF model forms for 3 and 4-leg roundabouts for Model Subset 1, taken from Chapter 6 of the report and seen in **Figure 1-11** below. AADT is the sum of all entering vehicle volumes from all legs.

SPF for three-leg roundabouts.

$$N_{SPF,3} = exp[-4.404 + 1.084 \times LN(EntAADT_3/1000) + 0.206 \times I_{rural}] \qquad \text{Equation 6-4}$$

SPF for four-leg roundabouts.

$$N_{SPF,4} = exp[-3.503 + 0.915 \times LN(EntAADT_4/1000) + 0.206 \times I_{rural}] \qquad \text{Equation 6-5}$$

where

$N_{SPF,m}$ = predicted average crash frequency for base conditions on all legs for roundabout with m legs ($m = 3, 4$), crashes/yr;

$EntAADT_m$ = entering annual average daily traffic (AADT) for roundabout with m legs ($m = 3, 4$), veh/d; and

I_{rural} = area type indicator variable (= 1.0 if area is rural, 0.0 otherwise).

Figure 1-11: Equation 6-4 and Equation 6-5 from NCHRP Report 888 (TRB 2019)

The authors developed CMFs that could be applied to the baseline SPFs, so that the SPF prediction can be adjusted when non-baseline conditions exist, i.e., to account for site-specific conditions, this follows the method prescribed in the HSM. CMFs were developed for the following conditions:

- Inside circle diameter (urban and suburban only) with a range of 90-160 feet,
- Outbound-only leg at interchange cross-ramp terminal roundabouts in urban/suburban/rural settings (not applicable if more than one outbound-only leg),
- Right-turn bypass lane in any setting with add-lane, merge, or yield controlled (can include bypass lanes on all legs if each is independently operated), and
- Access point frequency, which is leg specific for use in all settings, (counts number of driveways or unsignalized access points on a leg within 250 feet of the yield line).

Model calibration requires that all leg-specific CMFs be aggregated to determine a combined CMF. The CMF and SPF values can then be used to predict crash frequency. This can be followed by five optional steps which include:

- Applying a leg-specific severity adjustment factor to adjust predicted severity distribution as a function of speed limit for speeds of 10-60 mph,
- Determining and applying an aggregate leg-specific adjustment factor,
- Applying severity distribution to determine the predicted distribution of FI crashes,
- Applying a crash type distribution, and
- Computing predicted crash frequency by crash type and severity.

Figure 1-12 shows the relationship between crash frequency and traffic demand as determined by this particular model, with some assumptions listed in the figure. The authors conclude that crash frequency increases with entering AADT volume and that rural roundabouts have about 25% more crashes than urban.

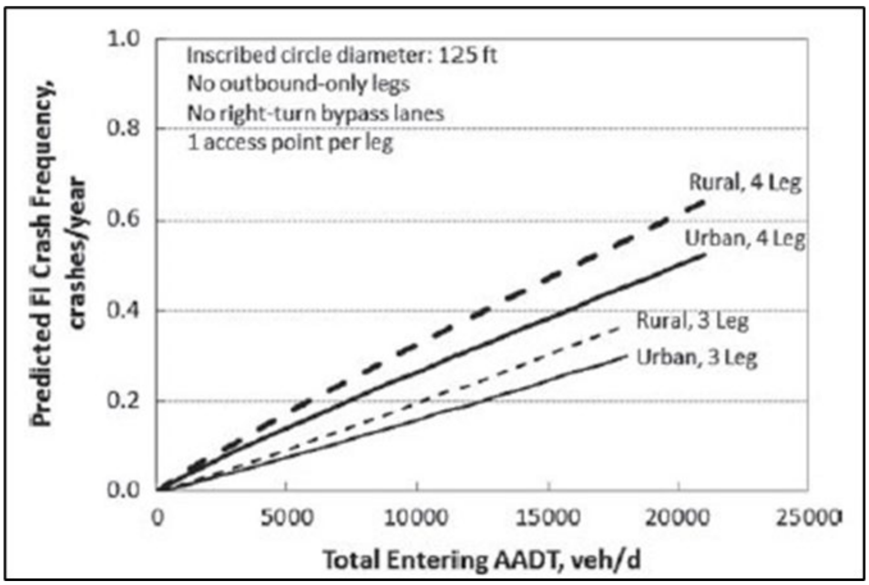

Figure 1-12: Figure 6-1a from NCHRP Report 888 (TRB 2019)

Other observations made during this subset model development included: reduced crashes with large inscribed circle diameter which was thought to be an indirect result of improved visibility and reduced speeds; 57% fewer crashes at roundabouts with one out-bound only leg versus one with all legs serving two-way traffic, thought to be due to reduced conflict points; large crash reductions with a right turn bypass lane which eliminates conflict points; CMFs increasing above 1.0 with increasing access points frequency on legs; crashes at 4-leg roundabouts tend to be less severe than those at 3-leg roundabouts; and increasing speed brings increasing crash severity.

The report presents baseline SPF model forms for 3 or 4-leg roundabouts for Subset 2, taken from Chapter 6 of the report and seen in **Figure 1-13** below.

SPF for three-leg roundabouts:

$$N_{SPF,3} = exp[-3.887 + 1.306 \times LN(EntAADT_3/1000) + 0.250 \times I_{rural}] \quad \text{Equation 6-29}$$

SPF for four-leg roundabouts:

$$N_{SPF,4} = exp[-3.535 + 1.276 \times LN(EntAADT_4/1000) + 0.250 \times I_{rural}] \quad \text{Equation 6-30}$$

where

$N_{SPF,m}$ = predicted average crash frequency for base conditions on all legs for roundabout with m legs ($m = 3, 4$), crashes/yr;

$EntAADT_m$ = entering AADT for roundabout with m legs ($m = 3, 4$), veh/d; and

I_{rural} = area type indicator variable (= 1.0 if area is rural, 0.0 otherwise).

Figure 1-13: Equation 6-29 and Equation 6-30 from NCHRP Report 888 (TRB 2019)

Similar to the first subset, CMFs that could be applied to the baseline SPFs when non-baseline conditions exist were developed for the following conditions:

- Outbound-only leg for any setting, only applicable to interchange cross-ramps terminal roundabouts with one outbound-only leg.
- Right turn bypass lane, which is leg-specific, for any setting, which can be extended to a situation where all legs have bypass lanes if independently operated with add-lane, merge, or yield control.
- Entry width, which is leg specific, for any setting, with a baseline of 20 feet for one entering lane and 29 feet for two entering lanes on an approach. Width is measured as the perpendicular width of all entering lanes including shoulders and the entrance line from splitter island to curb face/paved edge of traveled way/edge of bypass lane; and
- Circulating lane, which is leg-specific, for any setting but not applicable to outbound-only legs.

As per Model Subset 1, to calibrate the model correctly, all leg-specific CMFs need to be aggregated to determine a combined CMF. The CMF and SPF values can then be used to predict crash frequency. This can be followed by the five optional steps which were outlined as part of Subset 1 above.

Figure 1-14 shows the relationship between crash frequency and traffic demand as determined by this particular model, with some assumptions listed in the figure. The authors conclude that crash frequency increases with entering AADT volume and that rural roundabouts have about 28% more crashes than urban.

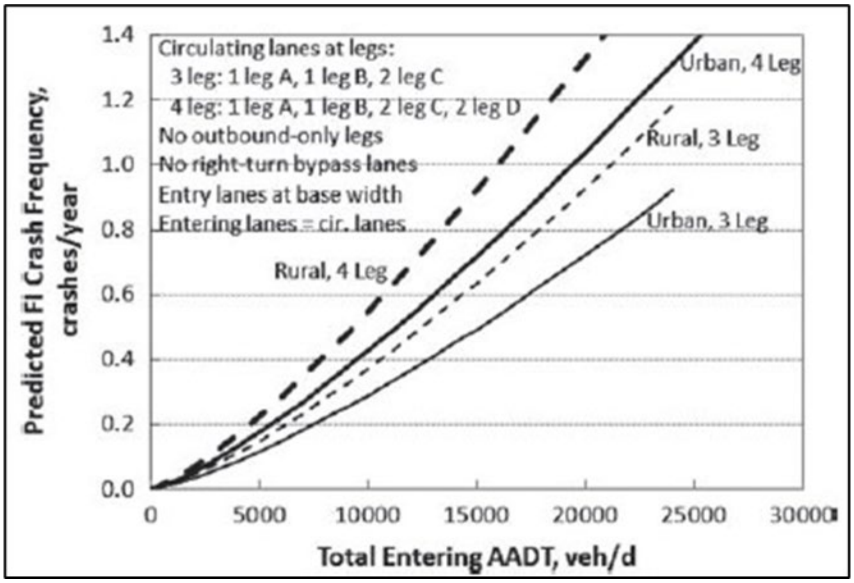

Figure 1-14: Figure 6-5a from NCHRP Report 888 (TRB 2019)

Other observations made during this subset model development included: roundabouts with one outbound-only leg have about 54.5% less crashes than one with all legs serving two-way traffic which is thought to be influenced by less conflict points; the presence of a right turn bypass panes reduces crashes because of reduced conflict points; a wider entry width produces a great crash reduction which is thought to be due to increased lateral separation between vehicles and objects and vehicles and adjacent lanes; trends show there are more crashes on roundabouts with two circulating lanes, thought to be due to more conflict points; there is a tendency for the number of more severe crashes (K and A) to increase as the number of lanes increases, however the number of B crashes is seen to decrease.

The report presents baseline SPF model forms for 3 or 4-leg roundabouts for Subset 3, taken from Chapter 6 of the report and seen in **Figure 1-15** below.

SPF for three-leg roundabouts:

$$N_{SPF,3} = exp[-1.720 + 0.486 \times LN(EntAADT_3/1000) + 0.168 \times I_{rural}] \quad \text{Equation 6-54}$$

SPF for four-leg roundabouts:

$$N_{SPF,4} = exp[-1.475 + 0.702 \times LN(EntAADT_4/1000) + 0.168 \times I_{rural}] \quad \text{Equation 6-55}$$

where

$N_{SPF,m}$ = predicted average crash frequency for base conditions on all legs for roundabout with m legs ($m = 3, 4$), crashes/yr;

$EntAADT_m$ = entering AADT for roundabout with m legs ($m = 3, 4$), veh/d; and

I_{rural} = area type indicator variable (= 1.0 if area is rural, 0.0 otherwise).

Figure 1-15: Equation 6-54 and Equation 6-55 from NCHRP Report 888 (TRB 2019)

Similar to the other model subsets, CMFs that could be applied to the baseline SPFs when non-baseline conditions exist were developed for the following condition:

- Access point frequency, which is leg-specific, for any setting, with the access point count representing the number of driveways or unsignalized access points on a leg within 250 feet of the yield line.

As per the other model subsets, to calibrate the model correctly, leg-specific CMFs need to be aggregated to determine a combined CMF. The CMF and SPF values can then be used to predict crash frequency. This can be followed by two optional steps:

- Applying a crash type distribution for PDO crashes, and
- Computing the predicted crash frequency by crash type category.

Figure 1-16 shows the relationship between crash frequency and traffic demand as determined by this particular model, with some assumptions listed in the figure. The authors conclude that crash frequency increases with entering AADT volume and that rural roundabouts have about 18% more crashes than urban.

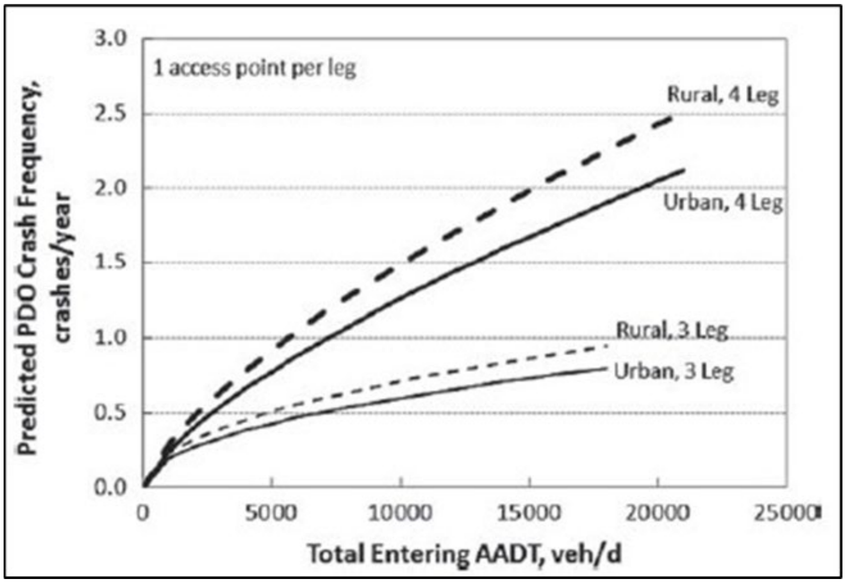

Figure 1-16: Figure 6-7a from NCHRP Report 888 (TRB 2019)

Another observation made during the development of this subset model includes the increase in the CMF above 1.0 as the number of access points increases, i.e., more access points are related to an increase in crashes.

The report presents baseline SPF model forms for 3 or 4-leg roundabouts for Model Subset 4, taken from Chapter 6 of the report and seen in **Figure 1-17** below.

$$N_{SPF,3} = exp[-1.565 + 1.055 \times LN(EntAADT_3/1000) + 0.496 \times I_{rural}] \quad \text{Equation 6-65}$$

SPF for four-leg roundabouts:

$$N_{SPF,4} = exp[-1.536 + 1.131 \times LN(EntAADT_4/1000) + 0.496 \times I_{rural}] \quad \text{Equation 6-66}$$

where

$N_{SPF,m}$ = predicted average crash frequency for base conditions on all legs for roundabout with m legs ($m = 3, 4$), crashes/yr;

$EntAADT_m$ = entering AADT for roundabout with m legs ($m = 3, 4$), veh/d; and

I_{rural} = area type indicator variable (= 1.0 if area is rural, 0.0 otherwise).

Figure 1-17: Equation 6-65 and Equation 6-66 from NCHRP Report 888 (TRB 2019)

Similar to the other model subsets, CMFs that could be applied to the baseline SPFs when non-baseline conditions exist were developed for the following conditions:

- Entry width, which is leg-specific, for any setting, with a base width of 20 feet for one entering lane and 29 feet for two entering lanes on an approach. Width is measured from the entrance line and is the perpendicular width of entering lanes and shoulders from the splitter island to the curb/outside paved edge of traveled way/edge of bypass lane.
- Circulating lane, which is leg-specific, for any setting and is not applicable to outbound-only legs.

As per the other model subsets, to calibrate the model correctly, leg-specific CMFs need to be aggregated to determine a combined CMF. The CMF and SPF values can then be used to predict crash frequency. This can be followed by two optional steps:

- Applying a crash type distribution for PDO crashes, and
- Computing the predicted crash frequency by crash type category.

Figure 1-18 shows the relationship between crash frequency and traffic demand as determined by this particular model, with some assumptions listed in the figure. The authors conclude that crash frequency increases with entering AADT volume and that rural roundabouts have about 62% more crashes than urban.

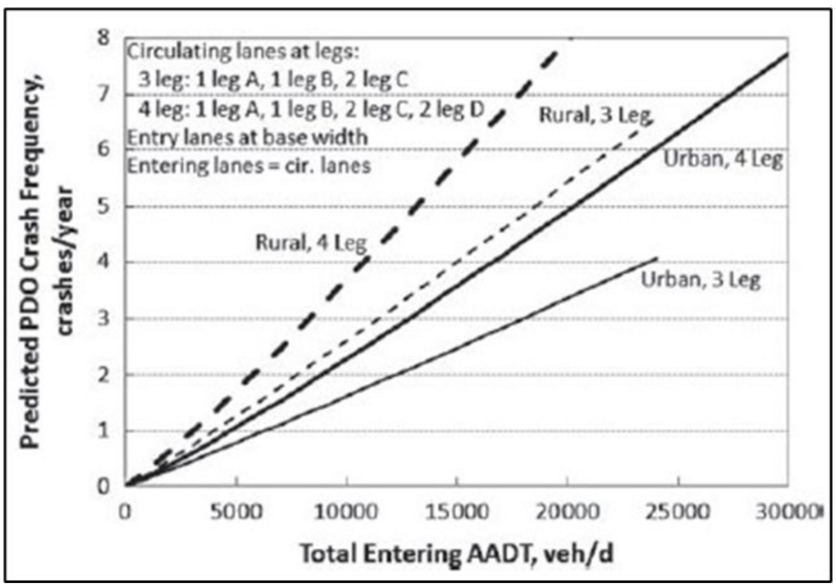

Figure 1-18: Figure 6-9a from NCHRP Report 888 (TRB 2019)

Other observations made during this subset model development included:

- An increase in entry width was observed to correspond with a decrease in crashes, thought to be due to increased lateral separation between vehicles and objects and between vehicles and adjacent lanes; and

- CMFs for roundabouts with two entering lanes were seen to be larger than for those with one entering lane, indicating crashes are increased with more circulating lanes, thought to be due to an increase in conflict points.

