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Isolated approaches at signalized intersections with posted speed limits of 45 mph or greater generally experience large numbers of rear-end and angle collisions. A combination of less attentive drivers, high operating speeds, and less than ideal intersection characteristics can result in crash frequencies well above expected rates. A number of treatment options are available to target specific safety concerns at intersections, but it can be difficult or time-consuming to determine when an intersection is experiencing abnormal crash trends. The Oregon Department of Transportation (ODOT) does not currently have a system in place for evaluating safety at isolated, high-speed, signalized intersections (IHSSIs). This thesis describes the development of a method for efficiently evaluating safety and determining potential treatment options for IHSSIs. Specifically, this method identifies data collection requirements, determines expected crash frequencies based on intersection configuration, and provides a list of safety treatment options. This information is packaged into a safety evaluation template to allow for efficient and effective IHSSI evaluations.

Note: The Oregon Department of Transportation funded this effort; therefore, copies of part or all of this research may be published by the Oregon Department of Transportation or their agents.

Evaluating Safety at Oregon's Isolated, High-Speed, Signalized Intersections

by
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APPROVED:

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Dean of the Graduate School

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

Neil H. Kopper, Author

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CONTRIBUTION OF AUTHORS

Dr. Ida van Schalkwyk and Dr. Karen Dixon each contributed to Appendix A, the safety treatments literature review. This literature review was part of a larger project for the Oregon Department of Transportation. Dr. Dixon also influenced this project's research questions and methodology. Mr. Raul Avelar assisted in the data collection required for the case studies provided in this report.

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LIST OF ACRONYMS AND TERMS

AADT	Average Annual Daily Traffic
AF	Accident Frequency
AR	Accident Rate
ARP	Accident Reduction Potential
AWEGS	Advanced Warning for End-of-Green System
AWF	Advance Warning Flasher
BODAWS	Blank-out Overhead Dynamic Advance Warning Signal
CCW	Cooperative Collision Warning
CFSSA	Continuous Flashing Symbolic Signal Ahead
CI	Confidence Interval
D-CS	Detection-Control System
EB	Empirical Bayes
EPDO	Equivalent Property Damage Only
FHWA	Federal Highway Administration
FSSA	Flashing Symbolic Signal Ahead
GES	General Estimates System
ICAV	Intersection Crash Avoidance, Violation
IHSSI	Isolated, High-Speed, Signalized Intersection
ITE	Institute of Transportation Engineers
LED	Light-emitting Diode
LOS	Level of Service
Mph	Miles per Hour
ODOT	Oregon Department of Transportation
PATH	Partners for Advanced Transit and Highways
PDO	Property Damage Only
PRT	Perception Reaction Time
PTSWF	Prepare to Stop when Flashing
RSA	Red Signal Ahead
RSA	Road Safety Audit
RSAR	Road Safety Audit Review
SAS	Signal Ahead Sign
SLOS	Safety Level of Service
SOS	Self Optimizing Signal
SPF	Safety Performance Function
SR	Simple Ranking
TAC	Technical Advisory Committee
TTC	Time-to-Collision
TTI	Texas Transportation Institute
VDOT	Virginia Department of Transportation

EVALUATING SAFETY AT OREGON'S ISOLATED, HIGH-SPEED, SIGNALIZED INTERSECTIONS

1.0 INTRODUCTION

The Oregon Department of Transportation (ODOT) *Traffic Signal Policy and Guidelines* (*2006*) provides guidance for the design, timing, and placement of rural traffic signals. This guideline indicates that traffic signals should generally not be installed at high-speed locations on rural highways. It further indicates that unfamiliar drivers on these higher speed facilities do not anticipate traffic signals. This unexpected signal placement is likely to result in longer reaction times and consequently longer stopping sight distance. However, Oregon highways contain many of these high-speed, rural, signalized intersections. These intersections are the focus of this research. The unexpected decelerations common at these intersections can result in a high number of rear-end and angle crashes. In Oregon, as well as the rest of the United States, crashes at high-speed, signalized intersections are a significant safety concern. For example, in the ODOT 2006 Amendment One for the "Oregon Transportation Safety Action Plan" these high-speed, signalized intersection crashes are specifically cited as a key safety emphasis area. ODOT continues to examine efforts to improve the transition between low-speed and high-speed sections of State highways. However, ODOT does not currently have a standardized system in place for evaluating safety at isolated, high-speed, signalized intersections (IHSSIs).

While there is research available for evaluating safety at signalized intersections and even high-speed, signalized intersections, there is no research available that exclusively addresses evaluating safety at high-speed, signalized intersections with isolated approaches. Furthermore, the available intersection safety evaluation methods do not specifically accommodate Oregon's unique resources and available transportation data.

This thesis, titled *Evaluating Safety at Oregon's Isolated, High-Speed, Signalized Intersections*, describes the development of a method for evaluating safety at IHSSIs as part of a research project for ODOT to evaluate safety and operations at high-speed, signalized intersections. This method is intended to facilitate efficient safety evaluations of IHSSIs and ensure that irregular crash trends do not go unnoticed. This project focuses on four-leg intersections with one or more approaches that are isolated from any previous stop control by at least one mile. Additionally, to focus on high-speed locations, this project only considers intersections located on State highways with posted speed limits of at least 45 miles per hour (mph).

The safety evaluation method developed for this project needs to be both effective and easily utilized. It is important that this method provide all essential information without requiring excessive data collection and that all processes are easily understood and repeatable. For these reasons, the safety evaluation methods described in this thesis do not involve long or statistically complex procedures and, when possible, use data that is already available. Ideally, this method will provide ODOT with a valuable safety tool that is straightforward and easily applied.

This project determines average expected crash type percentages and companion crash rates, establishes a hierarchy of treatment strategies for a given overrepresentation of crash types, and combines these values and strategies with other essential information into a logical reporting format. This reporting format, or safety evaluation template, will be demonstrated throughout this report using a sample intersection evaluation.

Chapter 2 of this thesis summarizes the published literature for evaluating safety at signalized intersections. Chapter 3 then describes the research methodology used in this project. Chapter 4 provides research results and Chapter 5 discusses recommendations for future research. Chapter 6 presents the conclusions of this research project. The Bibliography identifies the references cited in this document. Finally, the Appendix contains tables, figures, and other information referenced throughout the report.

2.0 LITERATURE REVIEW

Though many researchers and transportation professionals have noted the high crash frequencies of IHSSIs, there is no established method for evaluating safety at these locations. As is shown in Appendix A, many studies have documented the effects of various safety treatments on IHSSIs but they do not establish an evaluation method. The following sections illustrate key findings from studies and reports that provide guidance for evaluating safety at high-speed, signalized intersections in general. However, none of these studies target isolated intersections. The primary goal of this literature review is to display current safety evaluation techniques employed at high-speed, signalized intersections. This information will serve as guidance for evaluating IHSSIs.

NCHRP Report 500 (*Antonucci et. al, 2004*) outlines a strategy for improving safety at signalized intersections. The first step of this strategy is to identify and define a problem which includes defining the scope, defining reactive evaluation metrics, defining proactive analysis procedures, collecting data, analyzing data, and reporting results. The following sections provide details on proactive analyses, reactive analyses, evaluation metrics, and necessary data collection. This literature review focuses on immediately applicable subjects as limited by the scope of the project, but it also briefly discusses other safety evaluation methods to provide a broader description of safety evaluation techniques.

2.1 Proactive Procedures

Proactive evaluations consider safety at an intersection before any unusual crash trends become apparent. These evaluations take into account traffic and geometric features and provide estimates of expected safety conditions. Types of proactive safety evaluations include safety audits, safety level of service, and safety performance functions.

2.1.1 Safety Audits

A road safety audit (RSA) is a formal safety evaluation of a future transportation project. A road safety audit review (RSAR) is a similar safety evaluation of existing transportation infrastructure. In an RSA or RSAR, an independent, multidisciplinary research team examines design standards, plans, traffic volume, information from site inspections, and other available data. The team considers safety for all possible users under all possible conditions before preparing a safety audit report. These safety audits generally do not consider crash records and are intended to increase safety at a location before any crash trends become apparent (*Wilson & Lipinski, 2004*).

2.1.2 Safety Level of Service

Kononov and Allery (*2003*) proposed a safety level of service (SLOS) to evaluate a location's crash frequency and severity based on characteristics such as average annual daily traffic (AADT). This safety level of service is conceptually similar to the Highway Capacity Manual's level of service (LOS) and can provide letter or number grades to indicate safety.

Pan, Lu, Xiang, and Zhang (*2007*) and Lu, Pan, and Xiang (*2008*) also support use of SLOS as a safety measure for signalized intersections. The authors develop models for SLOS at signalized intersections along highways. Conflict points are the major influencing factor for these models. Minor factors include signal phasing, geometric features, traffic signs, pavement markings, pavement condition, lighting, and traffic volumes. SLOS provides a quantified safety indication that can suggest the need for improvements when safety falls below a set level. The SLOS also allows for the consideration of safety effects when comparing design alternatives and is easily understood by the public.

Yuan and Lu (*2008*) describe a similar approach that results in an overall safety rating. Using this method, engineers rate existing intersection conditions based on both severity and significance. A summary of these rating results provides a safety rating for the intersection. Also, this method gives particular safety problems a safety index based on the significance and severity of the problem. The benefit of these proactive approaches is that they provide relatively fast safety evaluations without the need for crash data.

2.1.3 Safety Performance Functions

Safety performance functions (SPFs) are predictive models that use traffic volumes, operational characteristics, and geometric characteristics to predict expected crash experience. Lyon, Haq, Persaud, and Kodama (*2005*) developed an example of SPFs for signalized intersections in Toronto, Ontario. They developed one set of models involving only AADT and another more complex model incorporating variables related to pedestrian flows and the presence of turning lanes. Each individual model within a set describes a specific intersection configuration and road class. Additionally, property damage only (PDO) crashes are estimated separately from crashes involving injuries or fatalities. The form of the models only requiring AADT is shown below in Equation 1.

Equation 1: Safety Performance Function Model Form

$$\text{Collisions/year} = \alpha(F_1)^{\beta_1}(F_2)^{\beta_2}\exp(\beta_3 F_2)$$

Where

α, β = coefficients calibrated for specific models
F_1 = entering AADT on the major road
F_2 = entering AADT on the minor road

Coefficients α and β require recalibration for different areas or new intersection types.

Hauer, Ng, and Lovell (*1988*) noted that researchers have suggested many different models for estimating accident frequency based on traffic volumes. They also used traffic volumes to develop equations for estimating the safety of signalized intersections, but noted that accident history should also be reflected in these intersection safety estimates.

2.2 Reactive Procedures

Reactive evaluations consider safety based on a location's crash experience. These evaluations may or may not take into account traffic volumes or other intersection characteristics and generally involve hotspot identification.

2.2.1 Hotspot Identification Methods

The terms "hotspots", "blackspots", "high risk", and "sites with promise", refer to intersections or road segments with unusually high crash experience (*Cheng and Washington, 2005*). Hauer (*1996*) describes a two stage process for handling hotspots. The first stage identifies hotspots because transportation agencies do not have the resources to closely examine and implement safety projects at every intersection. The second stage involves detailed safety analysis with identification of problems and possible improvements. The following sections focus on the first stage of this process.

2.2.1.1 Number of Crashes

The most basic measure of a location's crash experience is to simply determine the total number of crashes. A location is a hotspot if it experiences more than a set number of crashes in a certain time period (e.g. more than 10 crashes in one year). This metric should not be used as the only criterion for determining hotspots because it does not account for volume or other characteristics (*Virkler & Sanford Bernhardt, 1999*).

2.2.1.2 Crash Severity

The crash severity metric is similar to using the number of crashes except greater weight is given to injury and fatality crashes. Transportation agencies define injury and fatality crashes equal to a certain number of PDO crashes and an equivalent-property-damage-only (EPDO) value can be calculated. This EPDO can then help estimate the safety of an intersection (*Virkler & Sanford Bernhardt, 1999*). Crash severity is also referred to as the severity index (*Wilson, 2003*). Similar to the number of crashes, this metric also does not take into account volumes or other intersection characteristics.

2.2.1.3 Crash Density

Crash density is the number of crashes that occur per unit length of a section of road. Road segments with higher than average crash density are considered hotspots (*Wilson, 2003*).

2.2.1.4 Crash Rate

A crash rate equals the number of crashes divided by the volume of a location. Volume is included to account for the opportunity for crashes to occur. Locations with crash rates higher than a predetermined level are hotspots (*Virkler & Sanford Bernhardt*, *1999*). By accounting for volume using crash rates, one assumes that the relationship between crashes and volume is linear. Hauer *(1995*), however, noted that this relationship is seldom linear.

2.2.1.5 Number-Rate

The number-rate metric considers the number of crashes and the crash rate. If both measures are above a given threshold, then the location is considered a hotspot. This combination mitigates some of the limitations of the individual measures. The crash rate accounts for vehicle exposure while the number of crashes ensures that low-volume locations are not mistakenly tagged (*Virkler & Sanford Bernhardt, 1999*).

2.2.1.6 Severity-Rate

The severity-rate is similar to the number-rate, but considers both crash severity and crash rate. Its advantage over the number rate is that it also takes into account the severity of crashes. Rather than consider crash severity and crash rate separately, this metric divides EPDO by volume to produce a single number to identify the safety of an intersection (*Virkler & Sanford Bernhardt, 1999*).

2.2.1.7 Number Quality Control and Rate Quality Control

Number quality control compares a location's number of crashes to average values for the state or region. Similarly, rate quality control compares a location's crash rate to average values. Quality control values higher than average values indicate hotspots. Statistical tests can indicate whether a number of crashes or crash rate is significantly above average values (*Virkler & Sanford Bernhardt, 1999*). Attempts to demonstrate statistical significance involve calculating standard deviations and confidence intervals (CI). Cheng and Washington (*2005*) note that these attempts can only serve as approximations because they assume normal distributions while crash frequencies typically reflect Poisson distributions.

2.2.1.8 Safety Performance Functions

The SPFs discussed in the proactive evaluation section can also be used for reactive analyses. SPFs are generally used in conjunction with more complex statistical procedures such as the empirical Bayes (EB) method. Kweon (*2007*) developed a method for identifying intersection hotspots for the Virginia Department of Transportation (VDOT) that utilizes SPFs and the EB method. He created SPFs using hourly turning volumes from the VDOT Synchro files. Each SPF represents an estimation of a specific crash type occurring during one of four time periods of the day. He used these SPFs and data from the VDOT crash database to develop a ten step procedure for evaluating crash trends. The scope of their project limits evaluations to four-legged signalized intersections in VDOT's Northern Virginia District.

2.2.1.9 Traffic Conflict Studies

Instead of using crash histories, researchers can perform conflict studies to estimate an intersection's safety. Traffic conflict analysis methods parallel the aforementioned crash analyses and can include total number of conflicts, conflict rates, and other models (*Hauer, 1986*). However, traffic conflict studies are very time-consuming and involve subjective judgment by observers (*Yuan & Lu, 2008*).

2.2.2 Evaluations of Hotspot Identification Methods

McGuigan (*1981*) recommends that potential accident reduction should be considered when determining hotspots. Potential accident reduction is a measure of the difference between observed crashes and average crashes for similar locations. He states that accident rate and total number of accidents should not be used to compare safety at different types of locations and recommends metrics that take into account potential accident reduction.

The Missouri Department of Transportation's *Manual on Identification, Analysis and Correction of High-Crash Locations* recommends that an initial location analysis should incorporate both the number of crashes and the crash rate. Then, locations with high crash concentrations should be further evaluated using crash severity and severity rate. Final hotspot identification should involve both number rate and severity rate (*Virkler & Sanford Bernhardt, 1999*).

Cheng and Washington (*2005*) used simulated data to compare simple ranking (SR) based on number of crashes, statistical CI based on number quality control, and EB methods. The authors compared these methods based on the percentage of false negatives, false positives, and total misidentifications. They concluded that EB methods generally outperform SR and CI methods. However, they note that EB benefits "...are contingent upon reliable and accurate safety performance functions" (*p. 880*). Based upon their comparisons, they also concluded that crash histories of three years are optimal, but that up to six years of crash data is preferable to periods shorter than three years. They note significant improvements resulting from including three to six years of crash data for SR and CI methods, but state that the EB method is still preferable. The Federal Highway Administration's (FHWA) "Highway Safety Evaluation Procedural Guide" (*1981b*) also recommends a three year analysis period to minimize issues of regression to the mean. Regression to the mean is the natural tendency of crash frequency to fluctuate about an average value due to the random nature of crashes. Because of this fluctuation, selecting sites based on high crash experience using shorter analysis periods can provide misleading results.

Cheng and Washington (*2008*) used crash data from road segments in Arizona to perform a comparison of commonly used evaluation methods. This study compared hotspot rankings based on accident frequency (AF, previously referred to as SR or number of crashes), accident rate (AR, previously referred to as crash rate), accident reduction potential (ARP, previously referred to as number quality control), and EB methods. The authors based the comparison of the different methods on five separate criteria. In the results, there is inconsistency among the best and worst performing methods for different criteria. The authors' overall conclusion was "...that the EB method is the most consistent and reliable method for identifying hot spots" (*p. 84*). The worst performing method is AR. The authors recommended that in many cases the AF method would be preferable to the AR method.

Hauer, Harwood, Council, and Griffith (*2002*) state that the EB method increases precision and avoids bias caused by regression to the mean. They recommend this method as the preferred safety evaluation practice when SPFs are available.

Hauer (*1996*) notes that choosing evaluation metrics is a difficult decision because different methods can lead to different results. The motives behind identifying hotspots include economic efficiency, professional and institutional responsibility, and fairness. He states that "It is not acceptable to have sites where the risk to a road user is considerably larger than at sites of similar class" (*p. 58*). It is important to provide engineers with the necessary tools to perform a safety diagnosis based on crash histories, site characteristics, and estimates of expected safety. The following sections will further explore these tools.

2.2.3 Evaluating Hotspot Intersections

After an intersection has been identified as a hotspot, many types of information are necessary for further evaluations. Wilson (*2003*) suggested that understanding the details of crashes and crash patterns can lead to isolation of specific factors influencing crashes. He listed approach speeds, vehicle types, and sight distance at corners as important characteristics to consider. Also, specifically for rural intersections, a driver's lack of awareness of an intersection could be an important factor to consider. While considering various data needs, Wilson emphasized that safety evaluation tools must be affordable and practical.

Virkler and Sanford Bernhardt (*1999*) note that collision diagrams, condition diagrams, and traffic data are beneficial for analyzing hotspots. Collision diagrams help identify predominant crash patterns and should show the general path of involved vehicles, the date and time of the crash, light conditions, pavement conditions, and instances of injuries or fatalities. Condition diagrams demonstrate existing intersection characteristics and help relate crash patterns to physical features of the roadway. Condition diagrams should include traffic control devices, geometric characteristics, speed limits, street widths, sidewalks and crosswalks, parking, sight obstructions, fixed objects, road surface irregularities, and other pertinent information. On-site inspections are necessary for completing condition diagrams. Addition traffic data may include traffic volumes, operating speeds, conflict studies, and evaluations of sight distances.