Leg-Level Crash Prediction Models

Leg level models were intended to also inform design decisions and to serve as a comparison with leg-level models from abroad which were found by the authors to be frequently developed for roundabouts. The leg-level crash prediction models were split into subsets as follows:

1. Entering-Circulating Crash Models,
2. Exiting-Circulating Crash Models,
3. Rear-End Approach Crash Models,
4. Single Vehicle Approach Crash Models,
5. Circulating-Circulating Crash Models,
6. Single Vehicle Circulating Plus Single Vehicle Approach Crash Models, and
7. Total Crash Models

Because there were not sufficient fatal and injury (FI) level crashes, all models were developed using combined PDO plus FI crashes.

Subset 1 models were developed using the equations seen in **Figure 1-19**, taken from Chapter 6 of the report.

$$EntCirc = exp^{a} EntAADT^{b} CircAADT^{c} exp^{(d \times ICD + e \times Bypass + f \times Statevar)}$$

Equation 6-77

$$EntCirc = exp^{a} EntAADT^{b} CircAADT^{c} exp^{(d \times ICD + e \times Angle + f \times COS(Angle))}$$

Equation 6-78

$$EntCirc = exp^{a} EntAADT^{b} CircAADT^{c} exp^{(d \times ICD + g \times CircWidth)}$$

Equation 6-79

$$EntCirc = exp^{a} EntAADT^{b} CircAADT^{c} exp^{(e \times Angle + f \times COS(Angle) + g \times CircWidth)}$$

Equation 6-80

$$EntCirc = exp^{a} EntAADT^{b} CircAADT^{c} exp^{(d \times ICD + e \times Angle + f \times COS(Angle) + h \times TwoEnteringLanes)}$$

Equation 6-81

Figure 1-19: Equation 6-77 through 6-81 from NCHRP Report 888 (TRB 2019)

The variables incorporated into the models included inscribed circle diameter (ICD), bypass lane, a state variable, circulating width, intercept, angle and COSAngle, as well as a variable for 2-entering lanes and one for the overdispersion parameter, k.

It was observed that CMFs for entering-circulating crashes decreased with an increasing ICD and angle to the next leg, as well as when a bypass lane is present and when circulating width is increased on roundabouts with two circulating lanes, which contrast with single lane roundabouts where an increase in circulating width was observed to cause more entering-circulating crashes.

Subset 2 models were developed using the equations seen in **Figure 1-20**, taken from chapter 6 of the report.

$$ExtCirc = exp^{a} ExtAADT^{b} CircAADT^{c} exp^{(e \times CircWidth + g \times State)}$$

Equation 6-82

$$ExtCirc = exp^{a} ExtAADT^{b} CircAADT^{c} exp^{(d \times ICD + e \times CircWidth + g \times State)}$$

Equation 6-83

Figure 1-20: Equation 6-82 and Equation 6-83 from NCHRP Report 888 (TRB 2019)

The variables incorporated into the models included inscribed circle diameter (ICD), bypass lane, a state variable, circulating width, intercept, angle, as well as a variable for 2-entering lanes and one for the overdispersion parameter, k.

It is interesting to note that in the development of this model subset, models were not successful where there was only one circulating lane and one exiting lane, while CMFs could not be determined in the case of two circulating lanes and two exiting lanes because the model did not have any non-AADT variables. It was observed by the authors that a bigger ICD was associated with fewer crashes in the case of two circulating lanes and one exiting lane. They also observed that increasing circulating width is associated with more crashes in the case of one circulating lane and less crashes in the case of two circulating lanes.

Subset 3 models were developed using the equation seen in **Figure 1-21**, taken from chapter 6 of the report.

$$RearEnd\ Approach = exp^{a}\, ApprAADT^{b} CircAADT^{c}\, exp^{(d \times NumberAccess + e \times Luminaires)} \quad \text{Equation 6-84}$$

Figure 1-21: Equation 6-84 from NCHRP Report 888 (TRB 2019)

The variables used in the model included intercept, number of accesses, number of luminaires and the overdispersion parameter, k. The authors concluded that as the number of access points increases on an approach the number of rear-end approach crashes increases, while a decrease in rear-end approach crashes was observed with an increase in the number of luminaires.

Subset 4 models were developed using the equation seen in **Figure 1-22** taken from chapter 6 of the report. All legs were modeled together in this case.

$$SV\ Approach = exp^{a}\, ApprAADT^{b} exp^{(c \times PostedSpeed + d \times AreaType + e \times State)} \quad \text{Equation 6-85}$$

Figure 1-22: Equation 6-85 from NCHRP Report 888 (TRB 2019)

Variables incorporated into this model included intercept, posted speed, rural area type, state and the overdispersion parameter, k. The authors developed two models in this case, one based on posted speed limit and one based on setting (urban or rural). A limitation to the former is that the speed limit data was incomplete for all legs. The report concluded that single vehicle approach crashes increase as speed limit increases and are higher in rural than in urban areas due to the presence of higher speed limits.

Subset 5 models were developed using the form seen in **Figure 1-23** taken from chapter 6 of the report. The model was successful for just the two circulating lane leg configuration.

$$Circulating - Circulating = exp^{a} CircAADT^{b} exp^{(c \times CircWidth)} \quad \text{Equation 6-86}$$

Figure 1-23: Equation 6-86 from NCHRP Report 888 (TRB 2019)

Variables incorporated into the model included intercept, circulating width and the overdispersion parameter, k. The authors determined that for circulating-circulating crashes, the number of crashes decreases at the circulating width increases at locations with two circulating lanes.

Subset 6 models were developed using the form seen in **Figure 1-24** taken from Chapter 6 of the report. The researchers were unsuccessful in developing models to single vehicle circulating crashes, so these crashes were combined with single vehicle approach crashes to generate a new model. Two subsets of model were developed, one based on posted speed limit and one based on setting (urban or rural).

$$SV\ Approach + SV\ Circulating = exp^{a}\, ApprAADT^{b}\, exp^{(c \times PostedSpeed + d \times CircWidth + e \times TwoEnteringLanes + f \times AreaType + g \times State)} \quad \text{Equation 6-87}$$

Figure 1-24:Equation 6-87 from NCHRP Report 888 (TRB 2019)

Variables incorporated into the model included intercept, posted speed, circulating width, presence of two entering lanes, rural area type, state and the overdispersion parameter, k. The CMFs were derived from the speed limit-based model and showed that single vehicle crashes increased with increasing speed, are higher where legs have two entering lanes and are lower as the width of the circulating lane increases.

Subset 7 models (Total Crashes) were developed using the form seen in **Figure 1-25** taken from Chapter 6 of the report, but the authors did not develop CMFs with these. The purpose of the total crash models seems to have been to serve as a means of obtaining an estimate for a particular crash type in cases where models did not provide this, by subtracting from the total crash model. The authors developed models for one circulating lane and two circulating lanes which are shown, respectively, in **Figure 1-25** following taken from Chapter 6 of the report.

Variables incorporated into the successful models included area type, number of entering and number of exiting lanes and the overdispersion parameter, k.

$$Total = exp^{a}\, ApprAADT^{b}\, CircAADT^{c}\, exp^{(d \times AreaType + e \times TwoEnteringLanes)} \quad \text{Equation 6-88}$$

$$Total = exp^{a}\, ApprAADT^{b}\, CircAADT^{c}\, exp^{(d \times AreaType + e \times TwoEnteringLanes + f \times TwoExitingLanes)} \quad \text{Equation 6-89}$$

Figure 1-25:Equation 6-88 and Equation 6-89 from NCHRP Report 888 (TRB 2019)

The paper stresses the importance of calibration of the crash prediction models which were developed from this research and are outlined above (planning-level, intersection-level, and leg-level). If uncalibrated models were to be used it introduces the risk of making decisions and comparisons in error when it comes to comparing roundabout safety performance to other interaction forms.

The calibration procedure used by the authors follows that outlined in the HSM and which will be reviewed and enhanced by an NCHRP project, (project 17-63). They argue that applying that same procedure to roundabouts would ensure consistency in the HSM.

Effects of Driver Learning Curve on Roundabout Safety Performance

The authors investigated the effects of driver learning curve on roundabout safety performance, with the goal of detecting if there was a decreasing trend observable in crashes over time when changes for AADT over time were accounted for. 109 sites where the opening year was readily identifiable were used. The postconstruction data period was selected as 5 years. The authors conclusion of their findings was that there is not satisfactory evidence of a driver learning curve having an effect on roundabout safety.

Pedestrian and Bicycle Safety at Roundabouts

The authors assert that development of SPFs related to pedestrian and bicycle crashes is difficult due to inconsistent collection of pedestrian and bicycle traffic volumes and because these crash types are much rarer, with historical data being limited. From the project database the authors compiled, pedestrian crashes accounted for about 0.4% of all crashes and bicycle crashes for about 1%. It was decided that crash history was insufficient to develop separate models for predicting pedestrian and bicycle crashes at roundabouts. However, their research provides supporting evidence to show that most pedestrian/bicycle crashes result in injury crashes, which is widely accepted. In the dataset used by the researchers, the majority of those injury crashes were at the KABCO injury level B or C.

A lack of pedestrian and bicycle volume counts, as well as skews in that data (more urban than rural crash records) meant that the authors were unable to make any conclusions with certainty related to bicycle and pedestrian crashes in terms or an urban or rural context. Similarly, without volume and exposure data, and because of skews in the dataset, conclusions could not be drawn on ped/bike crashes as related to roundabout geometrics.

Speed at Roundabouts

A goal of the research was to explore a relationship between speed and roundabout crashes. The researchers determined the fastest path radii for right turning, left turning and through travel at a number of sites. Fastest path radii were used to predict speed at points along the path for different movements. Predicted speeds were compared against data from crash reports but it was determined that further research is required. A relationship was identified between posted speed limit and single vehicle crashes and led to the conclusion that single vehicle approach crashes increase as speed limit increases and are higher in rural than in urban areas due to the presence of higher speed limits. The authors suggest that future research into prediction of entering speed and crashes at roundabouts would be merited.

The repeated themes which arose as part of the research which are highlighted by the authors in their summary are:

- When traffic volume is constant, multilane roundabouts show a tendency to experience more crashes than single lane roundabouts, suggesting that overdesign of capacity may bring reduced safety performance.
- In terms of vulnerable road users, bicycle and pedestrian crashes account for a very small proportion of all crashes at roundabouts.
- There seems to be a relationship between crash severity and posted speed, with higher speeds associated with more severe crashes.
- Volumetric data on multimodal transportation is lacking and undermines the robustness of models.
- Further research into the relationship between vehicle speeds on roundabouts as a crash predictor is merited; and
- Calibration of the models which were developed is crucial for accurate application.

This project addressed the knowledge gap around specific characteristics of some roundabouts which make them more successful than others in terms of crash reduction and safety benefit. The results of this research allow practitioners to evaluate the safety benefits of design decisions related to urban/suburban and rural single lane and multilane roundabouts and to quantify crash reduction due to roundabout installation. The crash prediction models which were developed can aid practitioners at the planning level for network screening, or at the design decision level if the intersection-level and leg-level models are used. The report provides a guide for calibration of models to local conditions which increases the accessibility of models for practitioners. The findings of this report were also proposed for adoption into parts B and C of the HSM with accompanying sample problems and CMFs.

Summary of Findings

A review of extant literature showed that the negative binomial regression model is broadly accepted as the most suitable form for modeling of crash data because it is capable of accounting for overdispersion, which is typically encountered with crash data.

Review of literature indicates that because design guidelines and other characteristics such as modal type, environment, driver population, crash reporting etc. for roundabouts are different across countries, results from research in which SPFs have been developed for roundabouts in another country may not necessarily be valid in the United States. Indeed, the research undertaken by Giuffrè et al. (Giuffre, 2015) showed that an Italian developed site-specific SPF model, was shown to be a better fit than a calibrated U.S. model for a situation in the Italian context., showing less standard deviation. As such, it is best when a SPF is developed specifically for the geographic area to which it is to be applied using data directly from that area.

Within the United States the guidelines and procedure laid out within the Highway Safety Manual in regard to SPF model development appear to be widely accepted. It is also accepted that roundabout SPFs can be developed for baseline conditions and adjusted by applying CMFs for site specific conditions, or alternatively site-specific SPFs should be developed. All studies are in agreement when it comes to the importance of calibrating SPFs should conditions differ from baseline conditions, in order for interpretation to be accurate and meaningful in informing analysis and decisions.

Common elements which were considered as part of SPF development across the literature which was examined include:

- Inside circle geometrics,
- Presence of a right turn bypass lane,
- Number of circulating lanes,
- Width of circulating lanes,
- Width of entry lanes,
- Number of legs,
- Setting (urban/rural etc.) and
- Angle between intersection legs.

The report by Daniels et al. (Daniels, 2010) is the only one which deviates from other research where the importance of geometric features in terms of variables of importance are concerned in model development. Daniels et al. found that geometric features such as inscribed circle diameter, central island diameter and number of lanes were not variables of importance, however other studies found that geometric features such as these did affect crash rate prediction. Studies commonly show that an increase in traffic volume entering a roundabout (AADT is typically taken as the total entering volume from all approach legs) is associated with an increase in crash frequency, such that SPF development with AADT as the explanatory variable is logical. Literature evaluated in this report, and studies which are referred to within that literature, have generally found that in instances where a roundabout replaces a signalized intersection, crashes have been observed to increase, in particular amongst the population of vulnerable road users.

There are mixed results across studies in regard to crashes at roundabouts involving vulnerable road users like pedestrians and bicyclists. However, in general it seems that additional quantity and depth of data regarding these crash types is welcomed by all investigators as elements which underpin the robustness of any models which might be developed.

Another area where researchers differ is on what they considered as the applicable area for roundabout inclusive crashes, with parameters varying from 250 feet to 800 feet from about the inscribed circle.

The research performed by Gbologah (Gbologah, 2016) into the safety effects of illumination at roundabouts found that nighttime crash rates were approximately 61% lower in the presence of lighting compared to unlit conditions. While there are some questions over the breadth and depth of data employed by Gbologah, an interesting finding of his was that about 80% of the benefits achieved from full illumination can be achieved by only partial illumination (central circle), which contradicts other studies which recommended increasing the length of the illumination zone.

The research undertaken as part of the National Academies of Sciences, Engineering and Medicine which was published in 2019 appears to have had to greatest effect in reducing any knowledge gaps which existed in the HSM surrounding roundabout specific SPF and CMF development.

2. Chapter 2 – Dataset Preparation

The primary objective of this project is to develop a Colorado-specific base of safety knowledge for roundabout facilities, intended to assist CDOT staff with maximizing safety improvements at Colorado roundabouts within constraints of available budgets. This base of Colorado-specific safety knowledge is comprised of predictive tools in the form of Safety Performance Functions (SPF) and diagnostic tools in the form of diagnostic menus and pattern recognition algorithms.

The work on this project includes development of SPF and diagnostic norms for the following roundabout facilities:

- Urban 3-Leg 1-Lane Roundabouts,
- Urban 4-Leg 1-Lane Roundabouts, and
- Urban 4-Leg 2-Lane Roundabouts,

where "lane" refers to the number of circulating lanes around the inscribed circle.