2.3 Summary

The previous sections describe both proactive and reactive safety analyses. Information about reactive analyses is most immediately applicable to this study. Section 2.2.1 demonstrates the strengths and weaknesses of the different evaluation metrics. According to this section, it would be beneficial for evaluations of crash data to account for the amount of crashes, the severity of crashes, the volume of an intersection, and expected crash values. Also, Section 2.2.2 shows that use of multiple evaluation metrics can minimize negative effects from individual metrics.

Due to complexity and time requirements, the SPF and EB methods are beyond the scope of this project. The crash severity and severity-rate metrics are also beyond the scope of this project due to the need to assign EPDO values. The following chapter will describe the creation of an evaluation method that takes into account all necessary information without becoming time-consuming or complex. This method will also include the additional intersection information recommended in Section 2.2.3.

3.0 RESEARCH METHODOLOGY

This chapter describes the research methodology used in this project. This methodology includes preliminary crash analyses at sample locations, a compilation of a comprehensive list of Oregon's IHSSIs, formation of average expected crash type percentages and companion crash rates, sample intersection data collection, and creation of a safety evaluation template.

3.1 Preliminary Safety Evaluations

The author performed preliminary crash analyses at sample intersections both to gain a basic understanding of typical conditions and crash experience and to demonstrate the types of readily available data that can be applied while investigating these intersections. The author identified candidate case study locations using ODOT's online digital video logs. The evaluations described in this thesis are reactive evaluations because intersections have already been identified for analysis.

The preliminary evaluations include information from ODOT's digital video logs, aerial photographs from the internet, and crash history information. In order to evaluate historic safety conditions, the research team developed a graphic summary for candidate locations. The summaries indicate basic known site characteristics, unknown site characteristics (to be collected in the field), traffic control devices, aerial photographs, and basic crash statistics. These graphics provide an initial demonstration of typical site and crash information. Figure 1 and Figure 2 demonstrate a sample historic safety evaluation of the intersection of Cooley Road and US 97 in Deschutes County, Oregon. This intersection will be used as an example case study throughout this report.

The data that were available during the preliminary analyses include current advisory signs and safety techniques, AADT on state highway approaches, number of lanes, presence of turning lanes, posted speed limits, approximate distance from previous signalized intersections, presence of horizontal curves, type and location of traffic signals, crash history, and other basic geometric characteristics. Data that were not available and required a site visit to collect include turning volumes, volumes on minor approaches, operating speeds, road surface information, vertical grade, available stopping sight distance, and signal phasing.

Intersection of Cooley Rd and US 97; Deschutes County, OR

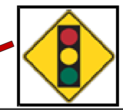
Basic site characteristics:

- Posted speed of 45 mph
- 2 lanes of traffic in each direction N/S
  1 lane each direction E/W
- Exclusive left turn lanes
- Skew intersection (65 degrees)
- No sight distance restrictions
- Signalized intersection ½ mile to the south
  No signalized intersections to the north
- Signal Ahead sign for southbound traffic

Signalized intersection located ½ mile south

Unknown site characteristics:

- Signal phasing
- Actual travel speeds
- Turning Volumes



SAS located 720 ft before stop bar

Traffic signal has good visibility from both directions

TITLE	DATE	PREPARED BY
Cooley Rd and US 97 Intersection	11/2009	OSU Research Team
DESCRIPTION	FILE	
Site Characteristics		VISIODOCUMENT

Oregon State University

Figure 1: Example Case Study Cooley and US 97 (Site Information)

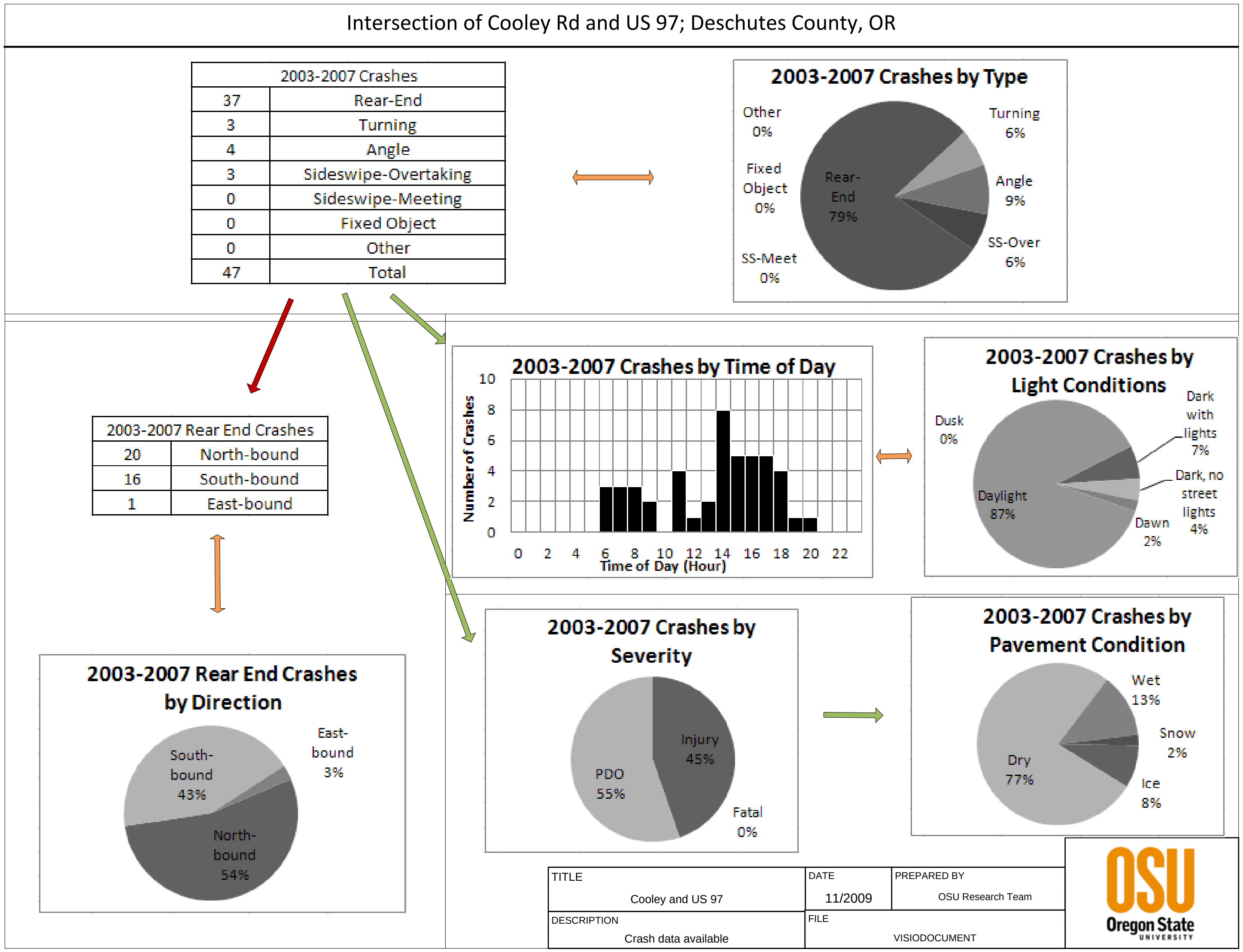


Figure 2: Example Case Study Cooley and US 97 (Crash Data)

3.2 Intersection Identification

In order to study Oregon's IHSSIs, the research team needed a comprehensive list of these intersections. Because ODOT currently does not maintain a data resource that can be used to directly identify IHSSIs, the author used the ODOT digital video logs to identify signalized intersections along state highways. After evaluating every signalized approach in the video log based on speed limits and distances from previous signalized intersections, the author compiled a comprehensive list of IHSSIs and sorted this list into categories of four-leg approach intersections (4-leg); T-intersections with the high-speed, isolated approach on the through road (T-thru); T-intersections where the high-speed, isolated approach ends (T-end); and other configurations (Other). Table 1 displays the number of approaches identified within each category. This table also contains the number of intersections associated with these approaches because some intersections have multiple isolated, high-speed approaches (note that one intersection falls under both the T-thru and T-end categories, resulting in a total number of intersections different than the sum of the individual categories).

Table 1: Oregon Isolated, High-Speed, Signalized Intersections by Type

Intersection Type	Number of High-Speed Approaches	Number of Intersections
4-leg	75	60
T-thru	18	16
T-end	5	5
Other	9	8
Total	107	88

The four-leg intersections account for approximately 70-percent of Oregon's IHSSIs. Due to this majority, the research team focused its efforts on these four-leg intersections.

Table 2 presents an example of data identified for the four-leg intersections. This table lists the "safety technology" associated with the sites as None (no advanced warning at all), SAS (Signal Ahead Sign), or CFSSA (Continuous Flashing Symbolic Signal Ahead). More information about the SAS and CFSSA is available in Appendix A. The research team further sorted the identified IHSSIs based on the speed limit at the intersection. Speed limit categories include 55 mph, 50 mph, 45 mph, and 45 mph sites with approaching speed limits of 55 mph upstream of the intersection. Because AADT values from minor approaches are not readily available, the included AADT values represent an averaged AADT value of the major approach from either side of the intersection corresponding to 2007 data. In situations where two major highways intersect, the highway with higher volumes determines the AADT. Table 2 also lists the number of standard lanes per direction for the major approach (one lane, two lanes, or a change from one to two lanes).

Table 2: Site Characteristics Summary for 45 mph IHSSIs

County	State Highway Number	Route Number	Cross Road	AADT (Major Road Approach)	Safety Technology[1]	Speed Limit	Change in Speed Limit	Standard Number of Lanes per Direction
Speed Limit 45mph								
Umatilla	54	US 395	Punkin Center	13600	SAS	45	--	1
Benton	33	US 20	53rd	15200	SAS	45	--	1
Benton	33	US 20	SW 15th	19750	SAS	45	--	1
Lincoln	9	US 101	Devils Lake	16600	CFSSA	45	--	1
Tillamook	9	US 101	Wilson River Loop	13800	None	45	--	2
Lane	15	OR 126	69th	13500	None	45	--	2
Deschutes	7	US 20	27th	16750	None	45	--	2
Jackson	63	OR 99	South Stage Rd	15950	None	45	--	2
Multnomah	123	US 30BY	NE 60th	21550	None	45	--	2
Josephine	25	US 199	Dowell	19750	None	45	--	2
Linn	58	OR 99E	Off-ramp (milepoint 7.9)	8250	SAS	45	--	2
Jackson	272	OR 238	Sage	13500	SAS	45	--	2
Curry	9	US 101	Zimmerman	15650	SAS	45	--	2
Clatsop	9	US 101	Pacific Way	16400	SAS	45	--	2
Deschutes[2]	4	US 97	Cooley	31800	SAS	45	--	2
Yamhill	39	OR 18	Norton	14450	CFSSA	45	--	2

[1] SAS = Signal Ahead Sign; CFSSA = Continuous Flashing Symbolic Signal Ahead
[2] Shaded row represents example case study location highlighted in this report

3.3 Determining Crash Trends

The compiled intersection list allowed for an evaluation of IHSSI crash trends using the previously discussed hotspot identification methods. The author obtained 5 years of crash data for the years 2003 through 2007 for all of the 4-leg IHSSIs. Appendix B includes distance calculations for determining which crashes were considered related to a specific intersection. Table 3 provides a summary of these boundary distances based on the speed limit at the intersection. As an example, the intersection of Cooley Road and

US 97 is a 45 mph intersection located at milepoint 134.11. When collecting crash data for this intersection, the research team collected data coded as US 97 crashes between milepoints 134.03 and 134.19 (or 134.11 ± 0.08).

Table 3: Crash Distances Considered Intersection-Related

Speed Limit	Distance Considered
45 mph	.08 miles
50 mph	.09 miles
55 mph	.10 miles

The author also briefly evaluated each intersection to determine whether or not it was suitable for inclusion in later average crash frequency calculations. The final list of intersections does not include recently installed intersections, as determined by comparing satellite imagery to the digital video logs, because representative crash data is not yet available for these sites. The final list also excludes intersections with crash data that is incomprehensible or inconsistently coded. These problems and other issues resulted in the removal of 16 of the original 60 4-leg intersections. Appendix B contains a comprehensive list of the included intersections.

The author used the crash data to determine crash trends based on intersection characteristics. In order to be able to specifically target unusual crash trends at an intersection, it is necessary to determine crash trends based on crash type rather than total number of crashes. As discussed in the literature review, there are many different metrics available for evaluating crash trends. The author chose to utilize the rate quality control metric and a basic percentage breakdown of crash type. The rate quality control allows for an expected value comparison of crash types based on volume. Because comparing intersections of vastly different volumes can be misleading using crash rates, crash percentages are also used to allow for a similar comparison without the effects of volume. Metrics involving severity and total number of crashes are not specifically calculated but will be accounted for in the collision diagram discussed in Section 3.5. Calculating SPFs is beyond the scope of this project and would not be practical for the small sample sizes this project investigates.

The calculated average crash percentages and average crash rates are sorted into categories based on associated speed limits and number of lanes. As shown in Equation 2 and Equation 3, *crash percentages* relate the number of crashes of one type of collision to the total number of crashes while *crash rates* relate the number of crashes of one type of collision to the AADT. Equation 3 includes multiplication by a constant in order to avoid extremely small values and to make the numbers more functional.

Equation 2: Crash Percentage Calculation

Crash Percentage = (Number of one type of crash) / (Number of total crashes)

Equation 3: Crash Rate Calculation

Crash Rate = (Number of one type of crash in a 5 year period) x (10,000) / (AADT)

The author calculated the crash percentages and crash rates for each intersection and then averaged them to obtain expected crash trends. These trends, which will be presented in Section 4.1, allow for a comparison between an individual intersection and average expected values for similar intersections. Because many of the sample sizes are small and this procedure is intended to be fast and functional, the crash trends do not require tests of statistical significance. Instead, these values provide basic guidance and a simple method for detecting unusual crash trends.

Table 4 demonstrates a sample of raw crash statistics by collision type for 45 mph IHSSIs. Appendix B contains crash statistics for all intersections. Table 5 shows calculated values for the intersection of Cooley Road and US 97 (AADT = 31,800).

Table 4: Number of Collisions by Type for 45mph IHSSIs

Route Number	Cross Road	Number of Collisions												
		Rear-End	Turning	Angle	Sideswipe-Overtaking	Non-Collision	Other	Sideswipe-Meeting	Fixed Object	Backing	Pedestrian	Head-On	Parking	Total
US 395	Punkin Center	4	4	4	2	0	0	0	0	0	0	0	0	14
US 20	53rd	25	8	1	0	0	0	1	1	1	0	0	0	37
US 20	SW 15th	14	5	2	2	0	1	0	0	0	0	0	0	24
US 101	Devils Lake	13	3	0	0	0	0	0	1	0	0	0	0	17
US 101	Wilson River Lp	6	15	3	3	0	0	1	0	0	2	0	0	30
OR 126	69th	8	8	1	1	0	0	0	0	0	1	0	0	19
US 20	27th	10	8	0	0	0	0	0	1	1	0	0	0	20
OR 99	South Stage Rd	12	4	2	1	0	0	0	0	0	0	0	0	19
US 30BY	NE 60th	9	7	4	3	0	0	0	1	0	1	0	0	25
US 199	Dowell	9	5	8	0	0	0	0	1	0	0	1	0	24
OR 99E	Off-ramp	2	3	1	0	1	0	0	0	0	0	0	0	7
OR 238	Sage	10	2	4	0	0	0	0	0	1	0	0	0	17
US 101	Zimmerman	2	4	1	0	0	0	0	0	0	0	0	0	7
US 101	Pacific Way	5	6	1	0	0	0	0	0	0	0	0	0	12
US 97 [1]	Cooley	37	3	4	3	0	0	0	0	0	0	0	0	47
OR 18	Norton	13	3	1	0	0	0	1	2	0	0	0	0	20

[1] Shaded row represents example case study location highlighted in this report

Table 5: Sample Crash Data Calculations for Cooley and US 97

Cooley Road and US 97	Rear-End	Turning	Angle	Sideswipe-Overtaking	Sideswipe-Meeting	Fixed Object	Other	Total
Number of Crashes	37	3	4	3	0	0	0	47
Crash Percentages (%)	78.7	6.4	8.5	6.4	0.0	0.0	0.0	100.0
Crash Rates	11.6	0.9	1.3	0.9	0.0	0.0	0.0	14.8

The author also investigated the types of vehicles involved in these collisions. According to ODOT’s 2007 automatic traffic recorder data, heavy vehicles (including trucks, buses, farm equipment, and any other large vehicles) account for an average of more than seven-percent of the volume on highways with IHSSIs. The pie chart in Figure 3 indicates the division of vehicle types involved in collisions for all IHSSIs used in the determination of crash percentages and rates. As shown by the chart, passenger cars are involved in the vast majority of crashes. Despite being cited as a specific safety concern in much of the literature, heavy vehicles represent less than three-percent of the total vehicles involved in the reported crashes.

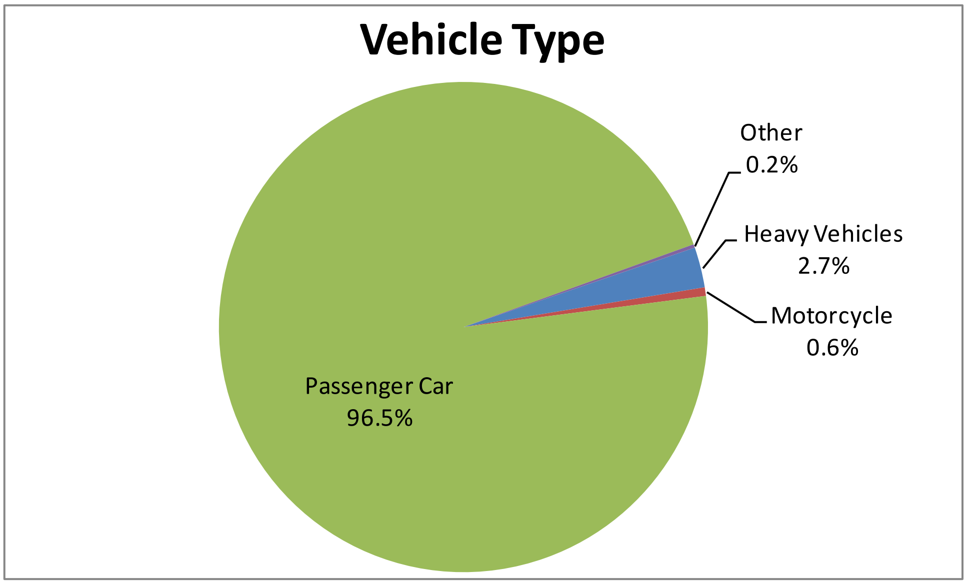


Figure 3: Percentage of Vehicle Types Involved in Collisions

3.4 Data Collection

In order to establish general IHSSI evaluation techniques, the research team first collected data for eight IHSSIs. The research project's Technical Advisory Committee (TAC) recommended these eight intersections based on input from signal timers across Oregon's five regions. Table 6 displays these eight intersections and their general characteristics.