This methodology also provides a platform for the planning of system level improvements, decision support analysis at the project level and risk management. The work elements include the following:

- Development of the Safety Performance Functions (SPF)
- Estimation of the Level of Service of Safety (LOSS) boundaries
- Development of Stratified Diagnostic Norms

Dataset Preparation

All of the dataset preparation was performed using the Colorado Department of Transportation (CDOT) crash database. Roundabout-related crash history over the study period of 5 years (1/1/2015-12/31/2019) and Annual Average Daily Traffic (AADT) for each entering leg (main line and side road) at roundabouts were collected for the same dataset.

Initially, crashes from the CDOT crash database which were coded as occurring at "ROUNDABOUT" in Vision Zero Suite (VZS) for the 2011 through 2020 period were extracted. This yielded approximately 6,200 crashes at approximately 500 discrete roundabout locations which were geo-coded onto the Colorado roadway network.

Following this a web map was developed with those geocoded crashes along with any available ADT from sources including the CDOT MS2 tool, the Denver Council of Regional Governments (DRCOG) tool, Pikes Peak Area Council of Governments (PPACG), Pueblo Area Council of Governments (PACOG), the Grand Valley Metropolitan Planning Authority (GVMPO), as well as other city and county sources. A summary of crashes and crash severity was generated for and attached to each roundabout location.

The next step was to validate each roundabout location. A location-by-location evaluation was made to determine if the facility adhered to what is typically considered a network level roundabout. For example, some facilities were found to be neighborhood turning circles or other decorative features in which a rotation around an inscribed circle in order to make a left turn was not necessarily strictly characteristic of the location. As such these locations were excluded from the dataset.

As part of the validation process it was apparent that some facilities were constructed more recently than others. In order to optimize accuracy, it was decided to restrict the collection period for crash data to 2015 through 2019, to ensure that the roundabout was in existence throughout the study period and that crashes were indeed roundabout related.

The most challenging part of the dataset preparation was the collection of AADT for each roundabout leg. Because entering and circulating volume are important characteristics when developing roundabout SPF models, it was important to ensure this information was captured as comprehensively as possible. Because a large proportion of AADT data was absent, an on the ground field collection of such data would have proved both time consuming and costly. In order to efficiently and effectively obtain the necessary AADT information, in concert with CDOT DiExSys employed the use of the StreetLight software to query 2021 traffic count data for statewide roundabouts. This involved over 500 queries in StreetLight, along with associated data extraction. The resulting tabular data was then joined with the spatial dataset for all roundabout legs.

Figure 2-1 below shows a sample from the web map, depicting the Carefree/New Center roundabout in Colorado Springs. The pink line defines the spatial boundary of a roundabout location to which crashes (seen as green dots in this case, all representing the PDO level), based on a coordinate system were coded. In this case the darker green diamonds to the east and west of the roundabout show where traffic counts were available locally. The bright red lines show the AADT counts obtained from the StreetLight queries, which were used to both validate/correct existing CDOT/regional/city/county counts, and to complete population of AADT data for all legs at each location. At most locations, such as at Carefree/New Center, both entering and exiting traffic counts were available from StreetLight queries on all legs. **Figure 2-2** and **Figure 2-3** provide just a sample of each one to avoid image overcrowding, although counts are accessible for all legs. However, at some locations only a combined count was available, in these circumstances the count was split 50% for entering and 50% for exiting flows. As has been described previously, the pink geo-fenced boundary typically includes crashes recorded within approximately 200 feet of the roundabout: a combination of crash history with crashes coded as "ROUNDABOUT," "AT-INTERSECTION" or "INTERSECTION-RELATED" was utilized to obtain the most accurate numbers.

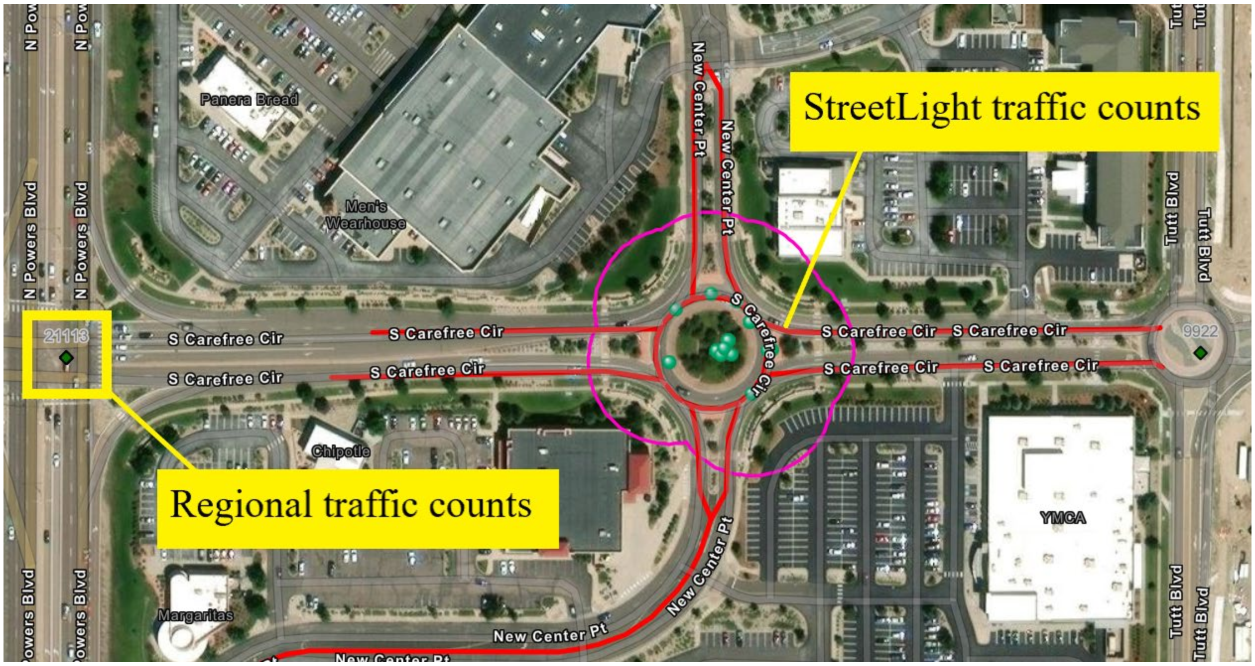

Figure 2-1: Web Map Example: Carefree & New Center Roundabout, Colorado Springs

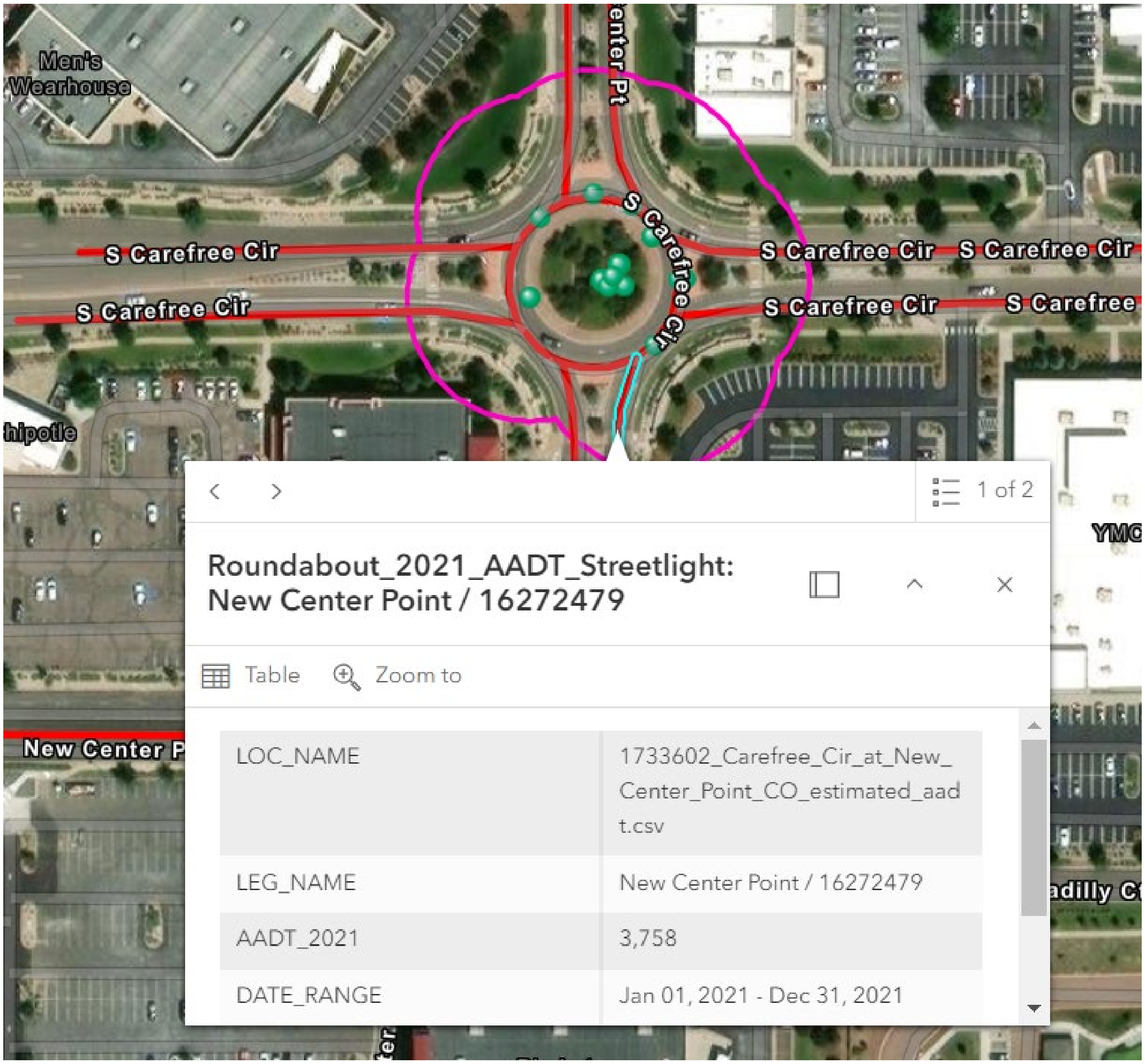

Figure 2-2: Web Map with Street Light AADT on Entering Leg, Carefree/New Center

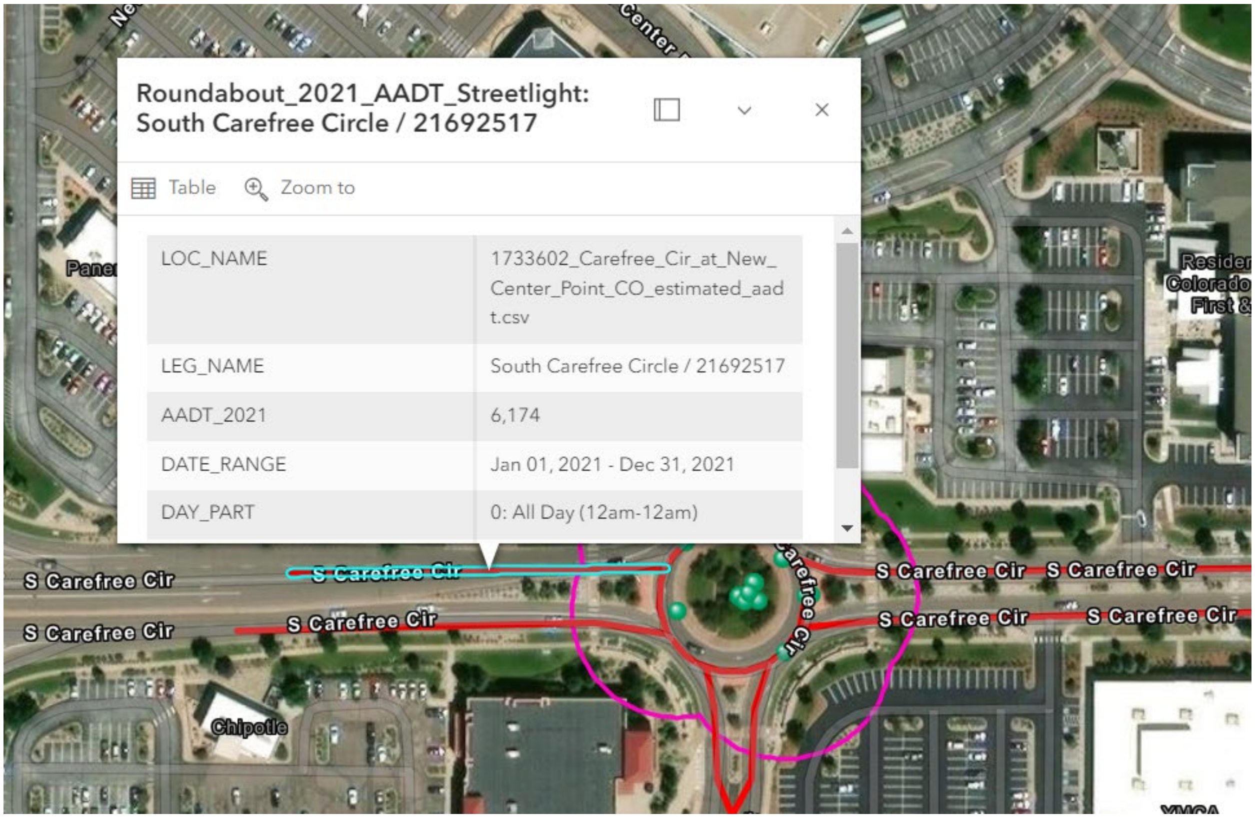

Figure 2-3: Web Map with Street Light AADT on Exiting Leg, Carefree/New Center

As part of the DiExSys quality assurance process it was determined that within the study period often crashes which occurred at a roundabout had been coded as "INTERSECTION" or "INTERSECTION-RELATED." Therefore, all crash counts were cross-referenced between the ROUNDABOUT and INTERSECTION/INTERSECTION-RELATED datasets on a location-by-location basis to obtain the most accurate crash record yield for each location.

In developing a robust SPF model, it is important that sufficient sample size be utilized. For this reason, at this stage of the dataset evaluation it was decided that there were three roundabout facility types which offered a sufficient number of locations with which to develop models. These facility types were:

- Urban 3-leg 1-lane,
- Urban 4-leg 1-lane, and
- Urban 4-leg 2-lane.

"Lane" refers to the number of circulating lanes. **Table 2-1** shows limited available inventory of other facility types when the number of available locations is considered.

Table 2-1: Roundabout Geometric Facility Type and Available Locations

Geometric Facility Type	No. of Locations
3-Leg 1-Lane	80
3-Leg 2-Lane	15
4-Leg 1-Lane	166
4-Leg 2-Lane	67
5-Leg 2-Lane	6
6-Leg 2-Lane	8

3. Chapter 3 – Development Of Colorado Roundabout Safety Performance Functions

This chapter discusses in further detail the approach involved in the development of the Colorado-specific SPFs as well as diagnostic norms.

Model Development

This project developed Safety Performance Functions (SPFs) for three types of Roundabout facilities in Colorado. Roundabout SPFs in essence are crash prediction models, which generally relate AADT to safety measured in the number of crashes over a unit of time. In statistical modeling of traffic crashes, we are interested in discovering what we can learn about underlying relationships from empirical data containing a random component. We suppose that some complex phenomenon manifested by crash occurrence (data generating mechanism) has produced the observations and we wish to describe it by some simpler, but still realistic, model that reveals the nature of the underlying relationship. Lindsey[1] observed that in a model we distinguish between systematic and random variability, where the former describes the patterns of the phenomenon in which we are particularly interested. A great deal of substantive and comprehensive work in the area of crash modeling was done by, Hauer[2], Hauer and Persaud[3], Miau and Lum[4], as well as others. The following is a brief description of modeling methodology used in this project using Generalized Linear Models (GLM). Two kinds of Safety Performance Functions were developed. The first one addresses the total number of crashes, and the second one looks only at crashes involving an injury or fatality. It allows us to assess the magnitude of the safety problem from the frequency and severity standpoints.

Selecting the Model Form and Evaluating Goodness of Fit

Creating a model out of data is a process that involves probing, computation, and the exercise of judgment[2]. The functional forms for the roundabout SPFs, were selected by conducting exploratory data analysis and evaluating goodness of fit for each of the trial models. The models with best goodness of fit characteristics and a reasonable representation of the physical phenomenon, as judged by the modeler were chosen for final use.

Based on substantial empirical evidence derived from observing safety performance of various transportation facilities as well as work of other researchers (Hauer[2]), Sigmoidal and Hoerl

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[1] Lindsey, J.K. *Applying Generalized Linear Models*. Springer-Verlag, New York, 1997.

[2] Hauer, E. *The Art of Regression Modeling in Road Safety*. Springer-International Publishing, Cham, Switzerland 2015.

[3] Hauer, E.& Persaud, B. *Safety Analysis of Roadway Geometric and Ancillary Features*. Transportation Association of Canada 1997.

[4] Miau S. & Lum H. (1993). Modeling Vehicle Accidents and Highway Geometric Design Relationships. Accident Analysis & Prevention 25(6):689-709.

functions were used to represent the underlying relationships between safety and exposure at roundabouts. These functions are very flexible nonlinear models capable of reflecting changes in crash rate across the range of exposure and capturing the overall shape of observed data.

The general model forms of these functions that were used in the exploratory analysis to develop Colorado roundabout SPFs are provided below:

$E(x) = \left((\beta_{Min}) + \frac{(\beta_{max})(X^{\beta_0})}{(X^{\beta_0})+(\beta_1^{\beta_0})} \right)$, Sigmoidal Function for 1 independent variable (AADT in the circulating roadway of a roundabout)

$E(x) = (\beta_0)(X^{\beta_1})(e^{\beta_1 X})$, Hoerl Function for 1 independent variable (AADT in the circulating roadway of a roundabout)

Where:

$E(x)$ - Number of crashes expected to occur annually at a roundabout

x – AADT in the circulating roadway of a roundabout

β - Model Parameters

$E(x_1, x_2) = (\beta_0 + \frac{\beta_1}{(1+\beta_2 x_1{}^{-\beta_3})(1+\beta_4 x_2{}^{-\beta_5})})$, Sigmoidal Function for 2 independent variables (AADTs on major and minor roads)

$E(x_1, x_2) = (e^{\beta_0})(x_1{}^{\beta_1})(x_2{}^{\beta_2})(e^{\beta_3 x_1})$, Hoerl Function for 2 independent variables (AADTs on major and minor roads)

Where:

$E(x_1, x_2)$ = Number of crashes expected to occur at a roundabout given the values of x_1 and x_2

x_1 =AADT Major Road

x_2 = AADT Minor Road

β = Model Parameters

The quality of fit was examined with the Cumulative Residuals (CURE) method described in Hauer and Bamfo[5]. This method consists of plotting the cumulative residuals for each independent variable. The goal is to graphically observe how well the function fits the dataset. To generate a CURE plot, sites are sorted by their average AADT. Then, for each site, the residual (= predicted crashes-observed crashes) is computed, and the cumulative residuals are determined and plotted for each value of the independent variables. Because of the random nature of crash counts, the cumulative residual line represents a so called 'random walk.' For a model that fits well in all ranges of AADT, the cumulative residual plot should oscillate around zero. If the cumulative residual value steadily increases within a range of values of the independent variable, this means that within that range the model predicts fewer crashes than have been observed. Conversely, a decreasing cumulative residual line indicates that in that range fewer crashes have been observed than are predicted by the model. A frequent departure of the cumulative residual line beyond two standard deviations of a random walk indicates a presence of outliers or signifies an ill-fitting model.

For instance, **Figure 3-1** and **Figure 3-2** show CURE plots reflecting a model fit relating total and injury crashes with main line AADT and side road AADT, respectively, for the Colorado 3-leg 1-lane Roundabout. Because the CURE residual line lies well within the two standard deviation and generally oscillates around zero, it can be concluded that the functional form and the model parameters fit the data well.

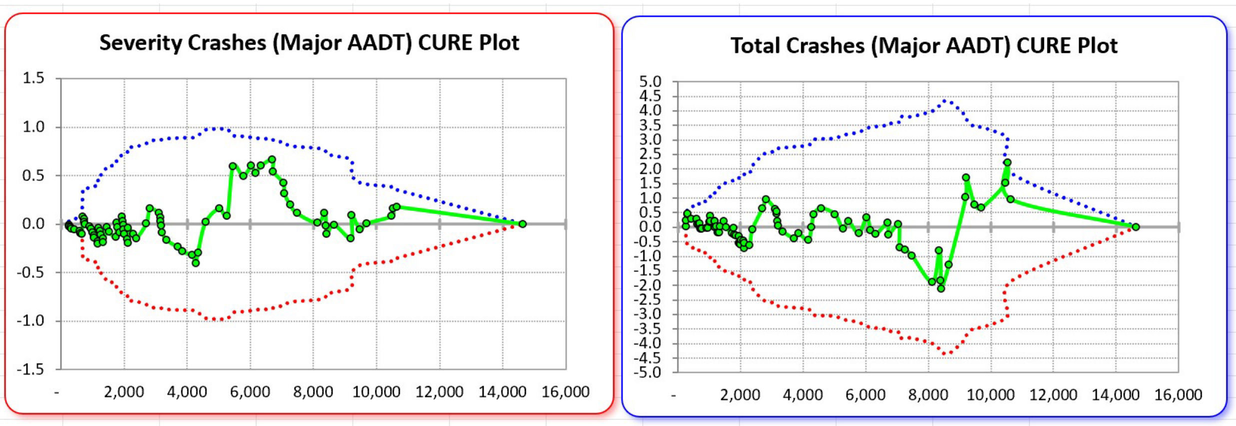

Figure 3-1: CURE Plot for Injury and Fatal Crashes and Total Crashes SPF 3-Leg 1-Lane Roundabouts Major (Mainline)

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[5] Hauer and Bamfo, Two Tools for Finding What Function Links the Dependent Variable to the Explanatory Variables. *ICTCT Conference Proceedings*. Lund, Sweden 1997.

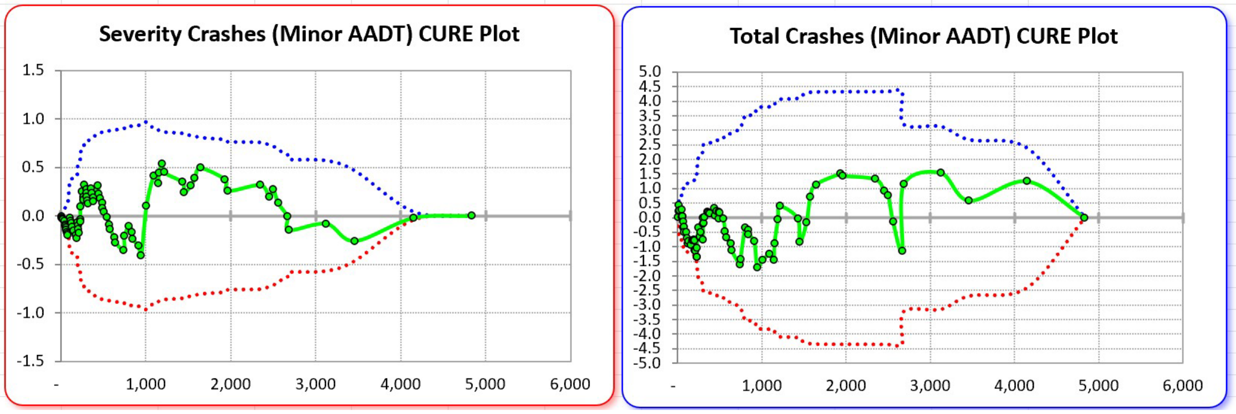

Figure 3-2: CURE Plot for Injury and Fatal Crashes and Total Crashes SPF 3-Leg 1-Lane Roundabouts Minor (Side Road)

Model parameters, graphs and CURE plots for the new Colorado SPFs are presented in the individual sections which follow later in this report for each model (SPF Models and Diagnostic Norms). The SPFs developed under this project show a very acceptable fit with over-dispersion parameters (α), well below 1, reflecting tight distribution around the mean. The final functional form chosen for all three of these models was Sigmoidal.

$$APY_{Sigmoid} = (\beta_0 + \frac{\beta_1}{(1+\beta_2 {x_1}^{-\beta_3})(1+\beta_4 {x_2}^{-\beta_5})})$$

The following example outlines the exploratory analysis and final model selection for a Urban 3-leg, 1-lane roundabout. Initially two models were estimated using AADT in the circulatory roadway of the roundabout as an independent variable for the Sigmoidal and Hoerl functions.

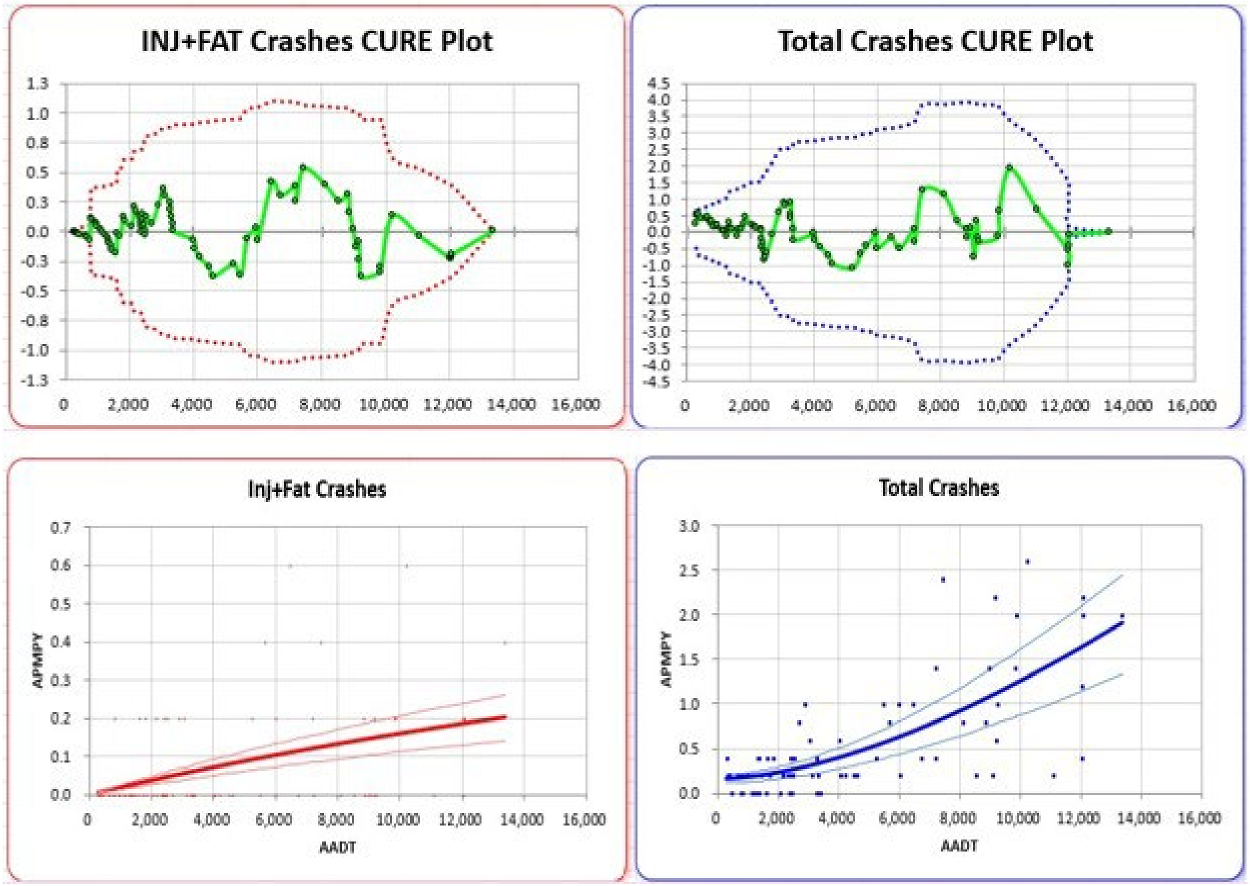

Figure 3-3: Sigmoidal Function 1-lane, 3-leg roundabout, ADT in Circulating Roadway

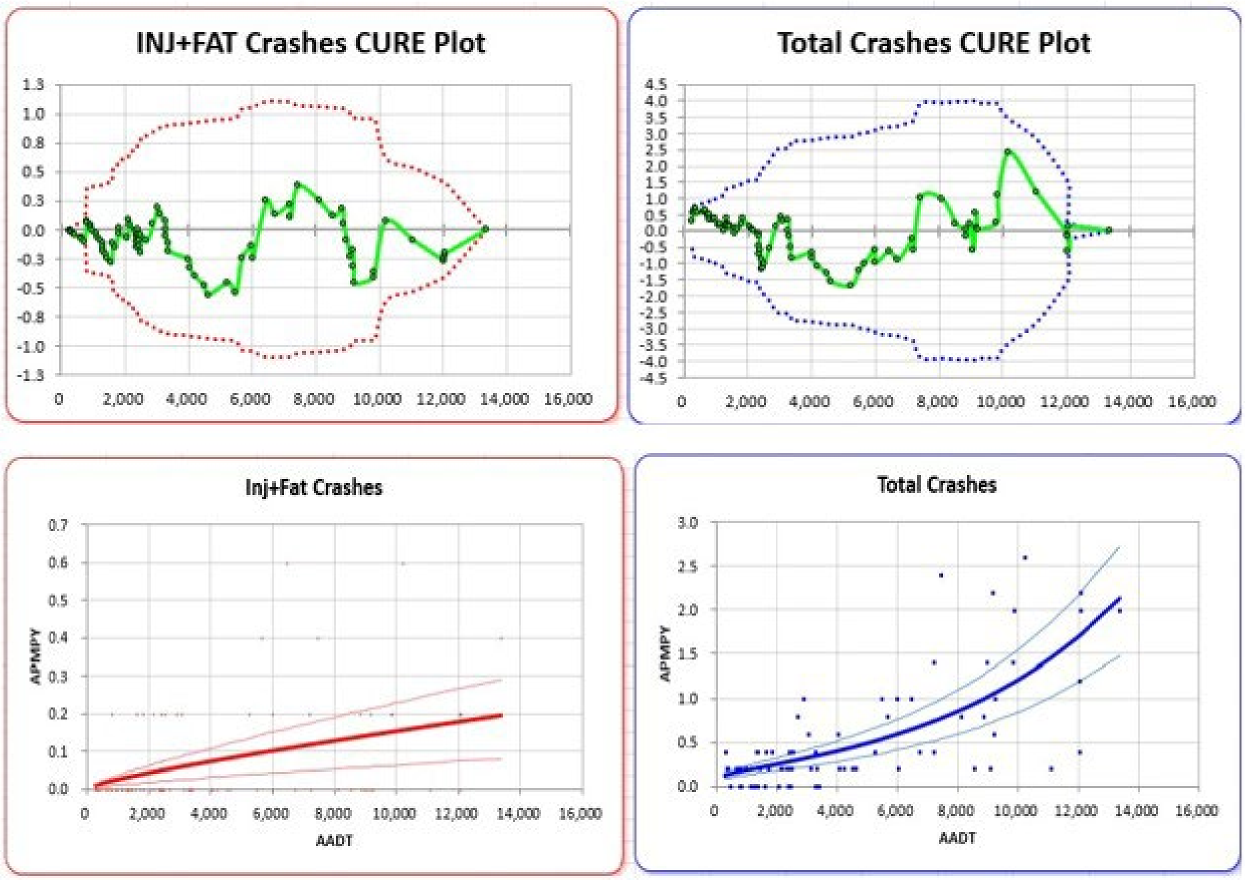

Figure 3-4: Hoerl Function 1-lane, 3-leg roundabout, ADT in Circulating Roadway

As can be seen in **Figure 3-3** and **Figure 3-4** the CURE plots for both models are quite acceptable, indicating well-fitting models. It is preferable, however, to develop a model capable of predicting frequency and severity of crashes at a roundabout reflecting a wide range of the demand on the main line and side road. This can only be achieved by using a model with two independent variables. Initially a model was developed where the mainline AADT was assigned to the pairing of the most oppositely positioned legs, with the sideroad ADT assigned to the remaining leg. The resulting model using sigmoidal function is provided in **Figure 3-5**. The Hoerl model, however, did not converge on a solution.