Table 6: General Characteristics of Intersections Selected for Further Investigation

Region	County	State Highway Number	Route Number	Cross Road	AADT	Safety Technology	Speed Limit	Change in Speed Limit	Standard # of Lanes / Direction	# of Isolated, High-Speed Approaches
4	Deschutes [1]	4	US 97	Cooley	35,900	SAS	45	--	2	1
1	Clackamas	26	US 26	J Jarl/Orient	28,800	SAS	55	--	2	1
5	Malheur	455	OR 201	SW 18th/Butler	6,800	CFSSA	55	--	2	2
2	Lane	69	OR 569	Roosevelt	23,100	SAS	55	45-55	2	2
1	Columbia	92	US 30	Deer Island/ Liberty Hill	15,300	SAS	50	--	2	1
2	Benton	91	OR 99W	Circle	18,200	SAS	50	--	2	1
2	Benton	91	OR 99W	Conifer	16,000	CFSSA	50	--	2	1
1	Clackamas	81	OR 99E	Barlow	11,000	CFSSA	55	--	2	2

[1] Shaded row represents example case study location highlighted in this report

The research team conducted site visits for each of the intersections shown in Table 6 and collected data that was not available via satellite imagery or the digital video logs. Information collected during the site visits included volumes (turning volumes and minor road volumes), operating speeds, road surface conditions, vertical grades (if necessary), available sight distance, and basic signal phasing data. Lane width data was not collected. Median data was also not collected because none of the intersections included in the average crash rate and crash percentage calculations had medians on the approaches. Appendix C contains sample data collection sheets. The research team performed all data collection during the early afternoon hours of clear weather weekdays.

The research team collected volumes on all approaches for 30 minutes to provide a representation of intersection operations. Collection of an accurate AADT value for the minor approaches was not practical, but the collected volume data provides an indication of AADT magnitude. The research team collected speed data using a Speed Laser for

300 vehicles on each isolated, high-speed approach. Appendix B contains a relationship for determining appropriate speed data sample size.

Because this project is primarily concerned with free-flow conditions, speed data includes values for every isolated vehicle, the first vehicle in every platoon, and every fifth vehicle in a platoon. The speed data also includes a description of the total platoon length. The researchers determined the presence of platoons as vehicle headways of approximately five seconds or less. The final speed datasets do not include vehicles that turned onto or off of the major road prior to the intersection of interest. Signal timing data for at least three full cycles of a traffic signal, collected using a stopwatch, provide basic signal phasing information. Photographs of each site demonstrate signal placement and other relevant intersection characteristics. Researchers obtained basic intersection distances and locations of signs using a distance wheel.

The author used the collected data and the previously obtained crash information to evaluate these intersections and determine potential safety treatments. Section 4.4.2 presents a sample evaluation.

3.5 Creating a Safety Evaluation Template for Future Intersection Diagnosis

Based on the systematic analysis of the study intersections, the author developed an evaluation template to aid in future safety evaluations of Oregon's IHSSIs. This template provides a logical reporting format to facilitate fast and effective evaluation of intersections. The template includes all easily obtained information that the author found useful while evaluating the sample intersections.

As shown in Section 4.3, the template includes space for basic site characteristics, speed data, volume data, and crash statistics. The template also includes the previously determined expected crash rates and crash percentages. Rather than include a condition diagram, the template contains a space for an aerial photograph of the intersection because much of the information recommended for condition diagrams is less applicable for isolated, high-speed intersections. Additionally, the template provides a space for a photograph or diagram depicting the visibility, arrangement, and number of signal heads. The third page of the template contains space for a collision diagram and feedback from users familiar with the intersection. The collision diagram depicts each crash within the past five years using arrows to indicate the direction, though not necessarily location, of vehicles. The intersection of two arrows represents a crash. To aid in determining contributing factors of crashes, the vehicle listed as at-fault can be indicated using a red arrow while other vehicles are indicated using a black arrow. As a minimum, each collision can include details about crash severity, pavement conditions, light conditions, and time of day. This collision diagram visually indicates information about severity, total number of crashes, and at-fault vehicles that are not generally included with the other crash statistics. The space for feedback from users familiar with the intersection complements the collision diagram by providing more information about possible contributing factors to crashes because individuals that regularly travel through an intersection have firsthand knowledge about the intersection and may have useful suggestions for improvements. Including crash rates, crash percentages, severity information, and total number of crashes mitigates the limitations of each individual measure.

This template does not contain information about signal timing and clearance intervals because that information should be more accurately available through signal timing plans. Users can compare these plans to ODOT’s signal policy guidelines. For the purposes of evaluating the eight studied intersections without the benefit of signal timing plans, Appendix C contains information on basic signal phasing and clearance intervals.

To aid in determining possible safety improvements, the final page of the template presents treatment options based on a prior literature review. The list of treatment options provides potential safety treatments for IHSSIs and is divided into categories to target specific crash types.

Section 4.4.2 will describe and demonstrate the use of this template for evaluating safety at IHSSIs. Also, Appendix C contains two additional case studies to demonstrate use of the template.

4.0 SUMMARY OF FINDINGS

This chapter summarizes the results obtained through the previously described research methodology.

4.1 Average Crash Rates and Crash Percentages

Table 7 and Table 8 display the average crash percentages and average crash rates for Oregon's four-leg IHSSIs as discussed in Section 3.3. In Table 7, the columns on the left depict expected average crash percentages separated by both speed limit and number of lanes. The indication '1→2' represents a change in the number of standard lanes from one to two in close proximity to the intersection (using the same distance thresholds used for the crash data). The columns on the right in Table 7 depict average crash percentages sorted only by speed limit, with the bottom row representing an average for all intersections. The column labeled "Number of Intersections" displays the number of intersections available to create the averages. For example, the average values for two-lane, 45 mph intersections are based on data from 12 candidate intersections. Table 8 follows the same format while displaying average crash rates.

Table 7: Average Crash Percentages for Oregon's Four-Leg IHSSIs

		Average Crash Percentages																	
Speed Limit (mph)	Number of Lanes	Rear-End	Turning	Angle	Sideswipe-Overtaking	Sideswipe-Meeting	Fixed Object	Other	Total	Number of Intersections	Rear-End	Turning	Angle	Sideswipe-Overtaking	Sideswipe-Meeting	Fixed Object	Other	Total	Number of Intersections
45	1	58	22	9.9	5.7	0.7	2.1	1.7	100	4	49	30	12	3.8	0.7	2.0	3.3	100	16
	2	46	32	12	3.2	0.7	1.9	3.8	100	12									
55 to 45	1	53	11	16	16	0.0	5.3	0.0	100	1	50	21	14	5.6	1.3	3.3	4.2	100	9
	2	47	25	17	2.9	1.2	3.3	4.0	100	6									
	1→2	58	15	7	8.9	2.2	2.2	6.7	100	2									
50	2	55	19	16	2.6	3.3	0.0	4.3	100	5	55	19	16	2.6	3.3	0.0	4.3	100	5
55	1	50	26	10	1.3	3.3	4.4	4.1	100	5	41	24	12	8.5	1.9	6.4	5.7	100	15
	2	37	23	13	12	1.1	7.4	6.4	100	10									
Overall											47	25	13	5.7	1.4	3.4	4.5	100	44

Table 8: Average Crash Rates for Oregon’s Four-Leg IHSSIs

Average Crash Rates (# Crashes in 5 year period x 10,000/AADT)																			
Speed Limit (mph)	**Number of Lanes**	**Rear-End**	**Turning**	**Angle**	**Sideswipe-Overtaking**	**Sideswipe-Meeting**	**Fixed Object**	**Other**	**Total**	**Number of Intersections**	**Rear-End**	**Turning**	**Angle**	**Sideswipe-Overtaking**	**Sideswipe-Meeting**	**Fixed Object**	**Other**	**Total**	**Number of Intersections**
45	1	8.6	3.1	1.2	0.6	0.2	0.3	0.3	14	4	6.3	3.5	1.4	0.5	0.1	0.3	0.4	13	16
	2	5.6	3.7	1.5	0.5	0.1	0.2	0.5	12	12									
55 to 45	1	11	2.2	3.3	3.3	0.0	1.1	0.0	21	1	5.4	2.1	1.3	0.7	0.2	0.5	0.3	11	9
	2	4.5	2.1	1.1	0.2	0.2	0.4	0.3	8.8	6									
	1→2	5.5	2.1	1.1	1.0	0.4	0.4	0.6	11	2									
50	2	6.7	2.6	2.2	0.5	0.3	0.0	0.5	13	5	6.7	2.6	2.2	0.5	0.3	0.0	0.5	13	5
55	1	5.3	2.7	0.9	0.2	0.2	0.6	0.4	10	5	4.2	2.2	1.3	0.6	0.1	0.6	0.4	9.4	15
	2	3.7	1.9	1.5	0.8	0.1	0.5	0.4	8.9	10									
Overall											5.4	2.7	1.4	0.6	0.1	0.4	0.4	11	44

The average crash percentages and average crash rates highlight a number of trends and many of the values are similar across different categories of intersections. The tables allow users to pinpoint expected values for a specific intersection configuration. However, when using these tables it is important to look at multiple rows because the average values for some configurations only represent a small number of intersections. Values for the same number of lanes and different speed limits, values averaged across multiple lane configurations for a given speed limit, and values for overall averages can also provide useful comparisons.

The safety evaluation template shown in Section 4.3 also provides these average crash percentages and average crash rates. Use of these values will be demonstrated through an example in Section 4.4.2.

4.2 Hierarchy of Treatment Strategies

Table 9 shows a list of treatment options for IHSSIs (*Caltrans, 2002; Ohio Governor's Task Force on Safety, 2009; New York State Department of Transportation, 2000; and FHWA, 1981*). Separate crash type categories allow users to quickly target a specific unusual crash trend. The categories include rear-end, angle, fixed object, turning, sideswipe, wet pavement, and nighttime crashes. The safety evaluation template shown in Section 4.3 incorporates this list.

Table 9: Potential Countermeasures for IHSSIs

Rear End	**Angle**	**Fixed Object**
▪ Create turn lanes	▪ Remove sight obstructions	▪ Remove/relocate obstacles
▪ Install advanced warning devices	▪ Install advanced warning devices	▪ Install barrier curbing
▪ Remove sight obstructions	▪ Install 12 inch signal lenses	▪ Install breakaway features
▪ Install 12 inch signal lenses	▪ Install visors	▪ Reduce number of utility poles
▪ Install visors	▪ Install/enhance backplates	▪ Relocate islands
▪ Install/enhance backplates	▪ Improve location/number of signal heads (e.g. near-side)	▪ Widen lanes
▪ Improve location/number of signal heads (e.g. near-side)	▪ Reduce speeds - traffic calming or lower speed limit (after study)	▪ Install/improve pavement markings (include edgeline delineation)
▪ Adjust/extend amber/all-red	▪ Adjust/extend amber/all-red	▪ Install edgeline rumble strips
▪ Provide progression (if not isolated approach)	▪ Adjust signal timing	▪ Protect objects with guardrail or attenuation device
▪ Adjust signal timing	▪ Provide progression (if not isolated approach)	▪ Re-align intersection
▪ Improve skid resistance	▪ Improve skid resistance	▪ Check vertical alignment
▪ Reduce speeds - traffic calming or lower speed limit (after study)	▪ Channelize intersection	▪ Upgrade roadway shoulders
▪ Lengthen mast arms	▪ Check equipment for malfunction	▪ Improve channelization
▪ Install additional loops	▪ Install transverse pavement markings	▪ Close curb lanes
▪ Check equipment for malfunction	▪ Install extension of green time systems (Advance Detection Control Systems)	▪ Install advanced warning devices
▪ Install transverse pavement markings		▪ Reduce speeds - traffic calming or lower speed limit (after study)
▪ Install extension of green time systems (Advance Detection Control Systems)		
▪ Remove signal (see MUTCD)		

Source: Caltrans (2002), Ohio Governor's Task Force on Safety (2009), New York State Department of Transportation (2000), and FHWA (1981)

Table 9: Potential Countermeasures for IHSSIs (Continued)

<u>Turning</u>	**<u>Sideswipe</u>**	**<u>Wet Pavement Treatments</u>**
General treatments	*General treatments*	▪ Overlay/groove existing pavement
▪ Remove sight obstructions	▪ Install/improve pavement markings	▪ Reduce speeds - traffic calming or lower speed limit (after study)
▪ Adjust signal timing	▪ Channelize intersection	▪ Provide "slippery when wet" signs
▪Adjust/extend amber/all-red		▪ Improve skid resistance
▪ Reduce speeds - traffic calming or lower speed limit (after study)	*Overtaking Sideswipe*	▪ Provide adequate drainage
	▪ Provide turning bays	▪ Upgrade pavement markings
If turning vehicle at fault	▪ Install acceleration/ deceleration lanes	▪ Install chip seal
▪ Add protected phase (remove permitted phase)	▪ Install/improve directional signing	▪ Install open graded asphalt concrete
▪ Increase/add turn lane	▪ Restrict driveway access near intersection	**<u>Night Accident Treatments</u>**
▪ Provide channelization	▪ Reduce speeds - traffic calming or lower speed limit (after study)	▪ Install/improve street lighting
▪ Increase curb radii		▪ Install/improve pavement markings
		▪ Install/improve warning signs
If through vehicle at fault refer to <u>Angle</u> treatments	*Meeting Sideswipe*	▪ Upgrade signing
	▪ Install median divider/barrier	▪ Provide illuminated signs
	▪ Widen lanes	▪ Install pavement markings
	▪ Install no passing zone signage	▪ Provide raised markers
		▪ Upgrade advance warning signs

Source: Caltrans (2002), Ohio Governor's Task Force on Safety (2009), New York State Department of Transportation (2000), and FHWA (1981)

4.3 Safety Evaluation Template

The following pages show the safety evaluation template discussed in Section 3.5. The template provides basic instructions for use by indicating the information that corresponds to each area. Section 4.4 provides more detailed instructions for completing and interpreting the template. For further guidance, Appendix C contains completed templates for two additional example intersections.

Intersection of ________ and ________ , _______ County (Page 1)

	Northbound	Southbound	Eastbound	Westbound
Speed Limit				
Isolated Major Approach (>1mile Isolation)				
Advanced Intersection Warning*				
Other				

*SAS = Signal Ahead Sign
CFSSA = Continuous Flashing Symbolic Signal Ahead
PTSWF = Prepare to Stop when Flashing

Aerial photograph or diagram indicating intersection geometry and lane configurations

Figure 4: Safety Evaluation Template (Page 1)

Intersection of ________ and ________ , ________ County (Page 2)

Picture showing typical arrangement and number of signal heads

Graphs of speed data for high-speed approaches

		Volumes between ______ and ______ on __/__/__ Su M T W R F Sa		
Direction	AADT	% left turns	% right turns	% total turns

Other notes:

Figure 5: Safety Evaluation Template (Page 2)

Intersection of ________ and ________ , _______ County (Page 3)

Collision Diagram showing five years of crash data. Include severity, pavement conditions, time of day, and light conditions. Indicate vehicle at fault with red arrow. Include description of symbols/abbreviations.

Feedback from users familiar with intersection:

Figure 6: Safety Evaluation Template (Page 3)

4-leg, Signalized Oregon Intersections with at Least One High-Speed, Isolated Approach

Average Crash Percentages

speed limit (mph)	# Lanes	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged
45	1	58	22	9.9	5.7	0.7	2.1	1.7	100	4	49	30	12	3.8	0.7	2.0	3.3	100	16
	2	46	32	12	3.2	0.7	1.9	3.8	100	12									
55 to 45	1	53	11	16	16	0.0	5.3	0.0	100	1	50	21	14	5.6	1.3	3.3	4.2	100	9
	2	47	25	17	2.9	1.2	3.3	4.0	100	6									
	1→2	58	15	6.5	8.9	2.2	2.2	6.7	100	2									
50	2	55	19	16	2.6	3.3	0.0	4.3	100	5	55	19	16	2.6	3.3	0.0	4.3	100	5
55	1	50	26	10	1.3	3.3	4.4	4.1	100	5	41	24	12	8.5	1.9	6.4	5.7	100	15
	2	37	23	13	12	1.1	7.4	6.4	100	10									
										OVERALL	47	25	13	5.7	1.4	3.4	4.5	100	44

Fill in data for specific intersection. Circle applicable averages listed above.

Crash % = (# of one type of crash) / (# total crashes)

Average Crash Rates (#Crashes in 5 year period x 10000 / AADT)

speed limit (mph)	# Lanes	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged
45	1	8.6	3.1	1.2	0.6	0.2	0.3	0.3	14	4	6.3	3.5	1.4	0.5	0.1	0.3	0.4	13	16
	2	5.6	3.7	1.5	0.5	0.1	0.2	0.5	12	12									
55 to 45	1	11	2.2	3.3	3.3	0.0	1.1	0.0	21	1	5.4	2.1	1.3	0.7	0.2	0.5	0.3	11	9
	2	4.5	2.1	1.1	0.2	0.2	0.4	0.3	8.8	6									
	1→2	5.5	2.1	1.1	1.0	0.4	0.4	0.6	11	2									
50	2	6.7	2.6	2.2	0.5	0.3	0.0	0.5	13	5	6.7	2.6	2.2	0.5	0.3	0.0	0.5	13	5
55	1	5.3	2.7	0.9	0.2	0.2	0.6	0.4	10	5	4.2	2.2	1.3	0.6	0.1	0.6	0.4	9.4	15
	2	3.7	1.9	1.5	0.8	0.1	0.5	0.4	8.9	10									
										OVERALL	5.4	2.7	1.4	0.6	0.1	0.4	0.4	11	44

Fill in data for specific intersection. Circle applicable averages listed above.

Crash rate = (#crashes in 5yr period)x(10,000)/(AADT)

Comments:

Figure 7: Safety Evaluation Template (Page 4)

Potential Countermeasures for Isolated, High-Speed, Signalized Intersections

Rear End

- Create turn lanes
- Install advanced warning devices
- Remove sight obstructions
- Install 12 inch signal lenses
- Install visors
- Install/enhance backplates
- Improve location/number of signal heads (e.g. near-side)
- Adjust/extend amber/all-red
- Provide progression (if not isolated approach)
- Adjust signal timing
- Improve skid resistance
- Reduce speeds - traffic calming or lower speed limit (after study)
- Lengthen mast arms
- Install additional loops
- Check equipment for malfunction
- Install transverse pavement markings
- Install extension of green time systems (Advance Detection Control Systems)
- Remove signal (see MUTCD)

Turning

General treatments

- Remove sight obstructions
- Adjust signal timing
- Adjust/extend amber/all-red
- Reduce speeds - traffic calming or lower speed limit (after study)

If turning vehicle at fault

- Add protected phase (remove permitted phase)
- Increase/add turn lane
- Provide channelization
- Increase curb radii

If through vehicle at fault refer to Angle treatments

Angle

- Remove sight obstructions
- Install advanced warning devices
- Install 12 inch signal lenses
- Install visors
- Install/enhance backplates
- Improve location/number of signal heads (e.g. near-side)
- Reduce speeds - traffic calming or lower speed limit (after study)
- Adjust/extend amber/all-red
- Adjust signal timing
- Provide progression (if not isolated approach)
- Improve skid resistance
- Channelize intersection
- Check equipment for malfunction
- Install transverse pavement markings
- Install extension of green time systems (Advance Detection Control Systems)

Sideswipe

General treatments

- Install/improve pavement markings
- Channelize intersection

Overtaking Sideswipe

- Provide turning bays
- Install acceleration/ deceleration lanes
- Install/improve directional signing
- Restrict driveway access near intersection
- Reduce speeds - traffic calming or lower speed limit (after study)

Meeting Sideswipe

- Install median divider/barrier
- Widen lanes
- Install no passing zone signage

Fixed Object

- Remove/relocate obstacles
- Install barrier curbing
- Install breakaway features
- Reduce number of utility poles
- Relocate islands
- Widen lanes
- Install/improve pavement markings (include edgeline delineation)
- Install edgeline rumble strips
- Protect objects with guardrail or attenuation device
- Re-align intersection
- Check vertical alignment
- Upgrade roadway shoulders
- Improve channelization
- Close curb lanes
- Install advanced warning devices
- Reduce speeds - traffic calming or lower speed limit (after study)

Wet Pavement Treatments

- Overlay/groove existing pavement
- Reduce speeds - traffic calming or lower speed limit (after study)
- Provide "slippery when wet" signs
- Improve skid resistance
- Provide adequate drainage
- Upgrade pavement markings
- Install chip seal
- Install open graded asphalt concrete

Night Accident Treatments

- Install/improve street lighting
- Install/improve pavement markings
- Install/improve warning signs
- Upgrade signing
- Provide illuminated signs
- Install pavement markings
- Provide raised markers
- Upgrade advance warning signs

Figure 8: Safety Evaluation Template (Page 5)

4.4 Providing Safety Treatment Recommendations

The following sections provide specific guidance for using the evaluation template to establish safety treatment recommendations. Section 4.4.1 will provide general instructions and Section 4.4.2 will demonstrate use of the template through an example case study. Appendix C contains an additional two example case studies for further guidance.