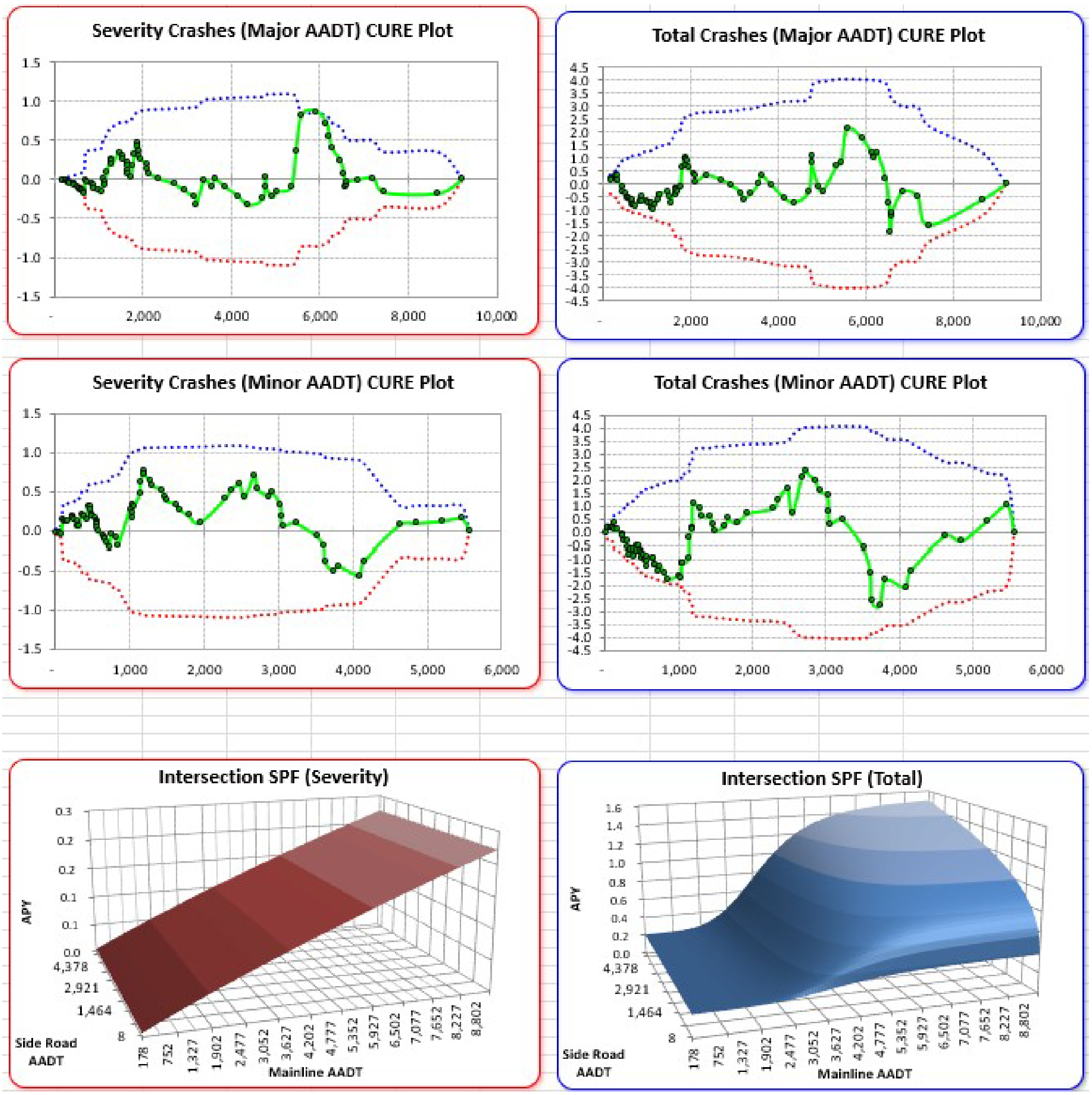

Figure 3-5: Sigmoidal Function 1-lane, 3-leg roundabout, Main Line and Sideroad ADT

As shown in **Figure 3-5**, the 3-dimensional response surface of severity model indicates that the number of injury crashes at a roundabout is independent of the side-road volume. Although the CURE plots of the severity model exhibit desirable characteristics, in our opinion the model does not effectively represent the physical phenomenon of crash occurrence. We have re-estimated model parameters with the assumption that the average of the two highest AADTs represent the mainline, while the AADT on the remaining leg represents the side-road. The resulting models are shown in **Figure 3-6**.

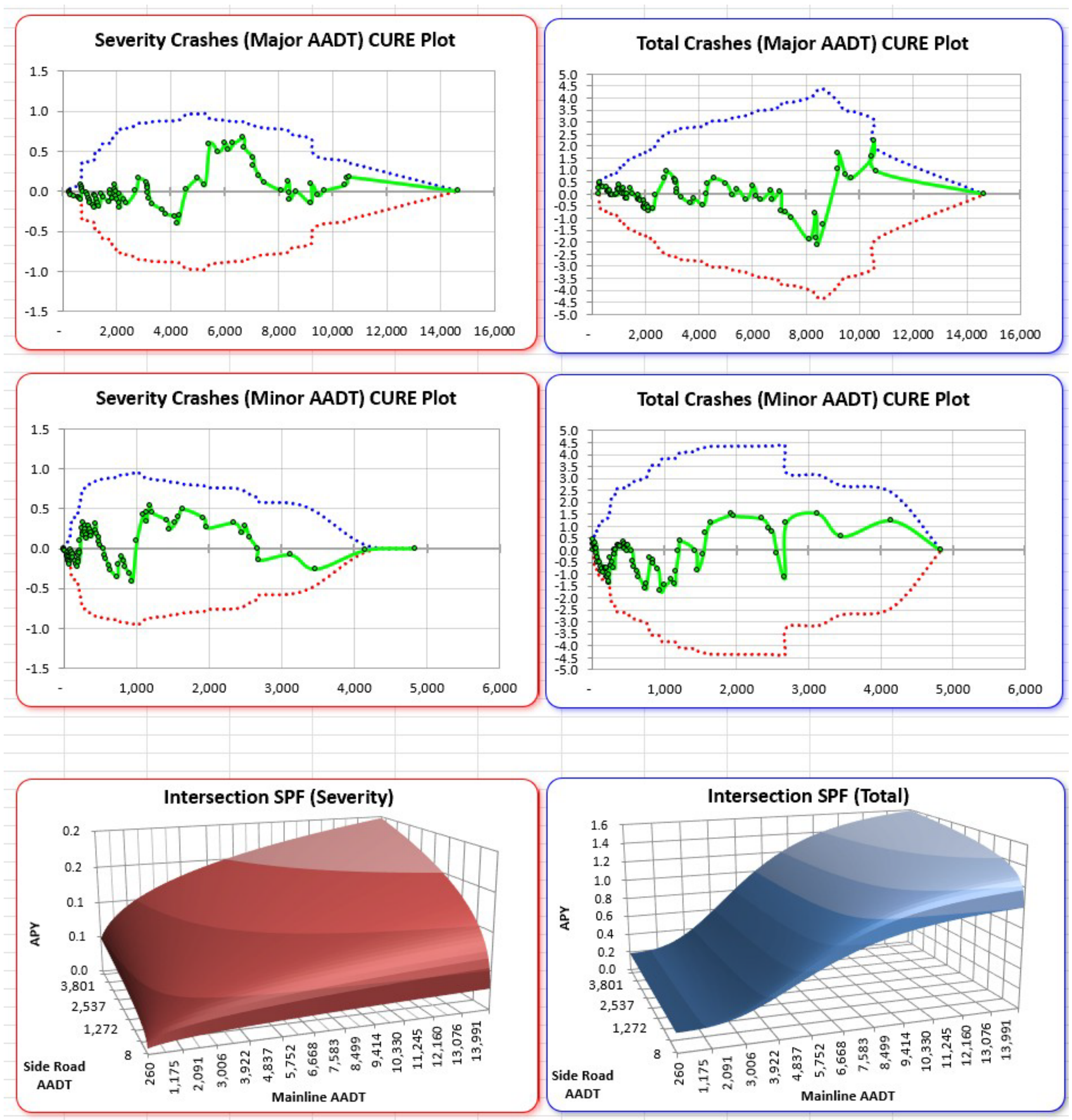

Figure 3-6: Sigmoidal Function 1-lane, 3-leg roundabout, Main Line and Sideroad ADT

The resulting CURE plots are quite acceptable, and the 3-dimenesional response surfaces of the model better align with our understanding of the physical phenomenon of crash occurrence, where the side-road volume has significant influence on the resulting severity of crashes.

Choice of the Underlying Distributional Assumptions

In statistical modeling of traffic crashes, it is assumed that the random variation follows certain probability laws and can be characterized by a probability function. Miau and Lum[4] observed that "the use of a continuous distribution, such as the normal distribution, is at best an approximation to a truly discrete process. The Poisson distribution, on the other hand, is a natural initial candidate distribution for such random discrete and, typically, sporadic events." At the same time, if a Poisson assumption is made about the underlying random variability, it will have a restricting effect of always equating the variance to the mean. In our experience with crash data this assumption is not always true. Similar findings are reported by Dean and Lawles[6]. In many cases crash data exhibit extra variation or over-dispersion relative to the Poisson model. In other words, the variance of the data is often greater than the mean. In this study, the datasets exhibited over-dispersion characteristics relative to the Poisson model.

Estimating Model Parameters

The model parameters were estimated by the maximum-likelihood method using Generalized Linear Modeling (GLM) methodology by maximizing log-likelihood function. Maximizing log-likelihood function has computational advantages over maximizing ordinary likelihood function L, which represents the product of the individual probability density functions of Poisson or Negative Binomial distributions. The datasets exhibited over-dispersion, and as a result, final regression parameters for Colorado Roundabout SPFs were estimated by maximizing log-likelihood function of the Negative Binomial distribution, details are shown below.

$$E(y) = \mu$$

$Var(y) = \mu(1 + \alpha\mu) = \mu + \alpha\mu^2 > \mu$, thus, the standard deviation of y is $\sqrt{\mu + \alpha\mu^2}$

$$L(\mu, \alpha) = \prod_{i=1}^{n} \frac{\Gamma(\alpha^{-1}+y_i)}{\Gamma(\alpha^{-1})y_i!} \left(\frac{\alpha\mu_i}{1+\alpha\mu_i}\right)^{y_i} \left(\frac{1}{1+\alpha\mu_i}\right)^{\alpha^{-1}}$$

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[6] Dean, C. & Lawless, J.F. Tests for Detecting Overdispersion in Poisson Regression Models. *Journal of the American Statistical Association 84*(406): 467-472; June 1989.

$$\ln\big(L(\mu,\alpha)\big) = \sum_{i=1}^{n} \ln\left(\frac{\Gamma(\alpha^{-1}+y_i)}{\Gamma(\alpha^{-1})y_i!}\right) + y_i \ln\left(\frac{\alpha\mu_i}{1+\alpha\mu_i}\right) + \alpha^{-1}\ln\left(\frac{1}{1+\alpha\mu_i}\right)$$

Where:

y – vector of random variables modeling annual crash counts at intersections

μ – expected values of y, estimated by the SPF

y_i – observed number of crashes at an intersection over one year, a sample from the i^{th} component of y.

α – scalar over-dispersion parameter

$L(\mu,\alpha)$ – Negative Binomial likelihood function

Γ – Gamma Function

Correcting for the Regression to the Mean (RTM) Bias

The best guess about the future is usually obtained by computing the average of past events. In road safety the average of several years of crash history of a highway segment or of an intersection, or in this case a roundabout, provides us with an estimate of what is likely to be observed in the future. The precision of this estimate, however, can be improved upon by correcting it for the Regression to the Mean (RTM) bias. RTM phenomenon reflects the tendency for random events, such as vehicle crashes to move toward the average during the course of an experiment or over time. For instance, if a segment, intersection, or roundabout exhibits unusually high or unusually low crash frequency in a particular year, because of RTM we need to be aware that over the long run its true average is closer to the mean representing safety performance of similar facilities. The existence of the RTM bias has been long recognized and is now effectively addressed by using the Empirical Bayes (EB) method[7]. The use of EB method is particularly effective when it takes a long time for a few crashes to occur, as is often the case at lower-volume intersections.

The empirical Bayes (EB) method for the estimation of safety increases the precision of estimation and corrects for the regression to the mean bias. It is based on combining the information contained in crash counts (known crash history) with the information contained in knowing the safety of similar entities. The information about safety of similar entities is brought into the EB procedure by the Safety Performance Function (SPF).

[7] Hauer et al. Estimating Safety by the Empirical Bayes Method. In *Transportation Research Record 1174,* TRB, National Research Council, Washington, D.C., 2002, pp 126-131.

Level Of Service Of Safety (LOSS)

Concept Description

Development of the SPF lends itself well to the conceptual formulation of the Level of Service of Safety (LOSS). The concept of LOSS uses quantitative assessment and qualitative description that characterize safety of a roadway segment in reference to its expected performance and severity. The level of safety predicted by the SPF represents a normal or expected number of accidents at a specific level of AADT, then the degree of deviation from the norm is stratified to represent specific levels of safety.

LOSS I - Indicates low potential for crash reduction.

LOSS II - Indicates low to moderate potential for crash reduction.

LOSS III - Indicates moderate to high potential for crash reduction.

LOSS IV - Indicates high potential for crash reduction.

Gradual increase in the degree of deviation of the LOSS boundary line from the fitted model mean reflects the observed increase of variability in Crashes Per Year (APY) as AADT increases. The delineated boundary lines represent 20^{th} and 80^{th} percentiles of the SPF population. Selection of the 20^{th} and 80^{th} percentiles is made to identify facilities with some potential for crash reduction or to recognize a particularly good performance.

Introduction of the LOSS concept enables transportation engineers to do the following:

- Qualitatively and quantitatively describe the degree of safety or un-safety of a roadway segment/intersection, or in this case roundabout.
- Effectively communicate the magnitude of the safety problem to other professionals and elected officials.
- Bring the perception of roadway safety in line with the reality of safety performance for a specific facility.
- Provide a frame of reference for decision making on non-safety motivated projects (resurfacing or reconstruction, for instance).
- Provide a frame of reference from a safety perspective for planning major corridor improvements.

LOSS reflects how the roundabout is performing in regard to its expected crash frequency and severity at a specific level of AADT on legs. It only provides an crash frequency and severity comparison with the expected norm. It does not, however, provide any information related to the nature of the safety problem itself. If a safety problem is present, LOSS will only describe its magnitude from a frequency and severity standpoint. The nature of the problem is determined through diagnostic analysis using Direct Diagnostics and Pattern Recognition techniques[8].

Calibration of the Level of Service of Safety (LOSS) Boundaries

Safety Performance Function (SPF) is initially calibrated using original data, which is over-dispersed and is well described by the Negative Binomial distribution. In the process of calibration, the over-dispersion parameter is estimated from the data and serves to establish a "link" function between the population's mean and its standard deviation. The relationship between standard deviation and the mean is described as follows:

$$\sigma = \sqrt{\mu + \alpha\mu^2}$$

where:

- μ - Expected frequency predicted by the SPF
- α - Over-dispersion parameter estimated from the SPF

Over-dispersion is typical in the crash data, however when the magnitude of the problem is assessed, it is important to correct observed crash frequency for the regression to the mean bias using the Empirical Bayes (EB) procedure. The Empirical Bayes (EB) method for the estimation of safety increases the precision of estimation, it is based on combining the information contained in crash counts (known crash history) with the information contained in knowing the safety of similar entities. The information about safety of similar entities is brought into the EB procedure by the mean (μ) of the Safety Performance Function (SPF). When an individual site is examined in the LOSS framework it is corrected for the RTM bias, therefore it is appropriate to compare its degree of deviation from the mean using the distribution reflecting the EB corrected population. When safety performance of all segments in the dataset is corrected for the RTM bias using the EB procedure the resulting population will naturally have a smaller variance than before correction. EB corrected population is well described by the Gamma distribution where the relationship between the mean and standard deviation is as follows:

$$\sigma = \sqrt{\alpha\mu^2}$$

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[8] Kononov, J., (2003) Identifying Locations with Potential for Accident Reduction: Use of Direct Diagnostics and Pattern Recognition Methodologies. In Transportation Research Record No. 1840, TRB, National Research Council, Washington, D.C. 2002, pp 57-66

LOSS boundaries were then calibrated by computing the 20th and the 80th percentiles using the Gamma Distribution Probability Density Function below[9]:

$$f(\mu) = \frac{a^b \mu^{b-1} e^{-a\mu}}{\Gamma(b)}$$

where:

μ - the mean

b - dispersion parameter estimated from the regression

a – b/μ

Γ – Gamma Function

Direct Diagnostics Methodology

General Concept

While LOSS provides a means of assessment of the magnitude of the safety problem, it is important to understand that crash patterns susceptible to correction may exist with or without over-representation in total frequency or severity, as detected by SPF. These patterns should be identified through Direct Diagnostics analysis. In the course of in-depth safety studies of intersections, a comprehensive methodology was developed to conduct diagnostic analysis of safety problems for different classes of intersections in various environments, and this methodology has been applied here in the context of roundabouts. Direct diagnostics methods and a pattern recognition algorithm are described by Kononov[9].

Because traffic crashes can be viewed as random Bernoulli trials, it is possible to detect deviations from the random statistical process by computing the observed cumulative probability of binomial distribution for each of the normative parameters. The cumulative probability can be computed as follows:

$$P(X \leq x) = B(x, n, p) = \sum_{i=0}^{x} \frac{n!}{(n-i)!\,i!} p^i (1-p)^{n-i}$$

where:

n – Total number of crashes

[9] Kononov, Durso, Lyon and Allery (2015), *Level of Service of Safety Revisited.* Transportation Research Record No. 2514 Transportation Research Board, National Research Council, Washington DC 2015

x – Number of observed crashes containing a specific attribute (crash type for example)

p – Expected % of this attribute based on statewide statistics

P – Cumulative probability of observing x crashes containing a specific attribute

If cumulative probability (P) exceeds a predetermined threshold, in most cases 95%, the observed crash profile would be considered a pattern which would require further examination.

A framework of normative parameters was developed specifically for Colorado roundabouts to provide a knowledge base for the direct diagnostics analysis. Colorado-specific diagnostic norms have been developed for the following facilities:

- Urban 3-Leg 1-Lane Roundabouts
- Urban 4-Leg 1-Lane Roundabouts
- Urban 4-Leg 2-Lane Roundabouts

Stratification of Diagnostic Norms

It is important to note that some, but not all, normative parameters within the same SPF change with AADT. For instance, in most cases, the severity of crashes gradually decreases and the distribution of crashes by crash type changes with AADT. When sample size for the development of diagnostic norms was sufficiently large the normative parameters were stratified for three ranges of AADT: low, medium, and high. In the process of assessing the nature and magnitude of safety problems at specific intersections, SPF analysis should be used in concert with an appropriate diagnostic investigation by using the direct diagnostics algorithm. The stratification of the diagnostic parameters by AADT improves the ability to identify crash patterns more accurately.

SPF Models And Diagnostic Norms

3-Leg 1-Lane Roundabouts

The SPF graphs of the frequency and severity models for the Colorado 3-Leg 1-Lane Roundabouts and CURE plots for each are presented in **Figure 3-7**, and model parameters are shown in **Table 3-1**. The SPFs developed under this project show a very acceptable fit with small over-dispersion parameters α reflecting tight distribution around the mean. Diagnostics for this facility type are shown in **Table 3-2**.

Table 3-1: Frequency and Severity SPF Model Parameters for 3-Leg 1-Lane Roundabouts

Severity	
Variable	**Value**
β_0	1.00E-04
β_1	2.50E+02
β_2	8.11E+00
β_3	3.75E-01
β_4	1.25E+02
β_5	3.05E-01
α	0.125

Frequency	
Variable	**Value**
β_0	1.86E-01
β_1	2.45E+02
β_2	2.38E-01
β_3	2.90E+00
β_4	1.51E+02
β_5	8.43E-02
α	0.125

Roadway	$AADT_{Min}$	$AADT_{Max}$
Major	5,000	22,500
Minor	1,000	12,000

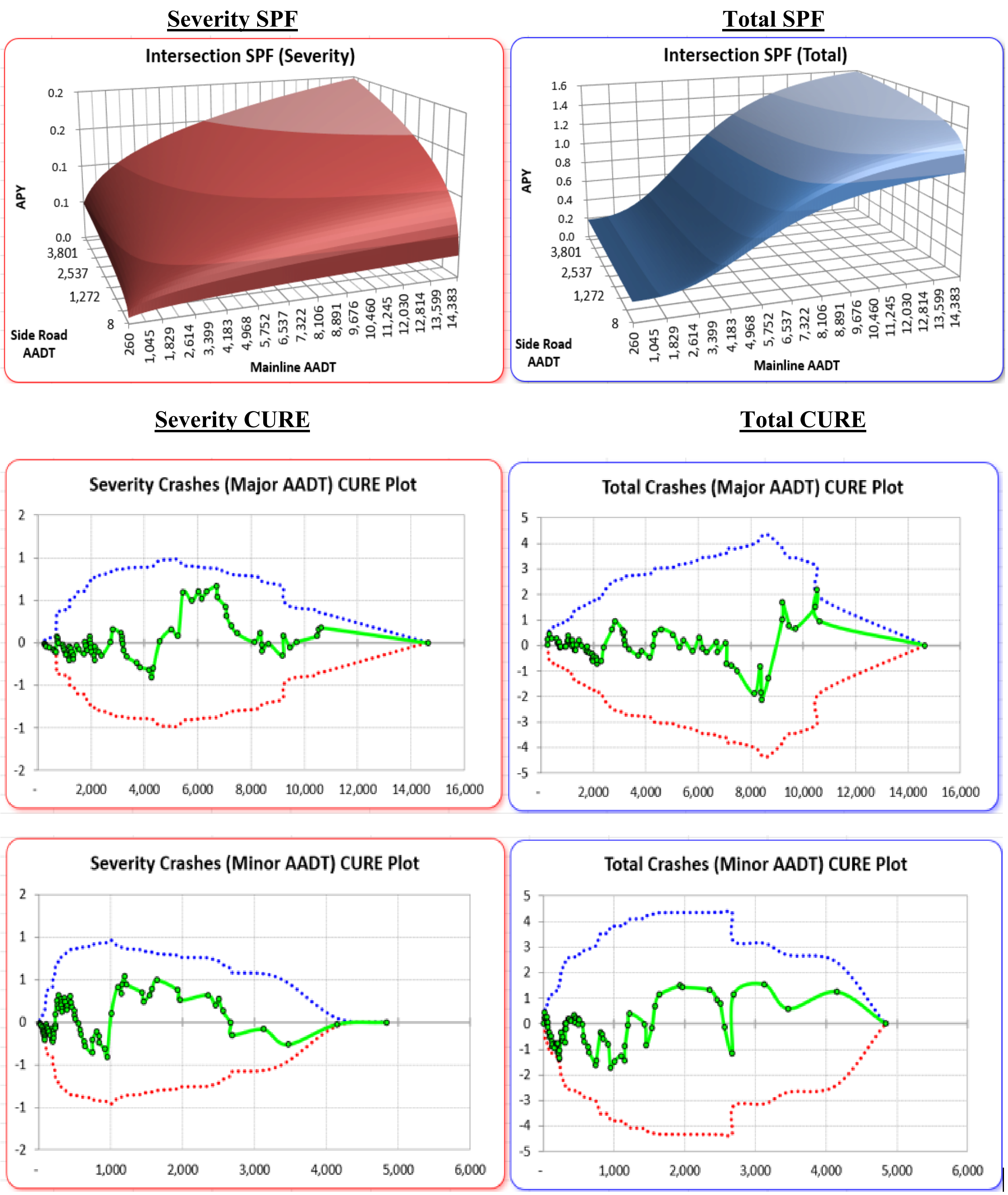


Figure 3-7: Frequency and Severity SPF Graphs and CURE Plots for 3-Leg 1-Lane Roundabouts

Table 3-2: Diagnostic Norms for Urban 3-Leg 1-Lane Roundabouts

Urban 1-Lane 3-Leg Roundabouts								
	0-10000 ADT		10000-20000 ADT		>20000 ADT		All Totals	
Description	Accidents	Percent	Accidents	Percent	Accidents	Percent	Accidents	Percent
Severity								
PDO	239	85.36%	101	84.87%	0		340	85.21%
INJ	41	14.64%	18	15.13%	0		59	14.79%
FAT	0	0.00%	0	0.00%	0		0	0.00%
Persons Injured	52	N/A	25	N/A	0	N/A	77	N/A
Persons Killed	0	N/A	0	N/A	0	N/A	0	N/A
Number of Vehicles								
Single Vehicle Accidents	179	63.93%	61	51.26%	0		240	60.15%
Two Vehicle Accidents	94	33.57%	56	47.06%	0		150	37.59%
Three or more Vehicle Accident	7	2.50%	2	1.68%	0		9	2.26%
Unknown Number of Vehicles	0	0.00%	0	0.00%	0		0	0.00%
Location								
On Road	115	41.07%	64	53.78%	0		179	44.86%
Off Road	163	58.21%	55	46.22%	0		218	54.64%
Off Road Left	58	20.71%	21	17.65%	0		79	19.80%
Off Road Right	90	32.14%	23	19.33%	0		113	28.32%
Off Road at Tee	7	2.50%	1	0.84%	0		8	2.01%
Off Road in Median	8	2.86%	10	8.40%	0		18	4.51%
Unknown Road Location	2	0.71%	0	0.00%	0		2	0.50%
Accident Type								
Overturning	5	1.79%	0	0.00%	0		5	1.25%
Other Non Collision	3	1.07%	1	0.84%	0		4	1.00%
Vehicle Cargo/Debris	0	0.00%	0	0.00%	0		0	0.00%
Pedestrian	3	1.07%	0	0.00%	0		3	0.75%
Broadside	22	7.86%	14	11.76%	0		36	9.02%
Head On	2	0.71%	2	1.68%	0		4	1.00%
Rear End	38	13.57%	31	26.05%	0		69	17.29%
Sideswipe (Same Direction)	15	5.36%	7	5.88%	0		22	5.51%
Sideswipe (Opposite Direction)	3	1.07%	3	2.52%	0		6	1.50%
Approach Turn	0	0.00%	0	0.00%	0		0	0.00%
Overtaking Turn	0	0.00%	0	0.00%	0		0	0.00%
Parked Motor Vehicle	17	6.07%	0	0.00%	0		17	4.26%
Railway Vehicle	0	0.00%	0	0.00%	0		0	0.00%
Bicycle/Pedal Cycle	1	0.36%	1	0.84%	0		2	0.50%
Motorized Bicycle	0	0.00%	0	0.00%	0		0	0.00%
Domestic Animal	0	0.00%	0	0.00%	0		0	0.00%
Wild Animal	3	1.07%	4	3.36%	0		7	1.75%
Light/Utility Pole	18	6.43%	5	4.20%	0		23	5.76%
Traffic Signal Pole/Equipment	4	1.43%	0	0.00%	0		4	1.00%
Traffic Sign/Post/Overhead Sign Structure	40	14.29%	20	16.81%	0		60	15.04%
Bridge Rail	0	0.00%	0	0.00%	0		0	0.00%
Guard Rail	2	0.71%	1	0.84%	0		3	0.75%
Cable Rail	0	0.00%	0	0.00%	0		0	0.00%
Concrete Barrier	2	0.71%	0	0.00%	0		2	0.50%
Bridge Abutment	0	0.00%	0	0.00%	0		0	0.00%
Column/Pier/Bridge Structure	0	0.00%	0	0.00%	0		0	0.00%
Culvert/Headwall	1	0.36%	0	0.00%	0		1	0.25%
Embankment/Ditch	1	0.36%	1	0.84%	0		2	0.50%
Curb/Island	42	15.00%	17	14.29%	0		59	14.79%
Delineator Post	0	0.00%	0	0.00%	0		0	0.00%
Fence/Fence Part	11	3.93%	1	0.84%	0		12	3.01%
Tree/Shrubs	11	3.93%	1	0.84%	0		12	3.01%
Large Boulder	12	4.29%	1	0.84%	0		13	3.26%
Rocks in Roadway	0	0.00%	0	0.00%	0		0	0.00%
Barricade	2	0.71%	0	0.00%	0		2	0.50%
Wall/Building	5	1.79%	4	3.36%	0		9	2.26%
Crash Cushion/Sand Barrels/Impact Attenuator	0	0.00%	0	0.00%	0		0	0.00%
Mailbox	1	0.36%	0	0.00%	0		1	0.25%
Other Fixed Object	12	4.29%	4	3.36%	0		16	4.01%
Other Object	4	1.43%	1	0.84%	0		5	1.25%
Road Maintenance Equipment	0	0.00%	0	0.00%	0		0	0.00%
Unknown Accident Type	0	0.00%	0	0.00%	0		0	0.00%
Total Fixed Objects	164	58.57%	55	46.22%	0		219	54.89%
Total Other Objects	4	1.43%	1	0.84%	0		5	1.25%

Table 3-2 (Cont.): Diagnostic Norms for Urban 3-Leg 1-Lane Roundabouts

Urban 1-Lane 3-Leg Roundabouts								
	0-10000 ADT		10000-20000 ADT		>20000 ADT		All Totals	
Description	Accidents	Percent	Accidents	Percent	Accidents	Percent	Accidents	Percent
Lighting								
Daylight	160	57.14%	60	50.42%	0		220	55.14%
Dawn or Dusk	8	2.86%	4	3.36%	0		12	3.01%
Dark - Lighted	76	27.14%	40	33.61%	0		116	29.07%
Dark - Unlighted	31	11.07%	14	11.76%	0		45	11.28%
Unknown Lighting	5	1.79%	1	0.84%	0		6	1.50%
Weather								
No Adverse Weather	218	77.86%	84	70.59%	0		302	75.69%
Rain	8	2.86%	4	3.36%	0		12	3.01%
Snow/Sleet/Hail	38	13.57%	25	21.01%	0		63	15.79%
Fog	1	0.36%	0	0.00%	0		1	0.25%
Dust	0	0.00%	0	0.00%	0		0	0.00%
Wind	3	1.07%	1	0.84%	0		4	1.00%
Unknown Weather	12	4.29%	5	4.20%	0		17	4.26%
Road Condition								
Dry Road	196	70.00%	81	68.07%	0		277	69.42%
Wet Road	20	7.14%	6	5.04%	0		26	6.52%
Muddy Road	0	0.00%	0	0.00%	0		0	0.00%
Snowy Road	22	7.86%	19	15.97%	0		41	10.28%
Icy Road	28	10.00%	8	6.72%	0		36	9.02%
Slushy Road	3	1.07%	3	2.52%	0		6	1.50%
Foreign Material Road	0	0.00%	0	0.00%	0		0	0.00%
With Road Treatment	0	0.00%	0	0.00%	0		0	0.00%
Dry with Icy Road Treatment	0	0.00%	0	0.00%	0		0	0.00%
Wet with Icy Road Treatment	1	0.36%	0	0.00%	0		1	0.25%
Snowy with Icy Road Treatment	2	0.71%	0	0.00%	0		2	0.50%
Icy with Icy Road Treatment	4	1.43%	1	0.84%	0		5	1.25%
Slushy with Icy Road Treatment	0	0.00%	1	0.84%	0		1	0.25%
Unknown Road Condition	4	1.43%	0	0.00%	0		4	1.00%
Contributing Factor								
No Apparent Contributing Factor	78	27.86%	30	25.21%	0		108	27.07%
Asleep at the Wheel	4	1.43%	1	0.84%	0		5	1.25%
Illness	3	1.07%	1	0.84%	0		4	1.00%
Distracted by Passenger	2	0.71%	0	0.00%	0		2	0.50%
Driver Inexperience	23	8.21%	7	5.88%	0		30	7.52%
Driver Fatigue	3	1.07%	0	0.00%	0		3	0.75%
Driver Preoccupied	13	4.64%	7	5.88%	0		20	5.01%
Driver Unfamiliar with Area	15	5.36%	5	4.20%	0		20	5.01%
Driver Emotionally Upset	6	2.14%	0	0.00%	0		6	1.50%
Evading Law Enforcement Officer	0	0.00%	0	0.00%	0		0	0.00%
Physical Disability	0	0.00%	0	0.00%	0		0	0.00%
Unknown Contributing Factor	133	47.50%	68	57.14%	0		201	50.38%
Condition of Driver								
No Impairment Suspected	205	73.21%	86	72.27%	0		291	72.93%
Alcohol	33	11.79%	12	10.08%	0		45	11.28%
RX Drugs or Medication	0	0.00%	0	0.00%	0		0	0.00%
Illegal Drugs	0	0.00%	0	0.00%	0		0	0.00%
Alcohol and Drugs	6	2.14%	1	0.84%	0		7	1.75%
Driver/Pedestrian Not Observed	0	0.00%	0	0.00%	0		0	0.00%
Unknown Condition	36	12.86%	20	16.81%	0		56	14.04%
Total Accidents:	**280**	**70.18%**	**119**	**29.82%**	**0**		**399**	**100.00%**

4-Leg 1-Lane Roundabouts

The SPF graphs of the frequency and severity models for the Colorado 4-Leg 1-Lane Roundabouts and CURE plots for each are presented in **Figure 3-8**, and model parameters are shown in **Table 3-3**. The SPFs developed under this project show a very acceptable fit with small over-dispersion parameters α reflecting tight distribution around the mean. Diagnostics for this facility type are shown in **Table 3-4**.