4.4.1 General Instructions

First, users can fill in the required information on the evaluation template and obtain signal phasing information. Each section of the template provides basic guidance for required information. Minor data collection may be necessary for operating speeds and turning volumes. The user can decide the amount of necessary data collection, but an hour of speed data and 30 minutes of volume data can provide a reasonable approximation of intersection operations. These requirements are dependent upon intersection operations and would likely change if, for example, a user wishes to differentiate between peak hour and other traffic conditions. The sample case studies in this thesis indicate an average value of speed data, but an 85^{th} percentile value or other metric can also be utilized. The collision diagram can either be created manually or through a software program and the crash percentages and rates can be calculated using the equations provided on the template. The collision diagram, crash percentages, and crash rates can be based on the five most recent years of crash data when possible. If a user chooses to use a crash history other than five years, the calculated crash rates can be adjusted using Equation 4 for comparison to the provided average crash rates. Crash histories shorter than five years may not accurately represent crash trends due to the random nature of crashes, but crash histories where substantial changes have occurred to an intersection or the crash reporting format during the analysis period may also be misleading. Also, note that AADT values represent the AADT of the major highway approaches (not a complete intersection volume) as discussed in Section 3.2.

Equation 4: Crash Rate Adjustment

$$\mathrm{Rate}_5 = \frac{5}{N}(\mathrm{Rate}_N)$$

Where

Rate_5 = Five year crash rate
N = Years of obtained crash history
Rate_N = N-year crash rate

After becoming familiar with the basic intersection characteristics and operating conditions using pages one and two of the evaluation template, the user can compare the intersection's crash percentages and crash rates to average values for similar intersections. As discussed in Section 4.1, multiple average values can provide useful information. The user should not expect an intersection's values to exactly match average values due to normal deviations. However, values that are considerably larger than average values can be further investigated using the collision diagram. The user can examine the collision diagram to determine which directions the at-fault vehicles are traveling and the conditions of the crashes. The user can document apparent trends such as crashes primarily caused by one approach, occurring at night, or occurring during wet conditions. Comparisons with average crash values and the collision diagram can be used in conjunction with one another. Crash values may appear average, but there may still be room for improvement if vehicles on the same approach caused all of the crashes. Alternatively, the collision diagram may appear to show an overrepresentation of crashes when actually that amount is average for a given intersection type.

After determining unusual crash trends, the list of potential countermeasures can suggest treatment recommendations. Though this template is primarily designed as a reactive tool, the user can also proactively search for apparent safety issues or intersection features that do not meet agency regulations. Users should exercise engineering judgment before recommending any treatment options.

4.4.2 Case Study: Cooley and US 97

This section uses an example case study to demonstrate use of the evaluation template for data collection and analysis. Figure 1 and Figure 2 (previously reviewed) depict the site investigation data and the historic crash information, respectively, for the Cooley Road at US 97 case study intersection. These figures are not required as part of the evaluation template, but they provide additional intersection information for readers who have not visited and studied the intersection firsthand. Figure 9 shows the completed template. The following sections will provide key observations and treatment recommendations for increasing safety as determined using Figure 9.

Intersection of Cooley and US 97 , Deschutes County (Page 1)

	Northbound	Southbound	Eastbound	Westbound
Speed Limit	45 mph	45 mph	35 mph	35 mph
Isolated Major Approach (>1mile Isolation)	No	Yes	No	No
Advanced Intersection Warning*	--	SAS	--	--
Other	--	--	--	--

*SAS = Signal Ahead Sign
CFSSA = Continuous Flashing Symbolic Signal Ahead
PTSWF = Prepare to Stop when Flashing

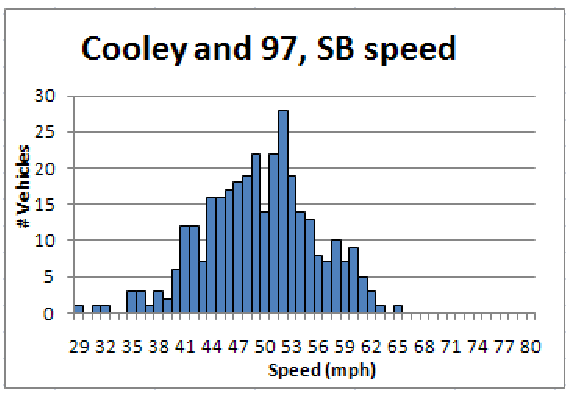
Aerial photograph or diagram indicating intersection geometry and lane configurations

Figure 9: Cooley and US 97, Safety Evaluation Template

Intersection of Cooley and US 97 , Deschutes County (Page 2)

Image shows southbound approach.

Picture showing typical arrangement and number of signal heads



Average southbound speed = 49.9 mph

Graphs of speed data for high-speed approaches

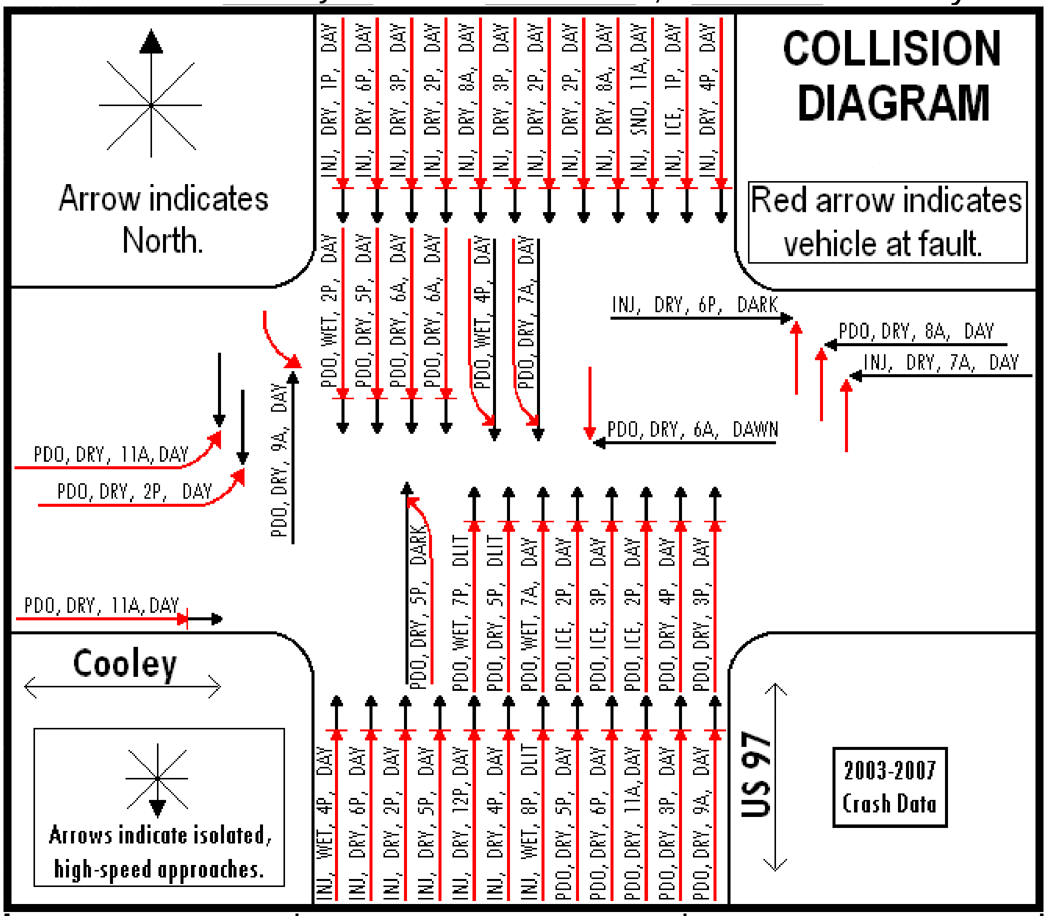
		Volumes between 2:05pm and 2:35pm on 9 /16/ 09 Su M T W R F Sa			
Direction	AADT	% left turns	% right turns	% total turns	Total # of Vehicles
Northbound	35,900	6.2	6.7	12.9	593
Southbound	27,700	5.0	4.5	9.5	462
Eastbound	unknown	53.3	15.0	68.3	107
Westbound	unknown	50.5	27.1	77.6	107

Other notes: Westbound traffic crosses railroad tracks ~270 ft before stop bar.

Eastbound and westbound traffic have two left turn lanes (one of which is a shared thru/left lane).

Figure 9: Cooley and US 97, Safety Evaluation Template (Continued)

Intersection of Cooley and US 97 , Deschutes County (Page 3)



Symbols	Collision Types	Abbreviations
Moving Vehicle	Rear-end	FAT = Fatality
Bicycle	Head-on	INJ = Injury
Fixed Object	Turning	PDO = Property Damage Only
Animal	Angle	DLIT = Dark with street lights
	Sideswipe-Overtaking	
	Sideswipe-Meeting	

Collision Diagram showing five years of crash data. Include severity, pavement conditions, time of day, and light conditions. Indicate vehicle at fault with red arrow. Include description of symbols/abbreviations.

Feedback from users familiar with intersection:

Figure 9: Cooley and US 97, Safety Evaluation Template (Continued)

4-leg, Signalized Oregon Intersections with at Least One High-Speed, Isolated Approach

Cooley and US 97

Average Crash Percentages

speed limit (mph)	# Lanes	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged
45	1	58	22	9.9	5.7	0.7	2.1	1.7	100	4	49	30	12	3.8	0.7	2.0	3.3	100	16
	2	46	32	12	3.2	0.7	1.9	3.8	100	12									
55 to 45	1	53	11	16	16	0.0	5.3	0.0	100	1	50	21	14	5.6	1.3	3.3	4.2	100	9
	2	47	25	17	2.9	1.2	3.3	4.0	100	6									
	1→2	58	15	6.5	8.9	2.2	2.2	6.7	100	2									
50	2	55	19	16	2.6	3.3	0.0	4.3	100	5	55	19	16	2.6	3.3	0.0	4.3	100	5
55	1	50	26	10	1.3	3.3	4.4	4.1	100	5	41	24	12	8.5	1.9	6.4	5.7	100	15
	2	37	23	13	12	1.1	7.4	6.4	100	10									
										OVERALL	47	25	13	5.7	1.4	3.4	4.5	100	44

Fill in data for specific intersection. Circle applicable averages listed above.

45	**2**	**79**	**6.4**	**8.5**	**6.4**	**0.0**	**0.0**	**0.0**	**100**

Crash % = (# of one type of crash) / (# total crashes)

Average Crash Rates (#Crashes in 5 year period x 10000 / AADT)

speed limit (mph)	# Lanes	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged
45	1	8.6	3.1	1.2	0.6	0.2	0.3	0.3	14	4	6.3	3.5	1.4	0.5	0.1	0.3	0.4	13	16
	2	5.6	3.7	1.5	0.5	0.1	0.2	0.5	12	12									
55 to 45	1	11	2.2	3.3	3.3	0.0	1.1	0.0	21	1	5.4	2.1	1.3	0.7	0.2	0.5	0.3	11	9
	2	4.5	2.1	1.1	0.2	0.2	0.4	0.3	8.8	6									
	1→2	5.5	2.1	1.1	1.0	0.4	0.4	0.6	11	2									
50	2	6.7	2.6	2.2	0.5	0.3	0.0	0.5	13	5	6.7	2.6	2.2	0.5	0.3	0.0	0.5	13	5
55	1	5.3	2.7	0.9	0.2	0.2	0.6	0.4	10	5	4.2	2.2	1.3	0.6	0.1	0.6	0.4	9.4	15
	2	3.7	1.9	1.5	0.8	0.1	0.5	0.4	8.9	10									
										OVERALL	5.4	2.7	1.4	0.6	0.1	0.4	0.4	11	44

Fill in data for specific intersection. Circle applicable averages listed above.

45	**2**	**12**	**0.9**	**1.3**	**0.9**	**0.0**	**0.0**	**0.0**	**15**

Crash rate = (#crashes in 5yr period)x(10,000)/(AADT)

Comments: **Rear-end crashes highly overrepresented.**

Overtaking sideswipe crashes are also slightly high.

Figure 9: Cooley and US 97, Safety Evaluation Template (Continued)

Potential Countermeasures for Isolated, High-Speed, Signalized Intersections

Rear End

- Create turn lanes
- Install advanced warning devices
- Remove sight obstructions
- Install 12 inch signal lenses
- Install visors
- Install/enhance backplates
- Improve location/number of signal heads (e.g. near-side)
- Adjust/extend amber/all-red
- Provide progression (if not isolated approach)
- Adjust signal timing
- Improve skid resistance
- Reduce speeds - traffic calming or lower speed limit (after study)
- Lengthen mast arms
- Install additional loops
- Check equipment for malfunction
- Install transverse pavement markings
- Install extension of green time systems (Advance Detection Control Systems)
- Remove signal (see MUTCD)

Turning

General treatments

- Remove sight obstructions
- Adjust signal timing
- Adjust/extend amber/all-red
- Reduce speeds - traffic calming or lower speed limit (after study)

If turning vehicle at fault

- Add protected phase (remove permitted phase)
- Increase/add turn lane
- Provide channelization
- Increase curb radii

If through vehicle at fault refer to Angle treatments

Angle

- Remove sight obstructions
- Install advanced warning devices
- Install 12 inch signal lenses
- Install visors
- Install/enhance backplates
- Improve location/number of signal heads (e.g. near-side)
- Reduce speeds - traffic calming or lower speed limit (after study)
- Adjust/extend amber/all-red
- Adjust signal timing
- Provide progression (if not isolated approach)
- Improve skid resistance
- Channelize intersection
- Check equipment for malfunction
- Install transverse pavement markings
- Install extension of green time systems (Advance Detection Control Systems)

Sideswipe

General treatments

- Install/improve pavement markings
- Channelize intersection

Overtaking Sideswipe

- Provide turning bays
- Install acceleration/ deceleration lanes
- Install/improve directional signing
- Restrict driveway access near intersection
- Reduce speeds - traffic calming or lower speed limit (after study)

Meeting Sideswipe

- Install median divider/barrier
- Widen lanes
- Install no passing zone signage

Fixed Object

- Remove/relocate obstacles
- Install barrier curbing
- Install breakaway features
- Reduce number of utility poles
- Relocate islands
- Widen lanes
- Install/improve pavement markings (include edgeline delineation)
- Install edgeline rumble strips
- Protect objects with guardrail or attenuation device
- Re-align intersection
- Check vertical alignment
- Upgrade roadway shoulders
- Improve channelization
- Close curb lanes
- Install advanced warning devices
- Reduce speeds - traffic calming or lower speed limit (after study)

Wet Pavement Treatments

- Overlay/groove existing pavement
- Reduce speeds - traffic calming or lower speed limit (after study)
- Provide "slippery when wet" signs
- Improve skid resistance
- Provide adequate drainage
- Upgrade pavement markings
- Install chip seal
- Install open graded asphalt concrete

Night Accident Treatments

- Install/improve street lighting
- Install/improve pavement markings
- Install/improve warning signs
- Upgrade signing
- Provide illuminated signs
- Install pavement markings
- Provide raised markers
- Upgrade advance warning signs

Figure 9: Cooley and US 97, Safety Evaluation Template (Continued)

4.4.2.1 Observations

As shown in Figure 9, a comparison of the crash rates and crash percentages for the Cooley Road at US 97 intersection to typical values shows that rear-end collisions are highly overrepresented. As shown in the collision diagram, these collisions are primarily occurring on the northbound and southbound approaches. The northbound approach has slightly more rear-end collisions than the isolated southbound approach. However, the southbound approach has more rear-end crashes involving injury. Values for overtaking-sideswipe collisions are also slightly above average.

Based on the speed data, a large percentage of the southbound traffic at this location is traveling above the posted speed limit of 45 mph (average speed = 49.9 mph). While collecting this speed data, the researchers also observed long queues extending to distances upstream of the existing SAS. It is likely that some drivers are not becoming aware of the need to stop before intersection queues with sufficient stopping distance.

4.4.2.2 Recommendations

Based on the previously described observations, treatments to reduce rear-end collisions have the greatest potential for increasing safety at this location. Though this evaluation method is primarily focused on isolated approaches, the northbound approach should also be considered due to the number of rear-end collisions on that approach. Near-side signal heads at the intersection may be beneficial for giving advance warning to drivers on both the northbound and southbound approaches. Signs or transverse pavement markings installed prior to the existing SAS may prove beneficial when long queues are present. Converting the SAS to a CFSSA by installing a beacon may draw more attention to the sign. Additionally, techniques to reduce speeds on the southbound approach may be advantageous for reducing the likelihood and severity of rear-end collisions. All of these treatments have promise for increasing safety, but an additional contributing factor for collisions at this intersection is likely the high volumes—an area for improvement outside the scope of these evaluations.

4.4.3 Case Study Summary

Table 10 summarizes the key findings and recommendations for the primary case study intersection and the two supplemental case studies included in Appendix C. The second column labeled "Unusual Crash Trends" provides a list of overrepresented collision types as compared to expected values. The third column describes possible contributing factors for these overrepresentations. The fourth and final column lists specific treatment recommendations to improve safety based on the crash trends and contributing factors.

The information in the table is based on the historic safety evaluations and completed templates for these intersections. The Barlow and OR 99E and Circle and 99W intersection forms are presented in Appendix C. These completed templates provide additional guidance for evaluating IHSSIs.