Table 3-3: Frequency and Severity SPF Model Parameters for 4-Leg 1-Lane Roundabouts

Severity		Frequency	
Variable	**Value**	**Variable**	**Value**
β_0	1.00E-04	β_0	1.24E-01
β_1	2.49E+02	β_1	2.51E+02
β_2	1.96E+01	β_2	1.80E+01
β_3	9.38E-01	β_3	1.12E+00
β_4	2.39E+01	β_4	3.61E+00
β_5	2.17E-01	β_5	2.87E-01
α	0.125	α	0.125

Roadway	$AADT_{Min}$	$AADT_{Max}$
Major	5,000	22,500
Minor	1,000	12,000

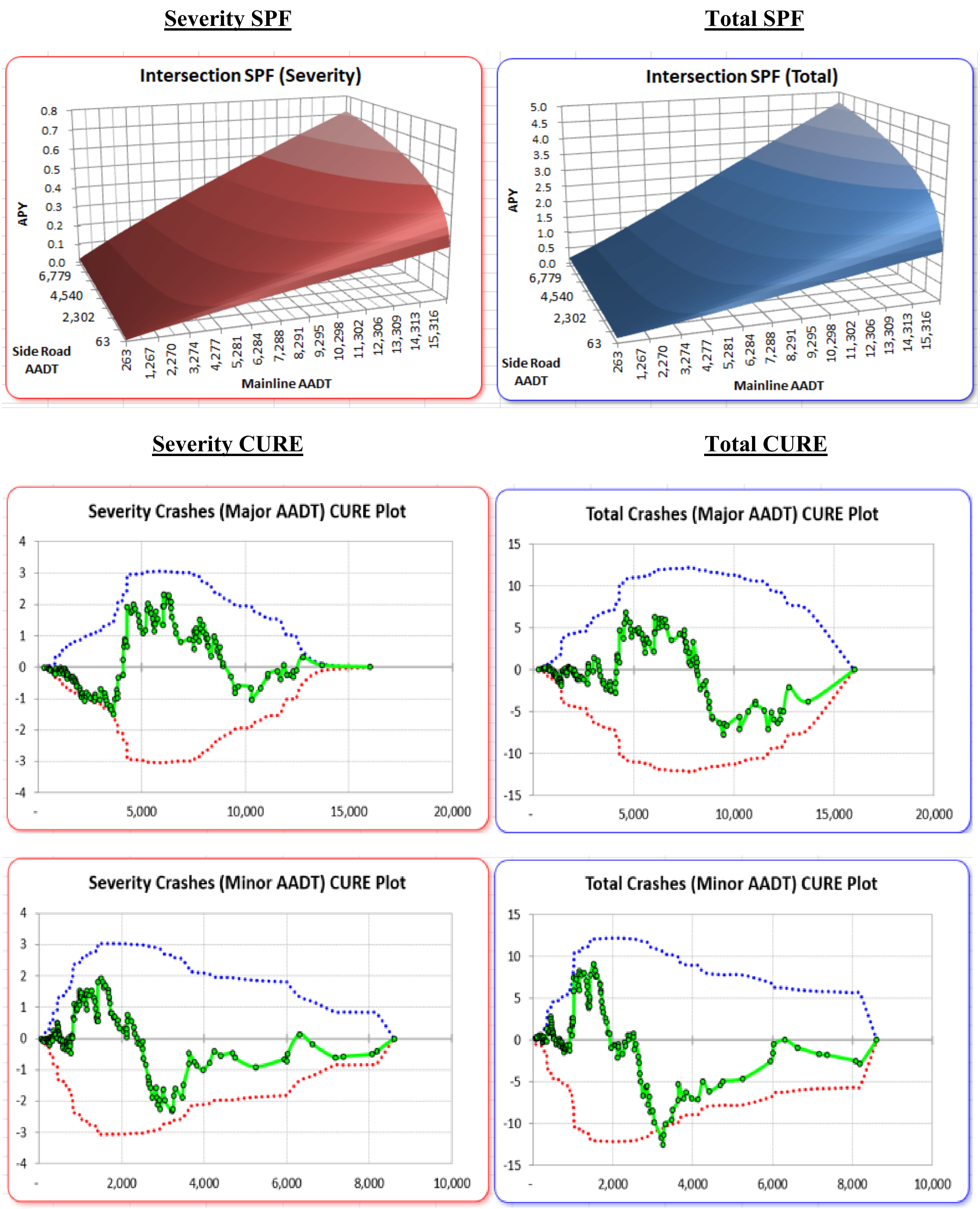


Figure 3-8: Frequency and Severity SPF Graphs and CURE Plots for 4-Leg 1-Lane Roundabouts

Table 3-4: Diagnostic Stratified Norms for Urban 4-Leg 1-Lane Roundabouts

Urban 1-Lane 4Leg Roundabouts								
	0-12500 ADT		12500-25000 ADT		>25000 ADT		All Totals	
Description	Accidents	Percent	Accidents	Percent	Accidents	Percent	Accidents	Percent
Severity								
PDO	507	82.84%	378	85.91%	0		885	84.13%
INJ	105	17.16%	62	14.09%	0		167	15.87%
FAT	0	0.00%	0	0.00%	0		0	0.00%
Persons Injured	121	N/A	76	N/A	0	N/A	197	N/A
Persons Killed	0	N/A	0	N/A	0	N/A	0	N/A
Number of Vehicles								
Single Vehicle Accidents	275	44.93%	100	22.73%	0		375	35.65%
Two Vehicle Accidents	319	52.12%	328	74.55%	0		647	61.50%
Three or more Vehicle Accident	18	2.94%	12	2.73%	0		30	2.85%
Unknown Number of Vehicles	0	0.00%	0	0.00%	0		0	0.00%
Location								
On Road	350	57.19%	342	77.73%	0		692	65.78%
Off Road	262	42.81%	98	22.27%	0		360	34.22%
Off Road Left	121	19.77%	42	9.55%	0		163	15.49%
Off Road Right	137	22.39%	54	12.27%	0		191	18.16%
Off Road at Tee	3	0.49%	0	0.00%	0		3	0.29%
Off Road in Median	0	0.00%	2	0.45%	0		2	0.19%
Unknown Road Location	0	0.00%	0	0.00%	0		0	0.00%
Accident Type								
Overturning	13	2.12%	5	1.14%	0		18	1.71%
Other Non Collision	3	0.49%	1	0.23%	0		4	0.38%
Vehicle Cargo/Debris	0	0.00%	0	0.00%	0		0	0.00%
Pedestrian	4	0.65%	2	0.45%	0		6	0.57%
Broadside	132	21.57%	117	26.59%	0		249	23.67%
Head On	4	0.65%	2	0.45%	0		6	0.57%
Rear End	90	14.71%	118	26.82%	0		208	19.77%
Sideswipe (Same Direction)	37	6.05%	77	17.50%	0		114	10.84%
Sideswipe (Opposite Direction)	4	0.65%	4	0.91%	0		8	0.76%
Approach Turn	7	1.14%	0	0.00%	0		7	0.67%
Overtaking Turn	3	0.49%	11	2.50%	0		14	1.33%
Parked Motor Vehicle	21	3.43%	1	0.23%	0		22	2.09%
Railway Vehicle	0	0.00%	0	0.00%	0		0	0.00%
Bicycle/Pedal Cycle	25	4.08%	3	0.68%	0		28	2.66%
Motorized Bicycle	0	0.00%	0	0.00%	0		0	0.00%
Domestic Animal	0	0.00%	0	0.00%	0		0	0.00%
Wild Animal	4	0.65%	2	0.45%	0		6	0.57%
Light/Utility Pole	38	6.21%	17	3.86%	0		55	5.23%
Traffic Signal Pole/Equipment	6	0.98%	2	0.45%	0		8	0.76%
Traffic Sign/Post/Overhead Sign Structure	69	11.27%	30	6.82%	0		99	9.41%
Bridge Rail	0	0.00%	0	0.00%	0		0	0.00%
Guard Rail	0	0.00%	0	0.00%	0		0	0.00%
Cable Rail	1	0.16%	0	0.00%	0		1	0.10%
Concrete Barrier	5	0.82%	2	0.45%	0		7	0.67%
Bridge Abutment	0	0.00%	0	0.00%	0		0	0.00%
Column/Pier/Bridge Structure	0	0.00%	0	0.00%	0		0	0.00%
Culvert/Headwall	3	0.49%	2	0.45%	0		5	0.48%
Embankment/Ditch	8	1.31%	1	0.23%	0		9	0.86%
Curb/Island	57	9.31%	21	4.77%	0		78	7.41%
Delineator Post	1	0.16%	0	0.00%	0		1	0.10%
Fence/Fence Part	6	0.98%	3	0.68%	0		9	0.86%
Tree/Shrubs	13	2.12%	3	0.68%	0		16	1.52%
Large Boulder	20	3.27%	1	0.23%	0		21	2.00%
Rocks in Roadway	0	0.00%	0	0.00%	0		0	0.00%
Barricade	0	0.00%	0	0.00%	0		0	0.00%
Wall/Building	5	0.82%	4	0.91%	0		9	0.86%
Crash Cushion/Sand Barrels/Impact Attenuator	0	0.00%	0	0.00%	0		0	0.00%
Mailbox	0	0.00%	0	0.00%	0		0	0.00%

Table 3-4 (Cont.): Diagnostic Stratified Norms for Urban 4-Leg 1-Lane Roundabouts

	Urban 1-Lane 4Leg Roundabouts							
	0-12500 ADT		12500-25000 ADT		>25000 ADT		All Totals	
Description	Accidents	Percent	Accidents	Percent	Accidents	Percent	Accidents	Percent
Other Fixed Object	28	4.58%	6	1.36%	0		34	3.23%
Other Object	4	0.65%	5	1.14%	0		9	0.86%
Road Maintenance Equipment	1	0.16%	0	0.00%	0		1	0.10%
Unknown Accident Type	0	0.00%	0	0.00%	0		0	0.00%
Total Fixed Objects	260	42.48%	92	20.91%	0		352	33.46%
Total Other Objects	5	0.82%	5	1.14%	0		10	0.95%
Lighting								
Daylight	392	64.05%	302	68.64%	0		694	65.97%
Dawn or Dusk	33	5.39%	29	6.59%	0		62	5.89%
Dark - Lighted	143	23.37%	94	21.36%	0		237	22.53%
Dark - Unlighted	41	6.70%	13	2.95%	0		54	5.13%
Unknown Lighting	3	0.49%	2	0.45%	0		5	0.48%
Weather								
No Adverse Weather	463	75.65%	341	77.50%	0		804	76.43%
Rain	23	3.76%	14	3.18%	0		37	3.52%
Snow/Sleet/Hail	66	10.78%	49	11.14%	0		115	10.93%
Fog	2	0.33%	2	0.45%	0		4	0.38%
Dust	0	0.00%	0	0.00%	0		0	0.00%
Wind	4	0.65%	2	0.45%	0		6	0.57%
Unknown Weather	54	8.82%	32	7.27%	0		86	8.17%
Road Condition								
Dry Road	462	75.49%	336	76.36%	0		798	75.86%
Wet Road	42	6.86%	28	6.36%	0		70	6.65%
Muddy Road	0	0.00%	0	0.00%	0		0	0.00%
Snowy Road	32	5.23%	20	4.55%	0		52	4.94%
Icy Road	62	10.13%	46	10.45%	0		108	10.27%
Slushy Road	4	0.65%	2	0.45%	0		6	0.57%
Foreign Material Road	3	0.49%	0	0.00%	0		3	0.29%
With Road Treatment	0	0.00%	0	0.00%	0		0	0.00%
Dry with Icy Road Treatment	2	0.33%	1	0.23%	0		3	0.29%
Wet with Icy Road Treatment	0	0.00%	1	0.23%	0		1	0.10%
Snowy with Icy Road Treatment	2	0.33%	2	0.45%	0		4	0.38%
Icy with Icy Road Treatment	1	0.16%	2	0.45%	0		3	0.29%
Slushy with Icy Road Treatment	0	0.00%	0	0.00%	0		0	0.00%
Unknown Road Condition	2	0.33%	2	0.45%	0		4	0.38%
Contributing Factor								
No Apparent Contributing Factor	215	35.13%	206	46.82%	0		421	40.02%
Asleep at the Wheel	4	0.65%	2	0.45%	0		6	0.57%
Illness	8	1.31%	1	0.23%	0		9	0.86%
Distracted by Passenger	6	0.98%	2	0.45%	0		8	0.76%
Driver Inexperience	64	10.46%	46	10.45%	0		110	10.46%
Driver Fatigue	4	0.65%	4	0.91%	0		8	0.76%
Driver Preoccupied	44	7.19%	28	6.36%	0		72	6.84%
Driver Unfamiliar with Area	36	5.88%	33	7.50%	0		69	6.56%
Driver Emotionally Upset	1	0.16%	1	0.23%	0		2	0.19%
Evading Law Enforcement Officer	3	0.49%	0	0.00%	0		3	0.29%
Physical Disability	4	0.65%	0	0.00%	0		4	0.38%
Unknown Contributing Factor	223	36.44%	117	26.59%	0		340	32.32%
Condition of Driver								
No Impairment Suspected	547	89.38%	406	92.27%	0		953	90.59%
Alcohol	50	8.17%	29	6.59%	0		79	7.51%
RX Drugs or Medication	3	0.49%	3	0.68%	0		6	0.57%
Illegal Drugs	0	0.00%	0	0.00%	0		0	0.00%
Alcohol and Drugs	12	1.96%	2	0.45%	0		14	1.33%
Driver/Pedestrian Not Observed	0	0.00%	0	0.00%	0		0	0.00%
Unknown Condition	0	0.00%	0	0.00%	0		0	0.00%
Total Accidents:	612	58.17%	440	41.83%	0		1,052	100.00%

4-Leg 2-Lane Roundabouts

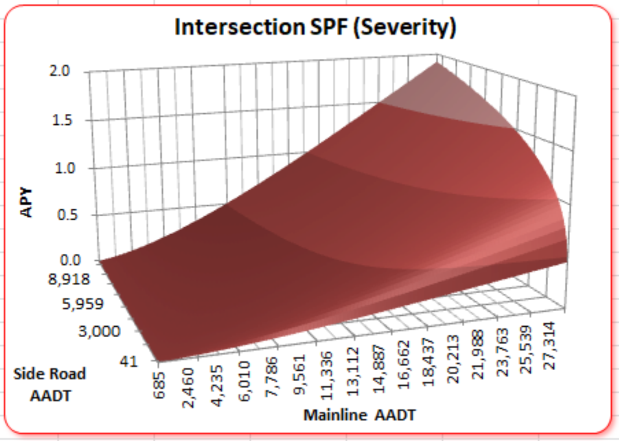
The SPF graphs of the frequency and severity models for the Colorado 4-Leg 2-Lane Roundabouts and CURE plots for each are presented in **Figure 3-9**, and model parameters are shown in **Table 3-5**. The SPFs developed under this project show a very acceptable fit with small over-dispersion parameters α reflecting tight distribution around the mean. Diagnostics for this facility type are shown in **Table 3-6**.