Table 10: Case Study Observations and Recommendations

Intersection	Unusual Crash Trends	Notes/Possible Contributing Factors	Recommendations
Cooley and US 97	Northbound and southbound rear-end collisions high	Long queues on southbound approach	Install signing or transverse pavement markings prior to SAS
			Add flashing beacon above SAS
			Near-side signal heads
		High speeds	Speed reduction techniques for southbound traffic
	Overtaking-sideswipes slightly overrepresented	High speeds	Rear-end recommendations are also applicable to sideswipes
Barlow and OR 99E	All crash rates appear high (except sideswipes), but percentages appear near average	High volumes on minor roads are not accounted for in crash rates and can make the rates appear high	Lighten backplate color to increase contrast for westbound approach
			Near-side signal heads
		Eastbound speeds are high	Speed reduction techniques
	Most collisions due to minor approaches	Likely errors in coding due to skew (It appears that crashes on minor approaches may have occurred on major approaches.)	
	Turning crashes are slightly overrepresented	Minor approach has no protected phase	Protected left-turn phase for minor approaches
	Fixed object collisions are overrepresented	Many objects near road	Relocate objects further from road
Circle and 99W	Crash rates all appear high	Possibly due to high volumes on minor road	
	At-fault westbound vehicles in angle collisions are overrepresented	All seven collisions are coded DLIT/DARK/DAWN (dark with lights, dark without lights, or dawn)	Improve lighting
	At-fault northbound vehicles in angle collisions are overrepresented	Intersection is very wide for both the major and minor approaches	Near-side signal heads (for major and minor approaches)
		No all-red phase	Add all-red phase
	At-fault northbound and southbound vehicles in turning collisions are overrepresented		Evaluate signal timing plan, consider extending green or amber phases

5.0 FUTURE RESEARCH

This thesis provides a tool for evaluating IHSSIs across Oregon. Use of the safety evaluation template can provide a convenient summary of initial conditions for a before-after study. After evaluating and implementing safety treatments at selected intersections, these locations can be reevaluated in the future and then compared to initial conditions. This study could be based on many intersections to evaluate the effectiveness of the template, or it could specifically target certain treatment options to evaluate the effectiveness of those treatments. Before-after studies are especially beneficial because external effects that may be present in case studies would be minimized while examining the same intersection.

This research specifically focuses on isolated intersections, rather than high-speed, signalized intersections as a whole, due to the additional potential for crashes at isolated intersections. However, non-isolated, high-speed, signalized intersections also experience many crashes. These intersections could also be studied to determine whether the extent of their crash experience warrants a similar safety evaluation tool with new average crash rates and crash percentages. The procedures and results outlined in this thesis could serve as a guide for researchers evaluating these intersections.

The installation of near-side signal heads has potential for increasing safety at IHSSIs. Intuitively, this safety treatment seems like a promising method for drawing attention to traffic signals located on isolated approaches. Additionally, this treatment could be beneficial because many IHSSIs have particularly wide intersections. Installing near-side signal heads at wide intersections would provide signal indications more than 100 feet before far-side signal heads and could provide extra time for drivers to decelerate while approaching red indications. Identification of this type of distance information is readily available from aerial photographs. However, there is no available research documenting safety effects of near-side signal heads. The effects of this treatment should be investigated to provide practitioners with the best possible safety treatment options.

6.0 CONCLUSIONS

It is important to regularly evaluate safety conditions at IHSSIs because they have high potential for frequent and severe crashes. However, ODOT does not currently have a formalized method for IHSSI evaluations. This thesis describes the development of an IHSSI safety evaluation method and summarizes the published literature relevant to this topic. In particular, the literature review in Chapter 2 summarizes proactive and reactive intersection safety evaluations. Chapter 3 then describes the research methodology used to accomplish the research objectives. Chapter 4, along with the appendix, detail the final recommended procedure and results of this research and Chapter 5 provides recommendations for future research.

This report describes the creation of a safety evaluation template to efficiently evaluate IHSSIs. The template contains expected crash percentages and crash rates for IHSSIs and a hierarchy of treatment strategies to be used when analyzing these intersections. The evaluation of three sample intersections demonstrates the use of this template. Though recommendations such as those shown in Table 10 are based on field observations and engineering judgment, the procedure outlined in this report demonstrates a consistent analysis method that provides documented recommendations when considering safety enhancements at IHSSIs.

The author recommends that ODOT utilize this safety evaluation template as a tool for evaluating and improving the safety of Oregon's IHSSIs by implementing a system requiring periodic analysis of all IHSSIs. This arrangement would ensure that irregular crash trends do not go unnoticed. When safety concerns are noted, the treatment hierarchy provided in the template can be used as guidance for establishing incremental measures to improve safety. The case studies included in this report outline specific ways to increase safety at three intersections, but implementation of this system has the potential to increase safety at IHSSIs all across Oregon.

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APPENDICES

APPENDIX A LITERATURE REVIEW: HIGH-SPEED SIGNALIZED INTERSECTION SAFETY TREATMENTS

A.1 Background

Intersections with approaching operating speeds of 45-mph or greater are often located on two-lane or multi-lane highways in rural areas. A survey of state departments (27 responses) by Jones and Sisiopiku (*2007*) revealed safety and operational concerns related to these intersections. The main safety concerns were red-light running, rear-end crashes, safe stopping of heavy vehicles, and right-angled crashes. The survey also listed operational concerns to include the wear on vehicular breaks and on the pavement surface at these intersection approaches as well as difficulty for heavy vehicles to accelerate at upgrade locations.

The sections that follow will present findings from a literature review covering the human, operational, and physical safety characteristics at high-speed intersections and identify a variety of candidate safety treatments that may be suitable for these locations. The review is limited to high speed (45 mph or greater) signalized rural intersections when feasible.

A.2 Dilemma and Decision Zones at High Speed Intersections

High speed signalized intersections are often characterized by abrupt stops (by less alert drivers) and vehicular acceleration during the yellow signal indication. When considering stopping and deceleration behavior at traffic signals, dilemma zones and decision zones are of particular relevance.

Drivers are faced with a dilemma zone when it is not possible to execute a safe stop behind the stop bar or legally enter the intersection. When signal settings and site conditions create such a dilemma zone, the driver will be unable to make a safe decision. It is for this reason that site specific conditions such as cross-street width and approach speeds are considered when setting the yellow and all-red times for a signal (*Mannering, Washburn, & Kilareski, 2009*).

The decision zone, also known as the Type II dilemma zone, refers to the distance and corresponding time that drivers have available to make a correct decision when approaching the intersection. The drivers must decide whether they can stop behind the stop bar or proceed safely through the intersection before the red indication. Urbanik and Koonce (*2007*) describe this zone as an "indecision" or "option" zone.

Research results regarding determining the specific boundaries of the decision zone varies. Zegeer (*1977*) initially quantified the zone as a static time duration based on approach operating speeds. He defined the time a vehicle occupies this zone as 4.2 to 5.2 seconds long and defined the start of the Type II dilemma zone as the point at which 90-percent of drivers would stop when presented with a yellow indication. He further defined the end of the Type II dilemma zone as the point at which only 10-percent of drivers would stop if presented with a yellow indication.

Liu et al. (*2007*) determined that this dilemma zone is in fact dynamic and depends on a number of factors: driving population, approaching speed, reaction time, acceleration/deceleration rates, and duration of the yellow interval. Rakha, El-Shawarby and Setti (*2007*), on the other hand, defined the decision zone as a function of driver age. They determined that the decision zone for older drivers 70 years of age or older is much shorter (1.5 seconds up to 3.2 seconds) than for drivers in the 20 to 30 year old range (1.85 seconds up to 3.9 seconds). They based their estimation on experimental results that defined the boundaries of the zone as a range between 10-percent and 90-percent probability of stopping (measured as vehicle time to intersection.

When developing the signal settings for an intersection, the *ITE Traffic Engineering Handbook* (*Pline ed., 1999*) provides a general formula shown as Equation 5 that can be used to eliminate the dilemma zone. The yellow and clearance interval should be equal to or greater than the non-dilemma change period. However, this equation provides adequate yellow and clearance interval time based on an assumed perception-reaction time and so does not directly address challenges presented by the decision zone where drivers may have a variable perception-reaction time (PRT) value or vehicles on the intersection approach have a variety of approach speeds.

Equation 5: Dilemma Zone Calculation

$$CP = t + \frac{v}{2a \pm 64.4\,g} + \frac{W+L}{v}$$

Where

CP	= non-dilemma change period (s)
t	= perception-reaction time (usually 1 sec)
V	= approach speed (ft/s)
g	= percent grade (+ for upgrade, - for downgrade)
a	= deceleration rate (ft/s^2)
W	= width of intersection (curb to curb) (ft)
L	= length of vehicle (usually 20 ft) (ft)

A.3 Human Factors at High-Speed Signalized Intersections

At high-speed signalized intersections, the PRT and braking behavior are of particular relevance. These two elements are reviewed in more detail in this section.

A.3.1 Perception-Reaction Time

PRT refers to the time interval that starts when an object enters the visual field of a driver and ends when the driver initiates a response. If various drivers' PRT values were plotted, they would resemble a left skewed normal distribution. As a result, PRT values should be evaluated by using references to the median and percentiles rather than averages (*Dewar & Olson, 2002*). Dewar and Olson (*2002*) determined that the majority of research results indicate that response time generally varies between 0.75 and 1.5 seconds when the driver is able to easily detect and readily identify the hazard (or situation) and have no problems during the decision or response time intervals.

Perchonok and Pollack (*1981*) distinguished four stages of PRT: detection, identification, decision, and response. In terms of PRT for high-speed intersections, each of these stages offers insight into likely errors and challenges that may potentially be addressed by the use of targeted countermeasures. In the *detection* stage, the driver is presented with the object within the visual field but may not be aware of it. This is particularly true when the driving environment is placing high demand on the driver, when the object is small, or when the object initially appears on the far side of the visual field. Detection is also affected by driver expectation. The *identification* stage is critical because it allows the driver to collect sufficient information to make an appropriate decision. The *decision* stage is where the driver actually decides on a particular action. This action is usually a speed change, a directional change, or both. In the case of a high-speed signalized intersection through movement, during the *response* stage the driver will decide to decelerate and stop behind the stop bar or to proceed through the intersection. In the case of a turning movement the driver will decelerate and laterally displace the vehicle into the appropriate lane to perform the turning movement.

A.3.2 Perception-Brake Time

Brake-reaction time, or perception-brake time, is particularly important when reviewing the human factors related to braking behavior at signalized intersections. This interval includes perception time and the time to complete the braking action. Green (*2000*) performed a critical review and a re-evaluation of brake-reaction time. He determined that braking time estimates from various sources differed by as much as a factor of four, likely resulting from differences in signals, responses, and conditions during testing. His analysis was limited to daylight time during clear weather and good visibility conditions and did not consider urgency as a key factor.

Information processing can be automatic or attentive. Automatic processing refers to responses to a common signal that are highly practiced. Attentive processing requires a driver to think more. When presented with an unusual situation, a driver needs to acquire more sensory input, recall memory to interpret the situation, and decide what response is warranted. Attentive processing is slower and the driver is more likely to make an error (*Kay, 1971*). Another factor that can affect response time is the level of driver expectation. When approaching an expected traffic signal, the driver would anticipate potential changes in the light but would not know the timing of these changes (*Kay, 1971*). However, when the presence of the signal itself is unexpected, driver expectancy is low and response times will be slower. Green (*2000*) also indicated that, in these cases, the movement by the driver will also be slower. He reported that basic reaction time for older drivers is generally slower; although some studies suggest that there is not a difference because older drivers tend to be more experienced (longer PRT but shorter decision time).

Braking behavior can also differ across age groups and gender. Bao and Boyle (*2007*) evaluated braking behavior at high-speed rural expressway intersections across younger (ages 18 to 25), middle-aged (ages 35-55), and older driver (ages 65 to 80) populations. Three different movement types were evaluated: crossing the intersection, turning left, and turning right. The braking profiles of younger and older drivers were distinctly different than observed for middle-age drivers. The middle-aged group had the highest frequency of complete stops, while the younger drivers were the least likely to come to a complete stop. The younger drivers delayed their initial response and then braked more suddenly and harder. Bao and Boyle concluded that the younger and older drivers tend to take higher risks at these intersections.

A.3.3 Elements in the Driving Task

Tijerina, Chovan, Pierowicz, and Hendricks (*1994*) and Chovan, Tijerina, Everson, Pierowicz, and Hendricks (*1994*) identified the elements in the driving tasks of straight-path movements and left-turn crossing-path movements at intersections. The elements in these tasks and likely associated errors provide valuable insight into the approaches to and likely successes of particular countermeasures to address concerns at high-speed intersections. Table A.1 summarizes these tasks.

Table A.1: Tasks in the Safe Negotiation of High-Speed Signalized Intersections

Straight-Path Maneuvers	**Left-Turn Crossing Path Maneuvers**
• Identify the intersection and appropriately reduce approach speed • Identify the status of the signal correctly • Determine whether sufficient time exists to cross if the signal changes from green to yellow • Foresee that the leading vehicle may suddenly decelerate on the approach to the intersection • Determine the presence or absence of cross traffic at the intersection • Determine whether the cross traffic, when present, present a safety concern (this may include speed estimation, and vehicle behavior such as acceleration or deceleration. • Identify objects that may reduce sight distance and adjust approach speed in an effort to overcome it if it exists • Detect and expect other road users (such as pedestrians) that may affect the decision to proceed through the intersection or influence the manner in which the driver proceeds through the intersection.	• Identify presence of intersection and intersection geometry • Activate turning signal in vehicle • Reduce speed sufficiently to allow for the accurate processing of critical information • Identify presence of traffic control device, along with characteristics such as phase timing • Correctly identify signal indication – includes correct perception of status (such as signal color, flashing/steady) • Take appropriate action based on signal indication • Identify any cross-traffic or oncoming traffic on the approaches to the intersection • Identify an appropriate gap for the left-turning maneuver if not prohibited by traffic signal • Correctly position the vehicle prior to execution of the left-turn movement as to maximize sight distance to oncoming approaching traffic • Identify the anticipated vehicle path of the oncoming approaching vehicle and anticipated vehicle behavior • Correctly adjust vehicle speed to execute the turning maneuver in a timely and safe manner. • Complete left turn maneuver successfully.

Source: Tijerina et al. (*1994*) and Chovan et al. (*1994*) as summarized in (*Lee et al., 2004*)

A.4 Crash Experience at High Speed Intersections

Two age groups exhibit higher crash risks at intersections: younger drivers (*Retting, Weinstein, & Solomon, 2003*) and older drivers (*Keskinen, Ota, & Katila, 1998; Guerriera, Manivannanb, & Nair, 1999; Stamatiadis, Taylor, & McKelvey, 1991; Zhang, Lindsay, Clarke, Robbins, & Mao, 2000*). As previously indicated these extreme driver age groups exhibit differences in perception-reaction time and braking behavior.

Three predominant crash types are of particular concern at high-speed signalized intersections: straight-path crashes, left-turn crossing-path crashes, and straight crossing-path crashes.

A rear-end crash is one of the most common straight-path crashes at high-speed intersections. Although a study of 476 signalized intersections in Florida by Wang and Abdel-Aty (*2006*) was not limited to high-speed intersections, their findings may be relevant in evaluating appropriate countermeasures at these intersection types. Their results indicate that the following factors are associated with an increase in rear-end crash potential: high traffic volumes on the minor and major approaches, left-turn protected phase on the minor approach, high posted speeds on major approach, and high population density areas. They found that the presence of turning lanes on the minor approaches, medians on minor approaches, and increased signal spacing were associated with a reduction in rear-end crash potential at an intersection.

In terms of left-turn crossing-path crashes, analysis of the 1991 General Estimating System (GES) data by Chovan et al. (*1994*) indicates that:

- The most common contributory factors were erroneous perceptions and sight distance restrictions (from vehicular presence).
- Older drivers tended to be overrepresented proportionally in this crash type.
- 15-percent of the crashes involved a signal violation.
- In 49-percent of crashes the left-turning vehicle was unaware of the presence of oncoming vehicles.
- 30-percent of the left-turning drivers in these crashes underestimated the gap.

Intersection treatments that can target these critical crash types may help enhance safety at these high-speed intersections. The following section introduces some of these candidate treatments as identified in the published literature.

A.5 Introduction to Treatments at High-Speed Signalized Intersections

The objective for placement of candidate safety-based treatments at high-speed signalized intersections is primarily to increase driver expectancy in order to reduce the need for abrupt stops. The treatments that have been previously used and evaluated for this purpose can be categorized as active, passive, or other.

Active treatments include those involving adjustments to signal timing or the use of flashing lights. *Passive treatments* relate to physical modifications to the driving environment such as signs, geometric features, or surface treatments. These passive engineering treatments are generally static and do not adapt to traffic conditions. Other non-engineering measures for high-speed signalized intersections include enforcement traffic control devices and other related efforts. Any of these treatments can also be targeted towards specific user groups, such as heavy vehicles.

A.5.1 Active Treatments

There are two primary groupings of active treatments at high-speed intersections. The first refers to any treatment involving only dynamic advance warning, and the second refers to any treatment involving modification of signal timing in response to real-time site conditions. Detection features are often part of these active treatment approaches. The activation of these treatments is often impacted by the length of the brake zone, the dilemma zone, and the clearance zone (*Lee, Knipling, DeHart, Perez, Holbrook, Brown, Stone, & Olson, 2004*).

A.5.1.1 Dynamic Advance Warning Treatments

There is extensive literature that focuses on the placement and performance of advance warning systems at high-speed intersections. The goal of advance warning treatments is to improve driver expectancy and thus alert the driver that he or she is approaching a high-speed intersection. The use of advance warning treatments can potentially increase driver awareness and, as a result, increase the length of the decision zone resulting in a gradual speed reduction and lower likelihood of red-light running events. Since these treatments can be active (by then adjusting signal timing) or passive (by simply providing the driver information), this summary only reviews the known active treatments. This review does not cover Advance Warning Flasher systems (AWF). These treatments are included as part of *Passive Treatments* (see Section 2.5.2).

The criteria used for activation of active advance warning treatments depend on several factors. These factors include the time required for the driver to brake (*Lee et al., 2004*), the time-to-collision (TTC) (*Green, 2000*), and the decision-making distance (as previously reviewed).

A.5.1.1.1 Speed Funnel

The concept of a speed funnel originated in Germany over 50 years ago and was tested as early as the 1960s in the United States. The speed funnel configuration establishes a system of dynamic signs that provide advisory speed guidance to drivers as they approach a high-speed intersection. If the signalized intersection operates under semi-actuated control, the system also includes sensors on both the major street and the cross street approaches so as to determine when the light may change unexpectedly. If the downstream traffic signal is expected to be green, the advisory speed signs provide higher speed information. If the downstream traffic signal is expected to change to a red indication, the advisory speed messages provide slower speeds. This treatment can then help optimize traffic flow by minimizing unnecessary speed reductions and can help enhance safety by alerting drivers to essential speed reductions when appropriate (*Dare,* *1969a; Dare, 1969b*). Though this treatment promises to provide safety benefits, a simulation study performed for the Minnesota Department of Transportation determined that the cost of deploying a speed funnel is substantially greater than other effective candidate treatments (*SRF, 2001*). Information regarding the effectiveness of this measure as it directly relates to safety is not available since this treatment has seen little use since its conception.

A.5.1.2 Signal Timing Adjustment Treatments

Signal timing adjustment treatments are primarily aimed at increasing the decision zone distance to accommodate alternative reaction or stopping times such as those for less alert drivers or for heavy vehicles.

A.5.1.2.1 Extension of Green Time

Extension of green time systems use multiple advance detectors along the high-speed approach and a controller to determine the appropriate extension time for a green indication. When the maximum green interval is reached or no vehicles are approaching the intersection, the controller ends the green phase (*Bonneson, Middleton, Zimmerman, Charara, & Abbas, 2002*). This treatment helps to reduce the number of vehicles caught in a decision zone and helps to reduce overall delays.

Zegeer and Deen (*1978*) performed two naïve before-after studies on a green time extension system. In the first, they observed a reduction in the frequency of total crashes of 54-percent as a result of the extension of green time system at three sites. In the second study, the crash rate reduced by 35-percent at ten isolated intersections.

The Detection-Control System (D-CS) developed by the Texas Transportation Institute (TTI) is an example of a recently developed system that extends the green time. This system uses the number of vehicles in the dilemma zone and the number of vehicles waiting on the minor approaches to determine the optimum time to terminate the green indication. It uses two detectors located 800-ft and 1000-ft upstream of the major approaches to the intersection. When comparing the D-CS system with the traditional multiple-detector system, the D-CS system had a lower risk of red-light running, lower rear-end crash occurrence, reduction of delays and stops for the major approach, and overall reduction of intersection delay (*Zimmerman & Bonneson, 2005*).

A.5.1.2.2 Enhanced Extension of Green Time

The principles of the standard green-extension system also apply to the enhanced green-extension system, but additional features are included for the enhanced system. These features may provide higher priority to heavy vehicles or allow for the through phases of the major roadway to terminate at different times. Two basic enhanced green-extension systems include the TTI Truck Priority System and the LHOVRA system that is used in Sweden. Each letter of the LHOVRA acronym stands for specific system functions, but a translation is not known. The L-function provides truck priority. The H-function provides priority to all major-road vehicles. The O-function targets dilemma zone protection. The V-function varies the yellow timing. The R-function enhances permitted left-turns, and the A-function influences the all-red phase. The LHOVRA system allows the engineer to customize for specific site characteristics and he or she can use some or all of the functions. In general, this Swedish system is used primarily in urban areas (*Bonneson et al., 2002*).

The TTI Truck Priority System extends the green time and holds the green interval when the approaching heavy vehicle is within 500 ft of the stop line. The primary goal of this system is to reduce the amount of stopping by heavy vehicles. In a limited evaluation at one intersection, Sunkari and Middleton (*2000*) found that the system reduced the number of heavy vehicle stops by four-percent; this translated into reduced pavement damage and a reduction in delay.

Zimmerman (*2007*) evaluated a modification of the D-CS to provide additional dilemma zone protection for heavy vehicles. By increasing the dilemma zone for heavy vehicles by 1.5 to 7 seconds, the number of heavy vehicles in the dilemma zone was reduced by 47-percent.

A.5.1.2.3 GREEN TIME TERMINATION SYSTEM

A *green time termination system* assesses the safety of through movements on the major roadway and delay on the minor approaches to determine the appropriate time to terminate the green phase.

The Self Optimizing Signal (SOS) system is an example of a green time termination system. The purpose of the SOS system is to prioritize the safety of traffic on the major approaches balanced with delay at the minor approaches to optimize the end of the green phase of the particular signal. This system is one of several that offer dynamic dilemma zone protection that permits the traffic controller to make modifications to the green time in an effort to enhance decision and dilemma zone operations. Kronborg and Davidsson (*1993*) found that SOS reduces the number of vehicles in the dilemma zone by as much as 38-percent, reduces red-light running by 16-percent, and reduces multiple vehicles in the dilemma zone by 58-percent.

TTI developed an Intelligent Detection-Control System (*Bonneson et al., 2002*). It predicts the presence of a vehicle in the dilemma zone on a per-vehicle basis and minimizes the number of vehicles in the dilemma zone. It offers the ability to process heavy vehicles (longer than passenger cars) as part of the optimization process.

A.5.1.2.4 EXTENSION OF YELLOW INTERVAL

A common signal modification is to extend the duration of the yellow interval so that when the driver of a vehicle becomes aware that the light is about to change, he or she can safely stop or continue through the intersection. By extending the yellow interval, drivers with slower reaction times or vehicles with diminished deceleration or acceleration capabilities can be accommodated safely. Results from extension of the yellow interval applications vary greatly.

Lee et al. (*2004*) argued that extension of the yellow interval only addresses crashes related to the Type II dilemma zone (the driver making improper decisions in the dilemma zone) and does not address crashes related to distraction. In a follow-up study Liu et al. (*2007*) determined that yellow indication extension may not eliminate the dilemma zones at high-speed intersections. They identified three groups of drivers: conservative, normal, and aggressive. Aggressive drivers tend to have a larger range of dilemma zones. In an analysis of six intersections, they increased the yellow time from 4.5 to 6.0 seconds and some drivers in the normal and aggressive driver population still experienced the Type II dilemma zone. The researchers evaluated two different safety improvements. In the first, three modules are used to extend the yellow or all-red indication to allow the driver to safely clear the intersection: a vehicle detection module, a driver behavior analysis module, and the signal control module. If a vehicle runs the red light, a ticket could be issued. In the second approach, classification, prediction, and dilemma zone distribution modules can be added. These additional modules allow the system to identify different potential for experiencing a dilemma zone based on specific site characteristics.

A.5.1.2.5 Provision of Flashing Amber Prior to Onset of Solid Amber

Mussa, Newton, Matthias, Sadalla, and Burns (*1996*) evaluated the provision of flashing amber prior to the onset of solid amber in an urban setting with 45-mph approach speeds. In all cases the response times during the four-phase configuration were longer than for the three-phase configuration. They found that the four-phase option increased the Type II dilemma zone and that response times had much larger variability (indicating higher probability of rear-end crashes). They recommend that this measure be evaluated at high-speed intersections with low traffic density – i.e. locations where the consequence of red-light running would be more severe than a rear-end crash.

A.5.1.2.6 Blank-Out Overhead Dynamic Advance Warning Signal

Schultz, Peterso, Eggett, and Giles (*2007*) described an experimental implementation of the blank-out overhead dynamic advance warning signal (BODAWS) system on a four lane divided highway with a 60-mph posted speed limit (64-mph 85th percentile speed). The intersection was a skew intersection (30 degrees counterclockwise from perpendicular) with limited sight distance on one approach because of horizontal curvature. On the other major approach sight distance to the signal heads was limited by a pedestrian overpass. The system consisted of an overhead-mounted dynamic-variable sign that displays the words “PREPARE TO STOP” combined with an AWF system that allows for green extension. The initial assessment indicated that the system resulted in a statistically significant reduction in red-light running.

A.5.1.2.7 Left-Turn Phasing

Mueller, Hallmark, Wu, and Pawlovich (*2007*) evaluated 101 urban high-speed intersections and found that protected left-turn phases had the lowest likelihood of crashes. When comparing the different left-turn phasing alternatives within the younger, middle-aged, and older driver groups, the highest likelihood of crashes was associated with protected/permitted and permitted phasing. It is unknown if these urban conditions would translate directly to the high-speed rural intersections of interest in this study.

A.5.1.2.8 Different Detector Configurations

Si, Urbanik and Han (*2007*) investigated four different detector configurations at high-speed signalized intersections and evaluated their effects on safety and efficiency. While they were unable to conclude that any one detector is better than another, they state that use of the Bonneson configuration published in the *Manual of Traffic Detector Design, 2nd Edition* results in less vehicles in the decision zone and a lower average total delay time (*Bonneson & McCoy, 2005*).

A.5.2 Passive Treatments

Passive treatments represent countermeasures that do not involve modification of signal settings or devices that account for the state of the signal indication on the particular approach. Passive treatments generally provide consistent information to the driver without consideration for the real-time traffic conditions. A number of these treatments are summarized in this section and, where available, the effectiveness of the particular measure is also provided.

A.5.2.1 Advance Warning Flasher Systems

The AWF treatment can take many different forms, but often consists of a system of flashers and a Signal Ahead Sign (SAS). These measures are placed to allow adequate distance for the driver to detect and respond to the flasher and execute a safe stop. When the particular measure involves activation of the flashers based on the signal timing of the downstream intersection, the onset of the yellow interval is used as a reference point to provide adequate warning to drivers.

A.5.2.1.1 Types of AWF Systems

There are several different types of AWF systems: *Prepare to Stop when Flashing (PTSWF), Flashing Symbolic Signal Ahead (FSSA), Continuous Flashing Symbolic Signal Ahead (CFSSA),* and the *Advance Warning for End-of-Green System (AWEGS)* developed by TTI. Each of these systems is briefly discussed in the following sections.

A.5.2.1.1.1 Prepare to Stop when Flashing

The PTSWF system consists of a warning sign with text “Prepare to Stop When Flashing” and two amber flashers. The amber flashers are activated a few seconds before the start of the yellow interval of the downstream intersection and deactivated at the end of the red interval (*FHWA & ITE, 2003*).

Figure A.1: Prepare to Stop when Flashing System
Source: FHWA & ITE, 2003

A.5.2.1.1.2 FLASHING SYMBOLIC SIGNAL AHEAD

The FSSA system consists of a warning sign with a schematic traffic signal (with solid red, yellow, and green circles) and two amber flashers. The amber flashers are activated a few seconds before the start of the yellow interval of the downstream intersection and deactivated at the end of the red interval (*Sayed, Vahidi, & Rodriguez, 1999*). Figure A.2 depicts a schematic of the FSSA configuration.

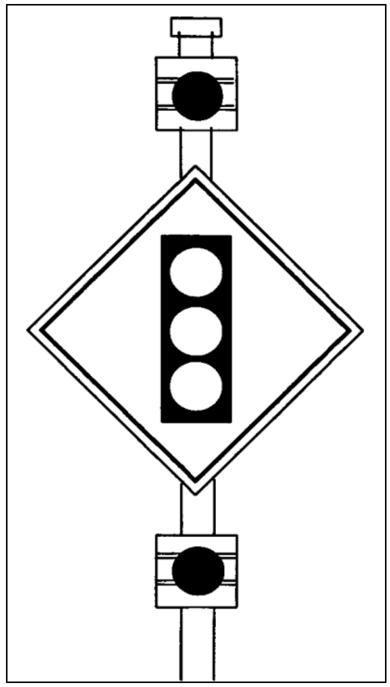

Figure A.2: Flashing Symbolic Signal Ahead System
Source: Pant & Cheng, 2001

A.5.2.1.1.3 Continuous Flashing Symbolic Signal Ahead

The CFSSA system consists of a warning sign with a schematic traffic signal (with solid red, yellow, and green circles) and two amber flashers that continuously flash (regardless of the state of the downstream traffic signal) (*Sayed, Vahidi, & Rodriguez, 1999*). This appearance of this system is identical to the FSSA system. The only difference is that the CFSSA system flashes constantly.

A.5.2.1.1.4 Advance Warning for End-of-Green System

AWEGS systems are often used alongside other AWF systems and utilize inductive loop detectors placed along an intersection approach to provide dilemma zone protection. TTI developed an AWEGS system for TxDOT with the primary goals of reducing red-light running and improved dilemma zone protection for heavy vehicles and high-speed vehicles. It is currently only installed at a few selected locations (*Messer, Sunkari, Charara, & Parker, 2004*).

A.5.2.1.2 EVALUATION OF AWF SYSTEMS

Sayed, Vahidi, and Rodriguez (*1999*) list two key considerations for AWF installations: location of the AWF measure to allow for driver response and timing of the onset of the yellow indication. Klugman, Boje, & Belrose (*1992*) reported that some agencies use primarily engineering judgment when deciding on installations. The effectiveness of AWF systems, according to Sayed, Vahidi, and Rodriguez (*1999*), should be measured by one or more of the following: a reduction in crash frequency, a reduction in the approach speed of vehicles, and a reduction in particular traffic conflict types. A Minnesota report indicates that their typical installation of AWF systems is in response to locations with observed high speeds, isolated or unexpected signalized intersection location, limited sight distance, marginal dilemma zone, crash history, or based on engineering judgment (*Farraher, Weinholzer, & Kowski, 1999*).

The following list represents research results for the general effects of AWF systems:

- A reduction in right-angle, rear-end, and total crash rates (multivariate study of 40 intersections with 10 years of crash data by Gibby, Washington, and Ferrara (*1992*));
- A reduction in the proportion of nighttime crashes (multivariate study of 40 intersections with 10 years of crash data by Gibby, Washington, and Ferrara (*1992*));
- Reductions or increases in right-angle, rear-end, and total crash rate depending on location (simple before-after study of 14 intersections with 6 years of crash data by Klugman, Boje, and Belrose (*1992*)); and
- Sayed, Vahidi, and Rodreguez (*1999*) (multivariate study of 25 intersections) determined that AMF systems are associated with an average reduction in rear-end, severe, and total crash frequency by 8-percent, 14-percent, and 18-percent respectively, but found that the reductions are not statistically significant.

When studying particular AWF systems, the impacts of these systems are less clear. A simulator study indicated that the FSSA sign is more easily understood and the PTSWF sign is more likely to be identified incorrectly (*Sabra, 1985*). However, in an Ohio study, Pant and Huang (*1992*) determined that FSSA and PTSWF have the same effect on driving behavior. They recommended the use of the CFSSA sign rather than the FSSA and PTSWF signs. They found that approach speeds tend to increase on tangent sections with PTSWF and FSSA systems when the signal indication was green (the flashers were not active) compared to when the flashers were active. This was similar to the findings by Klugman, Boje, and Belrose (*1992*). McCoy and Pesti (*2003*) compared two PTSWF systems, the first system was the conventional PTSWF system with multiple detectors at several locations on the approach and the second system had a single advance detector. With a fixed maximum allowable headway of 3 seconds, the single advance detector reduced the likelihood of loss of dilemma-zone protection. Unfortunately, this detector strategy also narrows the range of speeds for which it provides dilemma-zone protection. The researchers suggested a modification of the single detector installation to resolve this limitation.

In terms of crash reduction, Baker, Clouse, and Karr (*1980*) found that the PTSWF sign significantly reduced total, rear-end, property-damage only, and crashes contributed to trucks. Styles (*1982*) found that the flashing Red Signal Ahead (RSA) sign successfully reduced right-angle crashes at sign-obstructed signalized intersections. The RSA sign appeared to be more effective in reducing total and rear-end crashes on curved approaches.

When reviewing the impact on traffic conflicts, Klugman, Boje, and Belrose (*1992*) determined that red light running violations were consistently higher at locations without AWF systems. Pant and Xie (*1995*) compared the different systems and found that the likelihood of red-light running was twice as high with CFSSA signs compared to the other systems. In addition, they determined that PTSWF signs are associated with a higher incidence of abrupt stops when compared to other AWF systems. At two intersections with AWEGS, the incidence of red-light running reduced by 40 to 45-percent (*Messer et al., 2004*).

Sayed, Vahidi, and Rodreguez (*1999*) compared crash frequencies at locations with AWF in British Columbia. AWFs are considered for facilities with a posted speed of 43.5 mph (70 km/h), limited sight distance, a grade on the approach to the intersection, or locations where drivers transition from high-speed facilities into more developed land-use areas. Using 25 sites, their research suggests that AWF benefits increase as minor approach traffic increases. In other words, the benefits of AWF are negligible where minor approach volumes are low (average annual daily traffic [AADT] of 3,000). Consistent crash reduction was associated with high minor approach volumes (AADT of 18,000).

A.5.2.2 "Signal Ahead" Pavement Markings

An alternative to conventional traffic signs is the use of "Signal Ahead" pavement markings. Radwan, Yan, Birriel, and Gou (*2006*) evaluated "Signal Ahead" pavement markings with a driving simulator and observed a reduction in red-light running from 3.27-percent to 1.27-percent. In addition, Yan, Radwan, Guo, and Richards (*2009*) used a simulator to determine that the "Signal Ahead" markings result in lower deceleration rates for higher speed intersections; however, they do not appear to significantly influence the driver's brake response time.

A.5.2.3 Improve Traffic Signal Visibility

According to Antonucci, Hardy, Slack, Pfefer, and Neuman (*2004*), drivers may not be able to see traffic signals because the signals are blocked by physical objects, obscured by weather conditions, or surrounded by extraneous signs. Inadequate visibility of traffic signals may contribute to a driver's inability to stop at an intersection. Techniques for improving traffic signal visibility include installation of additional signal heads, installation of visors to shade the signal lenses from sunlight, installation of backplates, installation of 12-inch signal lenses instead of 8-inch signal lenses, and relocation of extraneous signs. Additional details about the installation of backplates are provided below. Two more examples of improving traffic signal visibility, high-intensity strobe lights and light-emitting diode (LED) signals, are also discussed.

A.5.2.3.1 BACKPLATES ON TRAFFIC SIGNALS

Backplates are installed with traffic signals to increase the visual contrast of the signal with the surrounding environment, particularly on east-west approaches. There are two common backplate configurations: backplates with a dull black finish, and backplates with a yellow retro-reflective tape strip around the edge (*Rodegerdts et al., 2004*). Miska, de Leur, and Sayed (*2002*) determined in an empirical Bayes before-after study that backplates with reflective yellow borders reduced insurance claims at 19 of 25 intersections by between 2.8-percent and 60.7-percent and increased claims at six intersections by 2.3-percent up to 20.6-percent. The average reduction in claims was 14-percent (a combined confidence interval for the measured reductions was not available).

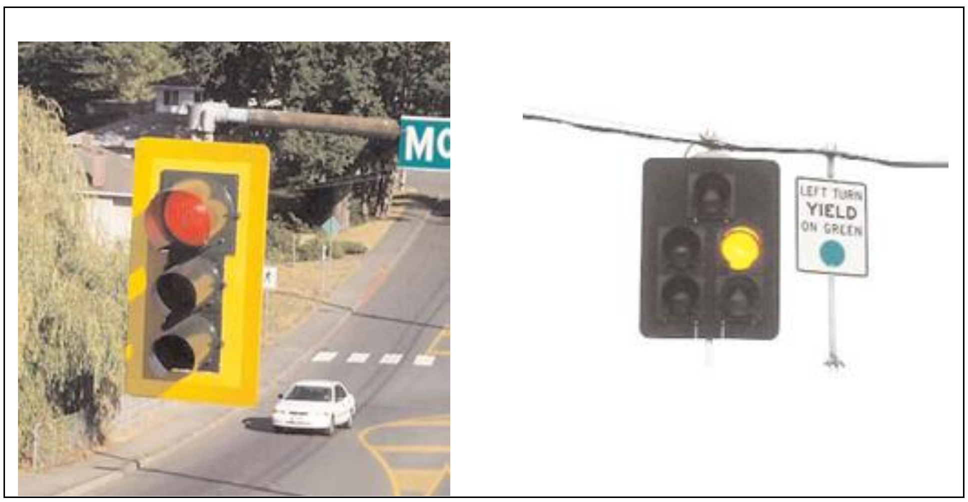

Figure A. 3: Traffic Signals with Back Plates
Source: FHWA & ITE, 2003

A.5.2.3.2 HIGH-INTENSITY STROBE LIGHTS

High-intensity strobe lights are intended to increase the visibility of a traffic signal. Ordinarily these lights are installed inside the signal head lens and flash at one-second intervals during the red indication. Studies by Cottrell (*1994*) and Ryan (*1984*) show that this treatment does not have a statistically significantly effect on crash occurrence.