Table 3-5: Frequency and Severity SPF Model Parameters for 4-Leg 2-Lane Roundabouts

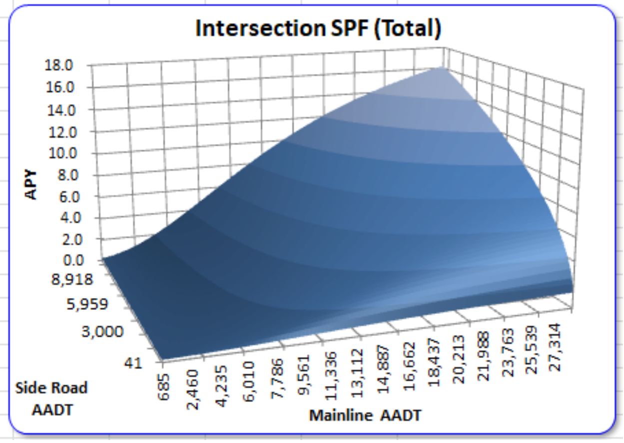
Severity		Frequency	
Variable	Value	Variable	Value
β_0	1.00E-04	β_0	2.01E-01
β_1	2.49E+02	β_1	1.00E+04
β_2	2.09E+01	β_2	2.64E+00
β_3	1.54E+00	β_3	1.92E+00
β_4	2.50E+01	β_4	4.89E+02
β_5	2.62E-01	β_5	4.68E-01
α	0.125	α	0.195

Roadway	$AADT_{Min}$	$AADT_{Max}$
Major	5,000	22,500
Minor	1,000	12,000

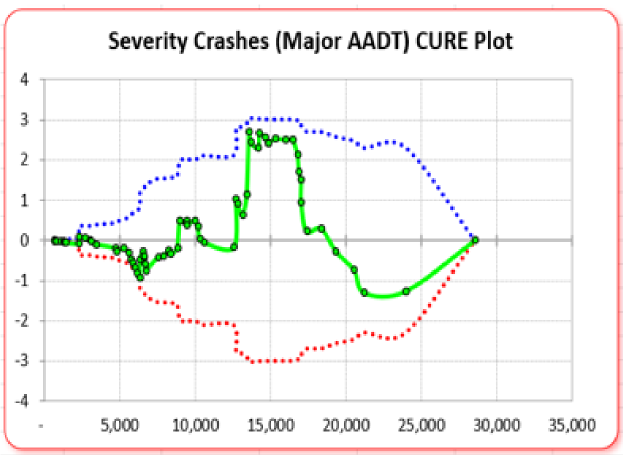
Severity SPF

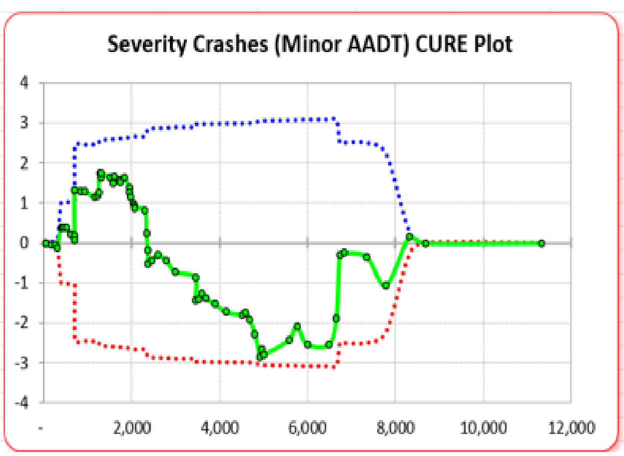


Total SPF

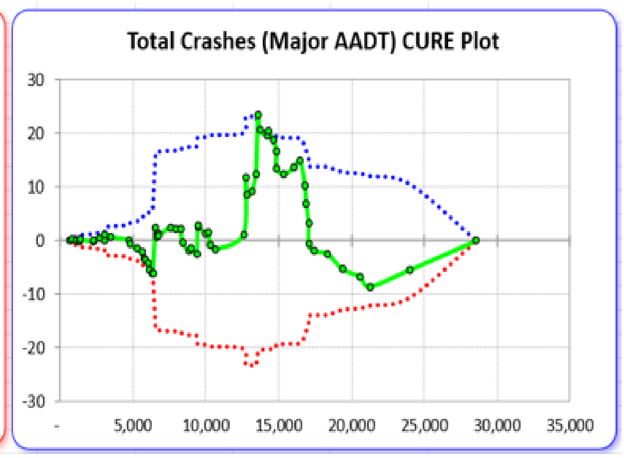


Severity CURE





Total CURE



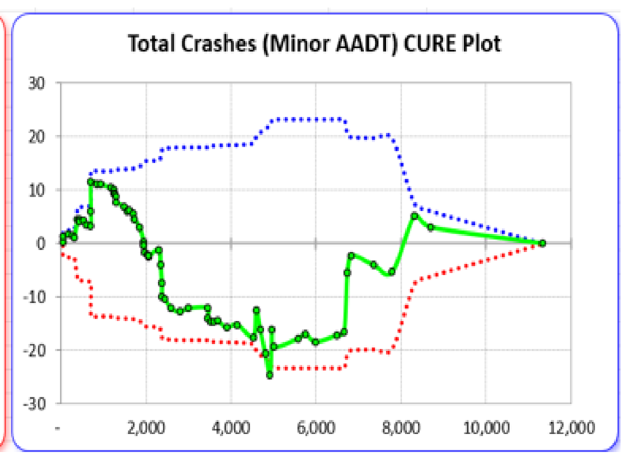


Figure 3-9: Frequency and Severity SPF Graphs and CURE Plots for 4-Leg 2-Lane Roundabouts

Table 3-6: Diagnostic Stratified Norms for Urban 4-Leg 2-Lane Roundabouts

Urban 2-Lane 4-Leg Roundabouts						
	0-20000 ADT		20000-35000 ADT		All Totals	
Description	Accidents	Percent	Accidents	Percent	Accidents	Percent
Severity						
PDO	543	88.87%	636	90.73%	1,179	89.86%
INJ	68	11.13%	65	9.27%	133	10.14%
FAT	0	0.00%	0	0.00%	0	0.00%
Persons Injured	84	N/A	83	N/A	167	N/A
Persons Killed	0	N/A	0	N/A	0	N/A
Number of Vehicles						
Single Vehicle Accidents	139	22.75%	83	11.84%	222	16.92%
Two Vehicle Accidents	464	75.94%	602	85.88%	1,066	81.25%
Three or more Vehicle Accident	8	1.31%	16	2.28%	24	1.83%
Unknown Number of Vehicles	0	0.00%	0	0.00%	0	0.00%
Location						
On Road	490	80.20%	623	88.87%	1,113	84.83%
Off Road	121	19.80%	78	11.13%	199	15.17%
Off Road Left	53	8.67%	30	4.28%	83	6.33%
Off Road Right	64	10.47%	42	5.99%	106	8.08%
Off Road at Tee	0	0.00%	1	0.14%	1	0.08%
Off Road in Median	2	0.33%	3	0.43%	5	0.38%
Unknown Road Location	0	0.00%	0	0.00%	0	0.00%
Accident Type						
Overturning	9	1.47%	2	0.29%	11	0.84%
Other Non Collision	0	0.00%	3	0.43%	3	0.23%
Vehicle Cargo/Debris	1	0.16%	0	0.00%	1	0.08%
Pedestrian	2	0.33%	1	0.14%	3	0.23%
Broadside	130	21.28%	121	17.26%	251	19.13%
Head On	2	0.33%	1	0.14%	3	0.23%
Rear End	83	13.58%	179	25.53%	262	19.97%
Sideswipe (Same Direction)	215	35.19%	235	33.52%	450	34.30%
Sideswipe (Opposite Direction)	3	0.49%	2	0.29%	5	0.38%
Approach Turn	1	0.16%	2	0.29%	3	0.23%
Overtaking Turn	31	5.07%	65	9.27%	96	7.32%
Overtaking Turn	31	5.07%	65	9.27%	96	7.32%
Parked Motor Vehicle	0	0.00%	4	0.57%	4	0.30%
Railway Vehicle	0	0.00%	0	0.00%	0	0.00%
Bicycle/Pedal Cycle	6	0.98%	5	0.71%	11	0.84%
Motorized Bicycle	0	0.00%	0	0.00%	0	0.00%
Domestic Animal	1	0.16%	1	0.14%	2	0.15%
Wild Animal	11	1.80%	1	0.14%	12	0.91%
Light/Utility Pole	14	2.29%	8	1.14%	22	1.68%
Traffic Signal Pole/Equipment	3	0.49%	2	0.29%	5	0.38%
Traffic Sign/Post/Overhead Sign Structure	33	5.40%	21	3.00%	54	4.12%
Bridge Rail	0	0.00%	0	0.00%	0	0.00%
Guard Rail	1	0.16%	6	0.86%	7	0.53%
Cable Rail	0	0.00%	0	0.00%	0	0.00%
Concrete Barrier	0	0.00%	1	0.14%	1	0.08%
Bridge Abutment	0	0.00%	0	0.00%	0	0.00%
Column/Pier/Bridge Structure	0	0.00%	0	0.00%	0	0.00%
Culvert/Headwall	1	0.16%	1	0.14%	2	0.15%
Embankment/Ditch	4	0.65%	0	0.00%	4	0.30%

Table 3-6 (Cont.): Diagnostic Stratified Norms for Urban 4-Leg 2-Lane Roundabouts

Urban 2-Lane 4-Leg Roundabouts						
	0-20000 ADT		20000-35000 ADT		All Totals	
Description	Accidents	Percent	Accidents	Percent	Accidents	Percent
Curb/Island	35	5.73%	23	3.28%	58	4.42%
Delineator Post	0	0.00%	0	0.00%	0	0.00%
Fence/Fence Part	1	0.16%	0	0.00%	1	0.08%
Tree/Shrubs	10	1.64%	2	0.29%	12	0.91%
Large Boulder	2	0.33%	4	0.57%	6	0.46%
Rocks in Roadway	0	0.00%	0	0.00%	0	0.00%
Barricade	0	0.00%	0	0.00%	0	0.00%
Wall/Building	1	0.16%	1	0.14%	2	0.15%
Crash Cushion/Sand Barrels/Impact Attenuator	0	0.00%	0	0.00%	0	0.00%
Mailbox	0	0.00%	0	0.00%	0	0.00%
Other Fixed Object	9	1.47%	7	1.00%	16	1.22%
Other Object	2	0.33%	3	0.43%	5	0.38%
Road Maintenance Equipment	0	0.00%	0	0.00%	0	0.00%
Unknown Accident Type	0	0.00%	0	0.00%	0	0.00%
Total Fixed Objects	114	18.66%	76	10.84%	190	14.48%
Total Other Objects	3	0.49%	3	0.43%	6	0.46%
Weather						
No Adverse Weather	502	82.16%	587	83.74%	1,089	83.00%
Rain	18	2.95%	25	3.57%	43	3.28%
Snow/Sleet/Hail	50	8.18%	49	6.99%	99	7.55%
Fog	0	0.00%	0	0.00%	0	0.00%
Dust	0	0.00%	0	0.00%	0	0.00%
Wind	3	0.49%	4	0.57%	7	0.53%
Unknown Weather	38	6.22%	36	5.14%	74	5.64%
Road Condition						
Dry Road	504	82.49%	561	80.03%	1,065	81.17%
Wet Road	38	6.22%	56	7.99%	94	7.16%
Muddy Road	0	0.00%	0	0.00%	0	0.00%
Snowy Road	29	4.75%	36	5.14%	65	4.95%
Icy Road	32	5.24%	32	4.56%	64	4.88%
Slushy Road	0	0.00%	3	0.43%	3	0.23%
Foreign Material Road	1	0.16%	0	0.00%	1	0.08%
With Road Treatment	0	0.00%	0	0.00%	0	0.00%
Dry with Icy Road Treatment	1	0.16%	0	0.00%	1	0.08%
Wet with Icy Road Treatment	0	0.00%	1	0.14%	1	0.08%
Snowy with Icy Road Treatment	2	0.33%	5	0.71%	7	0.53%
Icy with Icy Road Treatment	3	0.49%	4	0.57%	7	0.53%
Slushy with Icy Road Treatment	0	0.00%	2	0.29%	2	0.15%
Unknown Road Condition	1	0.16%	1	0.14%	2	0.15%
Contributing Factor						
No Apparent Contributing Factor	266	43.54%	346	49.36%	612	46.65%
Asleep at the Wheel	6	0.98%	3	0.43%	9	0.69%
Illness	6	0.98%	9	1.28%	15	1.14%
Distracted by Passenger	5	0.82%	2	0.29%	7	0.53%
Driver Inexperience	68	11.13%	60	8.56%	128	9.76%
Driver Fatigue	3	0.49%	1	0.14%	4	0.30%
Driver Preoccupied	32	5.24%	41	5.85%	73	5.56%
Driver Unfamiliar with Area	59	9.66%	65	9.27%	124	9.45%
Driver Emotionally Upset	5	0.82%	1	0.14%	6	0.46%
Evading Law Enforcement Officer	2	0.33%	1	0.14%	3	0.23%
Physical Disability	2	0.33%	2	0.29%	4	0.30%
Unknown Contributing Factor	157	25.70%	170	24.25%	327	24.92%

Table 3-6 (Cont.): Diagnostic Stratified Norms for Urban 4-Leg 2-Lane Roundabouts

Urban 2-Lane 4-Leg Roundabouts						
	0-20000 ADT		20000-35000 ADT		All Totals	
Description	Accidents	Percent	Accidents	Percent	Accidents	Percent
Condition of Driver						
No Impairment Suspected	580	94.93%	682	97.29%	1,262	96.19%
Alcohol	26	4.26%	14	2.00%	40	3.05%
RX Drugs or Medication	1	0.16%	0	0.00%	1	0.08%
Illegal Drugs	0	0.00%	0	0.00%	0	0.00%
Alcohol and Drugs	4	0.65%	5	0.71%	9	0.69%
Driver/Pedestrian Not Observed	0	0.00%	0	0.00%	0	0.00%
Unknown Condition	0	0.00%	0	0.00%	0	0.00%
Total Accidents:	611	46.57%	701	53.43%	1,312	100.00%

4. Chapter 4 – Conclusions

This project provides an important addition to the Colorado-specific base of safety knowledge, capturing safety performance characteristics of the following facilities:

- Urban 3-Leg 1-Lane Roundabouts
- Urban 4-Leg 1-Lane Roundabouts
- Urban 4-Leg 2-Lane Roundabouts

To achieve ultimate results all of the Safety Performance Functions (SPF) in this report were developed using original Colorado data. Use of this knowledge base will enable CDOT to identify existing safety problems with greater accuracy and effectiveness. Proposed methodology will support optimal investment of limited resources which will result in greater crash reduction. It provides a platform for the project level decision support analysis, planning of system level improvements and risk management. When applied statewide, this approach is expected to provide maximum safety improvements on Colorado roundabouts within constraints of budget allocations. Use of the proposed methodology is intended to assist CDOT staff in making decisions affecting safety of the traveling public.

The SPF models are ready for immediate use and are also encoded into the Vision Zero Suite software platform currently deployed by CDOT.

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