A.5.2.3.3 Light-Emitting Diode Traffic Signals

The recent trend in traffic signals is to replace traditional incandescent signals with LED signals because the LED units are more energy efficient, appear brighter, and last longer. Though this shift in technology appears to be determined, a report by the Traffic Engineering Division of the City of Little Rock, Arkansas (*2003*) lists a few additional considerations that may influence LED signal visibility:

- Incandescent bulbs stop emitting light and require immediate replacement when their single filament burns out. LED signals, however, contain several dozen LED diodes and will continue to function even after several individual diodes have failed.
- Reflectors behind incandescent bulbs can cause all three indications to appear illuminated during morning and evening hours when sunlight directly hits the traffic signal. LED signals do not require reflectors and do not experience this problem.
- LED signals tend to be visible from only one direction. Signals suspended from span wires should be tethered from both the top and the bottom to ensure correct orientation during high wind.
- LED signals do not generate as much heat as incandescent signals and may not be able to melt any snow or ice that can accumulate on the lenses during winter storms. Accumulation of snow or ice can greatly decrease visibility of the traffic signal.

A.5.2.3.4 Near-Side Signal Heads

According to the Federal Highway Administration's (FHWA) *Signalized Intersections: Informational Guide* (*Rodegerdts et al., 2004*), supplemental traffic signals may be installed on the near side of an intersection to increase visibility and are particularly useful on excessively wide intersections. The guide states that "Supplemental pole-mounted traffic signals appear to reduce the number of fatal and injury collisions at an intersection, according to the limited research that has been done on their effectiveness at preventing collisions." Increased signal visibility and decreased angle collisions are the two specific safety benefits listed.

Additional information about the effects of near-side signal heads at high-speed intersections is not readily available.

A.5.2.4 Lighted Warning Signs

A technique common to urban regions is the use of warning signs that are backlit. These lighted warning signs require regular maintenance and so are rarely used at isolated, rural locations. Lyles (*1980*) did evaluate signs at hazardous rural intersections and found that lighted warning signs are more effective than unlighted warning signs in terms of speed reduction and increased awareness.

A.5.2.5 Surface Treatment (Skid Resistance)

Vehicles approaching high-speed intersections may be unable to stop before entering the intersection if there is not sufficient friction between the vehicle's tires and the road. This scenario is particularly likely if the driver is not anticipating a stop and does not immediately recognize the need to apply the brakes. The friction allowing vehicles to stop before an intersection is influenced by factors such as pavement age, condition, texture, mix characteristics, etc. (*FHWA & ITE, 2003*). Additionally, a film of water only 0.05 mm thick can reduce friction by 20 to 30-percent (*Ali, Al-Mahrooqi, & Taha, 1999*). Rodegerdts et al. (*2004*) indicates that potential benefits of improved pavement treatments will help reduce wet-weather crashes, reduce angle crashes that are due to skidding, and reduce rear-end or sideswipe crashes that could be due to either skidding or braking.

A.5.2.6 Approach Curvature

According to Ray, Kittelson, Knudsen, Nevers, Ryus, et al. (*2008*), approach curvature is a method used to slow traffic approaching an intersection. Drivers are forced to negotiate a series of curves with progressively decreasing radii that are designed to encourage a desired approach speed. This method is generally applied to roundabouts, but has potential for slowing vehicles at other intersections as well. It is recommended that approach curvature be used in addition to advisory speed signs. Other factors that should be considered before implementation include right of way issues, grading, driver workload, and heavy vehicle movements. Additional information about how approach curvature affects vehicle speed and safety is primarily available for roundabouts (*Ray et al., 2008*). It is worth noting, however, that adequate intersection sight distance should be maintained when deploying this approach curvature treatment.

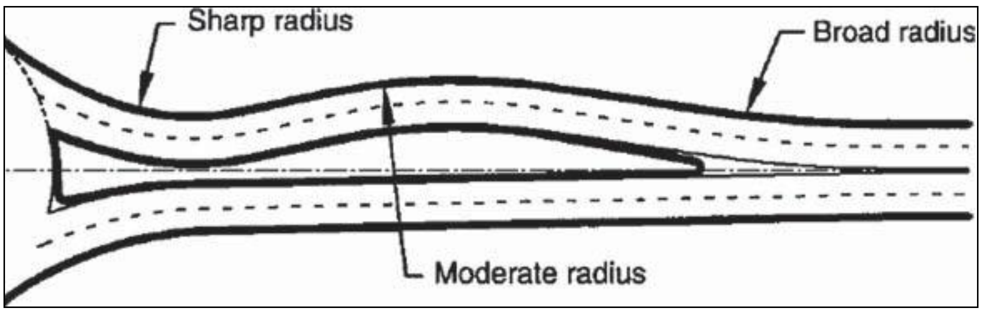

Figure A.4: Approach Curvature
Source: Ray et al., 2008

A.5.2.7 Transverse Rumble Strips

Rumble strips can be raised or depressed and provide both audible and tactile warnings to drivers (*Ray et al., 2008*). They are inexpensive to install and can span an entire lane or a region as narrow as the width of a vehicle's wheel path (allowing drivers familiar with the area to avoid the strip) (*Corkle, Marti, & Montebello, 2001*). Ray et al. (*2008*) indicate that the installation of rumble strips led to statistically significant speed reductions at their perception-response time collection point (250 feet from the intersection, upstream of the rumble strip location), but that speed reductions were not observed at the rumble strip location or at the crash avoidance location (100 feet upstream of the intersection).

While there are plenty of studies examining speed reduction capabilities of rumble strips, simply looking at speed reduction may not be an effective way to determine the effectiveness of rumble strips for unfamiliar or inattentive drivers. This point is noted by Martens, Comte, and Kaptein (*1997*) who expand on studies by Cheng, Gonzalez, and

Christensen (*1994*) and Ribeiro and Seco (*1997*). Researchers for both studies evaluated the effects of transverse rumble strips before pedestrian crossings. They found no reductions in driving speed, but found that the rumble strips improve safety by alerting drivers about the presence of the pedestrian crossing.

A study on sleep deprived drivers in a driving simulator found that the presence of rumble strips at an intersection approach prompts drivers to brake harder and earlier. This study also found that intersection approaches with rumble strips had statistically significantly slower mean speeds than intersection approaches without rumble strips (*Harder & Bloomfield, 2005*).

Other factors to consider for the installation of rumble strips include noise, damage caused by snow plows (for raised rumble strips), and adverse influences on motorcycles and bicycles (*Ray et al., 2008; Corkle, Marti, & Montebello, 2001*).

Figure A.5: Full Width Transverse Rumble Strips
Source: Corkle, Marti, & Montebello, 2001

Figure A.6: Wheel Path Transverse Rumble Strips
Source: Corkle, Marti, & Montebello, 2001

A.5.2.8 Transverse Pavement Markings

Transverse pavement markings, such as transverse bars or transverse chevrons, can be used to reduce speeds by modifying drivers' perceptions of the driving environment (*Rothenberg, Benavente, & Swift, 2004*). Installation of markings at gradually decreasing intervals (called *optical speed bars*) produces an illusion of acceleration that may cause drivers to decelerate in response (*Martens et al., 1997*).

Transverse pavement markings have been used in many situations where drivers have maintained high speeds and may be somewhat desensitized to the driving environment. These transverse markings are often placed at approaches to roundabouts, intersections, horizontal curves, construction areas, and freeway off-ramps (*Griffin & Reinhardt, 1995*).

Transverse pavement markings applied only along the edges of a lane are called *peripheral transverse markings*. Peripheral transverse markings are easy to install and maintain, are located outside of the wheel path of a vehicle (and thus do not contribute to slick surfaces on wet roads), and are very cost effective (*Katz, Duke, & Rakha, 2006*). In a driving simulator test, Godley, Triggs, and Fildes (*2000*) found that transverse markings are more effective than peripheral transverse markings for the beginning of a treatment area, but both methods produce similar speed reductions overall. They also found that optical speed bars provide no significant benefit over constantly spaced bars.

Many studies have shown the effects of transverse pavement markings on speed. At high speed intersections, however, it is important to examine the affect of these transverse markings on unfamiliar or inattentive drivers. Arnold and Lantz (*2007*) determined that even though installation of transverse pavement markings may result in initial speed reductions, the effect decreases as drivers become familiar with the markings. This result suggests that these markings are more effective on unfamiliar drivers than those who traverse the corridor on a regular basis.

Meyer (*2001*) examined the use of transverse pavement markings with both constant and decreasing spacing in work zones. He determined that the markings can create both a warning effect and a perceptual effect. Overall, he observed that following the placement of optical speed bars there was a reduction in mean speed, 85th percentile speed, and variation in operating speed.

Ray et al. (*2008*) note that "transverse pavement markings improve visibility and driver attention." Their study also documented the effects of transverse pavement markings at high-speed intersections after a 90-day acclimation period. Transverse pavement markings were found to be effective for minor reductions of speeds at high-speed intersections (mean speed reduction of 0.6 mph, standard error of 0.3 mph) and found to be slightly more effective for reducing speeds at the point where the driver would first see or react to an intersection (mean speed reduction of 0.9 mph, standard error of 0.4 mph).

Figure A.7: Full Width Transverse Bars
Source: Arnold & Lantz, 2007

Figure A.8: Peripheral Transverse Bars
Source: Arnold & Lantz, 2007

A.5.2.9 Interchange or Grade Separation

Construction of interchanges or grade separation is an expensive proposition to improve intersection safety, so other options are generally considered first and the construction of the interchange is often reserved for when other measures have failed. This approach can be used at locations with excessive crash records, but is often applied simply to accommodate very high volumes. By physically separating the intersecting roads, crossing and turning traffic is minimized and congestion can be reduced. These reductions can decrease the frequency and severity of rear-end and angle crashes (*Antonucci et al., 2004*).

A.5.3 Other Treatments

Because many other treatments fall outside of conventional safety treatments, other countermeasures may be considered for dangerous intersections. Two common treatments include the use traffic control enforcement via red light running cameras. This strategy should be used so as to help reduce intentional red light violations, but it is more common to high volume intersections and so may not be appropriate for isolated high-speed rural intersections.

A second alternative treatment that is not a standard department of transportation option is the use of in-vehicle systems. The Intersection Crash Avoidance, Violation (ICAV) warning system targets red-light running crashes (crossing-path crashes) by providing a warning to the driver when there is a strong likelihood that the driver will run the red light. The ICAV is an in-vehicle system that consists of four components: a driver-vehicle interface, a positioning component, in-vehicle sensors, and a dynamic algorithm for computations (*Lee et al., 2004*).

The Cooperative Collision Warning (CCW) project is an ongoing project by the University of California Partners for Advanced Transit and Highways (PATH) program and General Motors Research and Development. This system provides the driver with collision warnings through an in-vehicle system (*Misener, Sengupta, & Krishnan, 2005*).

For the purposes of this literature review, the focus is on roadway related measures rather than in-vehicle devices or systems. As a result, the ICAV and the CCW are not explored in detail.

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APPENDIX B DATA COLLECTION INFORMATION

This appendix contains supplemental data collection information including a description of data collection equipment, a sample calculation of crash-related distances, and a complete list of the intersections and crash data used to calculate average crash frequencies.

B.1 Data Collection Equipment

The research team used a SpeedLaser R from Laser Atlanta to collect operating speed data and a Jamar board to collect volume data. An ordinary stopwatch and distance wheel allowed researchers to obtain approximate signal phasing information and intersection distances. No other data variables required special equipment.

B.2 Speed Data Sample Size Calculation

Before collecting speed data, researchers may wish to perform a calculation to determine an appropriate speed data sample size for future statistical comparisons. For a 95% confidence interval, this calculation can be based on the following equation (*Roess, Prassas, & McShane, 2004*).

Equation 6: Sample Size Calculation

$N \geq (1.96^2)(s^2)/(e^2)$

Where

N	= required sample size
s	= sample standard deviation (often assumed to be 5 mph)
e	= desired tolerance

The research team's primary objective in collecting speed data was to gain an understanding of intersections' operation conditions. This use does not require statistical comparison. Researchers collected 300 speed data points, or approximately 1 hour of data. This amount of data collection provided an informative speed distribution, as displayed in the sample intersection templates, with minimal time and cost.

B.3 Intersection-Related Crash Distance Calculations

This section provides a sample calculation demonstrating the method used to determine which crashes can be considered related to an intersection. The following calculation assumes a combined perception-reaction and brake-reaction time of 2.5 sec (.000694 hr), a deceleration rate of 11.2 ft/sec^2 (27,500 mi/hr^2), and level grade. Also, because the milepoint for each intersection is coded to the center of the intersection, an approximate distance of 50 ft (.01 mi) is added to represent the distance from the center of the intersection to the stop bar. All final distances are rounded to the nearest .01 because the crash data is coded at .01 mile intervals.

Equation 7: Intersection-Related Distance Calculation

$d = (PRT)x(v)+(v^2)/(2a)+offset$

Where

d	= intersection related crash distance (mi)
PRT	= combined perception-reaction and brake-reaction time (hr)
v	= velocity (posted speed limit) (mi/hr)
a	= deceleration rate (mi/hr^2)
offset	= distance from center of intersection to stop bar (mi)

Sample calculation:

$d = (.000694)x(45)+(45^2)/(2x27,500)+.01$

$d = .08$ mi

Thus, for 45 mph intersections, crashes coded as less than or equal to .08 miles from the intersection can be included in crash frequency calculations. Table 3 in the body of this report summarizes the distances calculated for all relevant speed limits.

B.4 Complete Intersection List

Table B.1 contains a complete list of the intersections used to calculate expected crash trends.

Table B.1: Intersections Included in Crash Trend Calculations

County	State Highway Number	Route Number	Cross Road	AADT	Safety Technology	Speed Limit	Change in Speed Limit	Standard Number of Lanes per Direction
Speed Limit 45mph								
Umatilla	54	US 395	Punkin Center	13,600	SAS	45	--	1
Benton	33	US 20	53rd	15,200	SAS	45	--	1
Benton	33	US 20	SW 15th	19,750	SAS	45	--	1
Lincoln	9	US 101	Devils Lake	16,600	CFSSA	45	--	1
Tillamook	9	US 101	Wilson River Loop	13,800	None	45	--	2
Lane	15	OR 126	69th	13,500	None	45	--	2
Deschutes	7	US 20	27th	16,750	None	45	--	2
Jackson	63	OR 99	South Stage Rd	15,950	None	45	--	2
Multnomah	123	US 30	NE 60th	21,550	None	45	--	2
Josephine	25	US 199	Dowell	19,750	None	45	--	2
Linn	58	OR 99E	Off-ramp (mp 7.9)	8,250	SAS	45	--	2
Jackson	272	OR 238	Sage	13,500	SAS	45	--	2
Curry	9	US 101	Zimmerman	15,650	SAS	45	--	2
Clatsop	9	US 101	Pacific Way	16,400	SAS	45	--	2
Deschutes	4	US 97	Cooley	31,800	SAS	45	--	2
Yamhill	39	OR 18	Norton	14,450	CFSSA	45	--	2
Speed Limit 45mph (reduced from upstream of intersection)								
Lane	62	OR 126	Territorial/200	9,200	SAS	45	55-45	1
Curry	9	US 101	Benham	13,250	None	45	55-45	2
Deschutes	4	US 97	Odem Medo Way	33,050	None	45	55-45	2
Linn	16	US 20	Goldfish Farm Rd	9,850	SAS	45	55-45	2
Linn	58	OR 99E	Old Hwy 34	14,650	SAS	45	55-45	2
Multnomah	26	US 26	Palmquist/14th	30,100	SAS	45	55-45	2
Yamhill	39	OR 18	Norton	14,450	CFSSA	45	55-45	2
Marion	81	OR 99E	Chemewa/Hazel Green	13,750	SAS	45	55-45	1 to 2
Lane	69	OR 126	Terry/Lane Mem Gardens	21,050	SAS	45	55-45	1 to 2

Table B.1: Intersections Included in Crash Trend Calculations (Continued)

County	State Highway Number	Route Number	Cross Road	AADT	Safety Technology	Speed Limit	Change in Speed Limit	Standard Number of Lanes per Direction
Speed Limit 50mph								
Douglas	Hwy 35	OR 42	Carnes/Roberts Cr	24,400	None	50	--	2
Columbia	Hwy 92	US 30	Deer Island/Liberty Hill	15,300	SAS	50	--	2
Benton	Hwy 91	OR 99W	Circle	16,350	SAS	50	--	2
Columbia	Hwy 92	US 30	E St	13,100	CFSSA	50	--	2
Benton	Hwy 91	OR 99W	Conifer	14,950	CFSSA	50	--	2
Speed Limit 55mph								
Polk	Hwy 91	OR 99W	Hoffman Rd	12,700	SAS	55	--	1
Marion	Hwy 81	OR 99E	Douglas/Mt. Angel-Gervois	11,500	SAS	55	--	1
Lincoln	Hwy 09	US 101	Salashan Lodge and Center(?)	12,200	CFSSA	55	--	1
Lane	Hwy 69	OR 126	Greenhill	16,950	CFSSA	55	--	1
Jackson	Hwy 270	OR 140	Hwy 22	29,000	Overhead CFSSA	55	--	1
Linn	Hwy 58	OR 99E	Beta Dr	14,650	None	55	--	2
Columbia	Hwy 92	US 30	Rockcrest	14,600	SAS	55	--	2
Lane	Hwy 69	OR 569	Roosevelt	21,400	SAS	55	--	2
Clackamas	Hwy 26	US 26	J Jarl/Orient	29,850	SAS	55	--	2
Malheur	Hwy	OR 201	SW 18th/Butler	6,800	CFSSA	55	--	2
Lane	Hwy 91	OR 99	Airport Rd	18,700	CFSSA	55	--	2
Lane	Hwy 91	OR 99	Hwy 229	16,350	CFSSA	55	--	2
Clackamas	Hwy 81	OR 99E	Barlow	16,200	CFSSA	55	--	2
Umatilla	Hwy 8	OR 11	State Line Rd	14,100	CFSSA 2 flashers	55	--	2
Lane	Hwy 227	OR 126	High/52nd	26,300	Overhead CFSSA	55	--	2

B.5 Complete Crash Data List

Table B.2 provides crash data for all of the intersections listed in Table B.1.

Table B.2: Crash Data for All Intersections

Route Number	Cross Road	Number of Collisions												
		Rear-End	Turning	Angle	Sideswipe-Overtaking	Non-Collision	Other	Sideswipe-Meeting	Fixed Object	Backing	Pedestrian	Head-On	Parking	Total
Speed Limit 45 mph														
US 395	Punkin Center	4	4	4	2	0	0	0	0	0	0	0	0	14
US 20	53rd	25	8	1	0	0	0	1	1	1	0	0	0	37
US 20	SW 15th	14	5	2	2	0	1	0	0	0	0	0	0	24
US 101	Devils Lake	13	3	0	0	0	0	0	1	0	0	0	0	17
US 101	Wilson River Lp	6	15	3	3	0	0	1	0	0	2	0	0	30
OR 126	69th	8	8	1	1	0	0	0	0	0	1	0	0	19
US 20	27th	10	8	0	0	0	0	0	1	1	0	0	0	20
OR 99	South Stage Rd	12	4	2	1	0	0	0	0	0	0	0	0	19
US 30BY	NE 60th	9	7	4	3	0	0	0	1	0	1	0	0	25
US 199	Dowell	9	5	8	0	0	0	0	1	0	0	1	0	24
OR 99E	Off-ramp	2	3	1	0	1	0	0	0	0	0	0	0	7
OR 238	Sage	10	2	4	0	0	0	0	0	1	0	0	0	17
US 101	Zimmerman	2	4	1	0	0	0	0	0	0	0	0	0	7
US 101	Pacific Way	5	6	1	0	0	0	0	0	0	0	0	0	12
US 97	Cooley	37	3	4	3	0	0	0	0	0	0	0	0	47
OR 18	Norton	13	3	1	0	0	0	1	2	0	0	0	0	20
Speed Limit 45mph (reduced from upstream of intersection)														
OR 126	Territorial/200	10	2	3	3	0	0	0	1	0	0	0	0	19
US 101	Benham	4	2	0	1	0	0	0	0	0	1	0	1	9
US 97	Odem Medo Way	28	15	2	1	0	1	1	1	0	0	0	0	49
US 20	Goldfish Farm Rd	2	1	1	0	0	0	0	0	0	0	0	0	4
OR 99E	Old Hwy 34	2	2	3	0	0	0	0	0	0	0	0	0	7
US 26	Palmquist/14th	9	7	6	1	0	0	0	2	0	0	0	0	25
OR 18	Norton	13	3	1	0	0	0	1	2	0	0	0	0	20
OR 99E	Chemewa/Hazel Green	10	5	3	2	1	0	1	1	0	0	0	0	23
OR 126	Terry/Lane Mem Gardens	8	1	0	1	0	1	0	0	0	0	0	0	11

Table B.2: Crash Data for All Intersections (Continued)

Route Number	Cross Road	Number of Collisions												
		Rear-End	Turning	Angle	Sideswipe-Overtaking	Non-Collision	Other	Sideswipe-Meeting	Fixed Object	Backing	Pedestrian	Head-On	Parking	Total
Speed Limit 50 mph														
OR 42	Carnes/Roberts Cr	24	11	3	1	1	0	0	0	0	0	0	0	40
US 30	Deer Island/ Liberty Hill	3	2	0	0	0	0	1	0	0	0	1	0	7
OR 99W	Circle	20	7	12	2	1	0	1	0	1	0	0	0	44
US 30	E St	3	0	2	0	0	0	0	0	0	0	0	0	5
OR 99W	Conifer	11	4	1	1	0	0	0	0	0	0	0	0	17
Speed Limit 55mph														
OR 99W	Hoffman Rd	12	5	2	0	0	0	0	3	0	0	0	0	22
OR 99E	Douglas/Mt. Angel-Gervois	4	0	2	0	0	0	0	0	0	1	0	0	7
US 101	Salashan Lodge and Center	2	4	0	0	0	0	0	0	0	0	0	0	6
OR 126	Greenhill	7	1	1	0	0	0	2	1	0	0	0	0	12
OR 140	Hwy 22	23	16	2	3	1	0	0	0	2	0	0	0	47
OR 99E	Beta Dr	1	0	0	2	0	0	0	0	1	0	0	0	4
Hwy 92	Rockcrest	3	5	0	2	1	1	0	0	0	0	0	0	12
US 30	Roosevelt	31	4	5	2	0	0	0	1	0	0	0	0	43
US 26	J Jarl/Orient	7	1	3	2	1	2	0	5	0	0	0	0	21
OR 201	SW 18th/Butler	1	2	5	1	0	0	0	0	0	0	0	0	9
OR 99	Airport Rd	5	3	0	0	0	0	1	0	0	0	0	0	9
OR 99	Hwy 229	2	4	2	0	0	0	0	1	0	0	0	0	9
OR 99E	Barlow	8	7	4	1	0	1	0	2	1	0	0	0	24
OR 11	State Line Rd	1	2	0	1	0	0	0	1	0	0	0	0	5
OR 126	High/52nd	16	2	2	1	0	0	0	2	0	0	0	0	23

B.6 Sample Data Collection Forms

The following pages contain a blank sample of the data collection forms used in this project. General intersection information can be collected using Figure B.1 and basic signal phasing information can be determined using Figure B.2.

IHSSI Data Collection Form

Date: ___/___/___
Start Time: ___________
Data Collected By: ___________
Weather: __________
Major Rd Name: ______________________
Major Rd #: _______
Minor Rd Name: ______________________

All Red Time: ______sec
Yellow for Major: ______sec
Yellow for Minor: ______sec
Signal Control: Pretimed ☐
Fully Actuated ☐
Semi-Actuated ☐
Max Green Northbound: ________sec
Max Green Southbound: ________sec
Max Green Eastbound: ________sec
Max Green Westbound: ________sec

Volumes Collected ☐
Jamar Code __________________
Speed Data Collected ☐
Speed Collection Location: ______________

List additional traffic devices
and other comments below.

Major Approach 1 Direction: ___________
Isolated, High Speed ☐
Initial Speed Limit: _________mph
Final Speed Limit: ________mph
Change Location: ________ft behind stop bar
Advisory Sign: ________
Sign Location: _________ft behind stop bar

Major Approach 2 Direction: ___________
Isolated, High Speed ☐
Initial Speed Limit: _________mph
Final Speed Limit: ________mph
Change Location: ________ft behind stop bar
Advisory Sign: ________
Sign Location: _________ft behind stop bar

Minor Approach 1 Direction: ____________
Speed Limit: _________mph

Minor Approach 2 Direction: ____________
Speed Limit: _________mph

Draw intersection on back - include lane designations, signal heads, crosswalks, stop bars, north arrow, etc. ☐
Photographs ☐

____

____

____

____

____

Figure B.1: General Data Collection Form

Draw Phasing

Site: ______________________________

Date: ______________________________

Sketch Ring if Applicable

Transitions						
#	Yellow Time (sec)			All-Red Time (sec)		
1						
2						
3						
4						
5						
6						
7						
8						

Direction	Times

Figure B.2: Traffic Signal Phasing Form

B.7 Bibliography

Roess, R. P., Prassas, E. S., & McShane, W. R. (2004). *Traffic Engineering, Third Edition*. Upper Saddle River, NJ: Pearson Prentice Hall.

APPENDIX C CASE STUDY INFORMATION

This appendix contains information about the case studies presented in this thesis. These case studies are intended to further demonstrate the use of the described safety evaluation methods. Section C.1 presents signal phasing and clearance interval information for the three case studies. The safety evaluation templates do not contain this phasing information because more detailed information should be available to practitioners through signal timing plans. The following section provides historic evaluations and safety evaluation templates for the Barlow and OR 99E and Circle and 99W intersections. Table 10, contained in Section 4.4.3, lists key observations and treatment recommendations for these intersections.

C.1 Signal Phasing and Clearance Intervals

Figure C.1 presents the observed signal phasing diagrams and Table C.1 presents clearance interval timing for the eight studied intersections. In the phasing diagrams, black arrows indicate protected movements and gray arrows indicate permitted movements. Right turns are assumed to be permitted during the through phase. Major movements appear on the left half of the phasing, and minor movements appear on the right. All arrows follow the same convention for north.

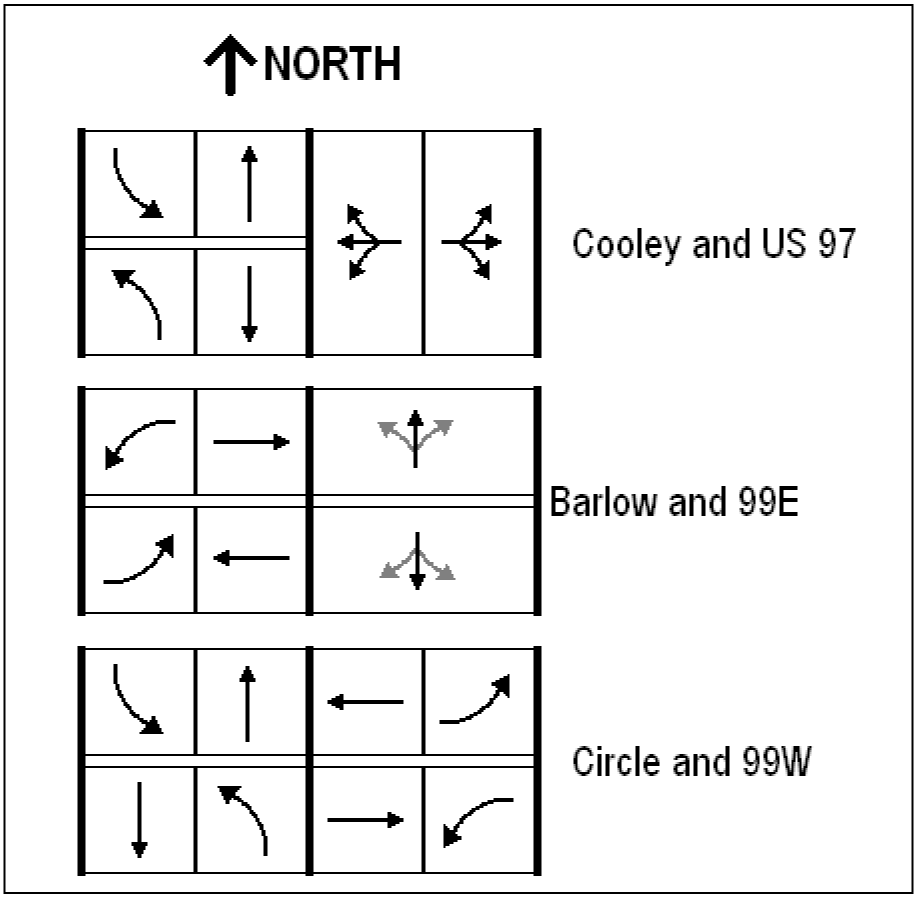


Figure C.1: Observed Signal Phasing

Table C.1: Intersection Transition Times

Intersection		Yellow Time (seconds)		All-Red Time (seconds)	
Minor Road	Major Road	Major to Minor	Minor to Major	Major to Minor	Minor to Major
Cooley	US 97	4	3	1	1
Barlow	OR 99E	4.5	4.5	1	1
Circle	OR 99W	5	4	0	0

C.2 Barlow and OR 99E/Circle and 99W Historic Evaluations and Safety Evaluation Templates

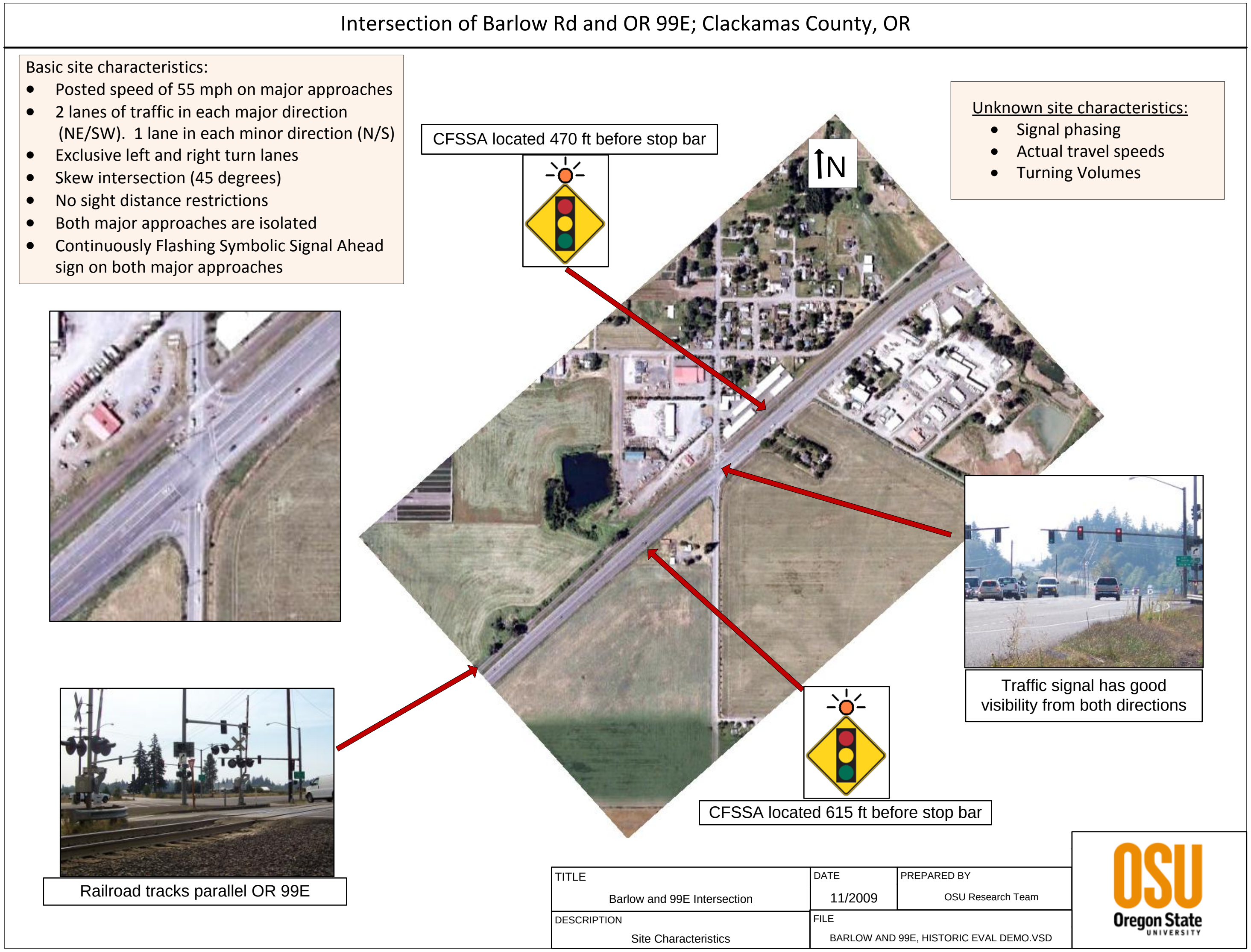
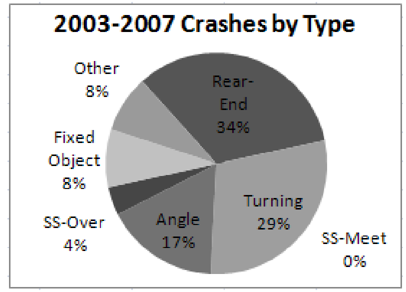


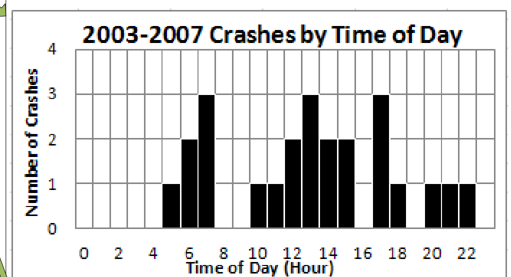
Figure C.2: Example Case Study Barlow and OR 99E (Site Information)

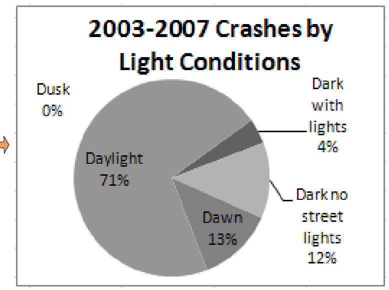
Intersection of Barlow Rd and OR 99E; Clackamas County, OR

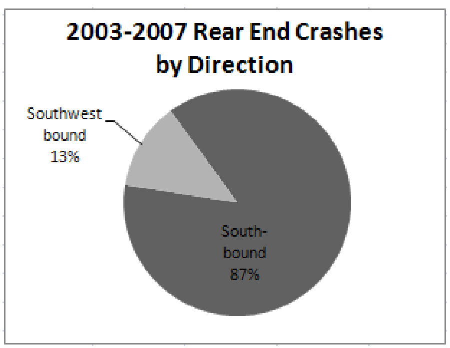
2003-2007 Crashes	
8	Rear-End
7	Turning
4	Angle
1	Sideswipe-Overtaking
0	Sideswipe-Meeting
2	Fixed Object
2	Other
24	Total

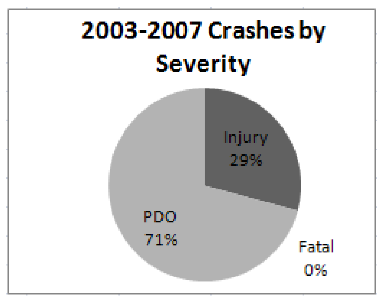


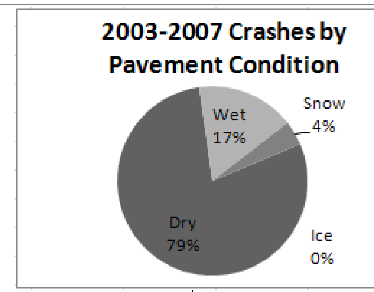
2003-2007 Rear End Crashes	
7	Southbound
1	Southwest-bound











TITLE	DATE	PREPARED BY
Barlow and 99E Intersection	11/2009	OSU Research Team
DESCRIPTION	FILE	
Crash data available	BARLOW AND 99E, HISTORIC EVAL DEMO.VSD	

Oregon State UNIVERSITY

Figure C.3: Example Case Study Barlow and OR 99E (Crash Data)

Intersection of Barlow and OR 99E , Clackamas County (Page 1)

	Northbound	Southbound	Eastbound	Westbound
Speed Limit	55 mph	35 mph	55 mph	55 mph
Isolated Major Approach (>1mile Isolation)	No	No	Yes	Yes
Advanced Intersection Warning*	CFSSA	CFSSA	CFSSA	CFSSA
Other	--	--	--	--

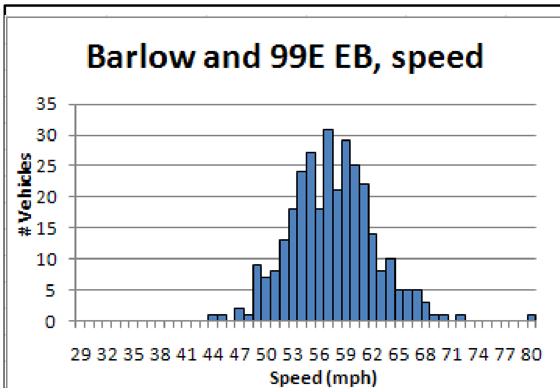
*SAS = Signal Ahead Sign
CFSSA = Continuous Flashing Symbolic Signal Ahead
PTSWF = Prepare to Stop when Flashing

Aerial photograph or diagram indicating intersection geometry and lane configurations

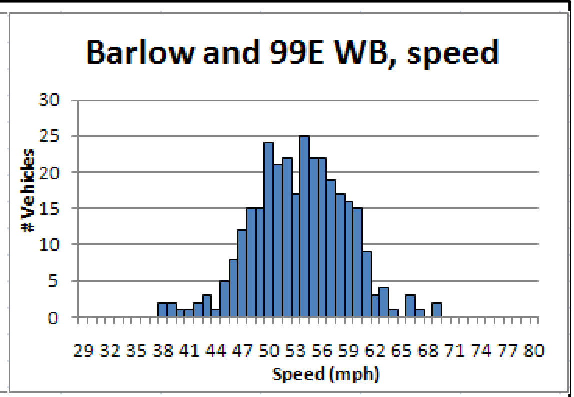
Figure C.4: Safety Evaluation Template, Barlow and OR 99E

Intersection of Barlow and OR 99E , Clackamas County (Page 2)

Picture showing typical arrangement and number of signal heads



Average eastbound speed = 57.9 mph



Average westbound speed = 53.9 mph

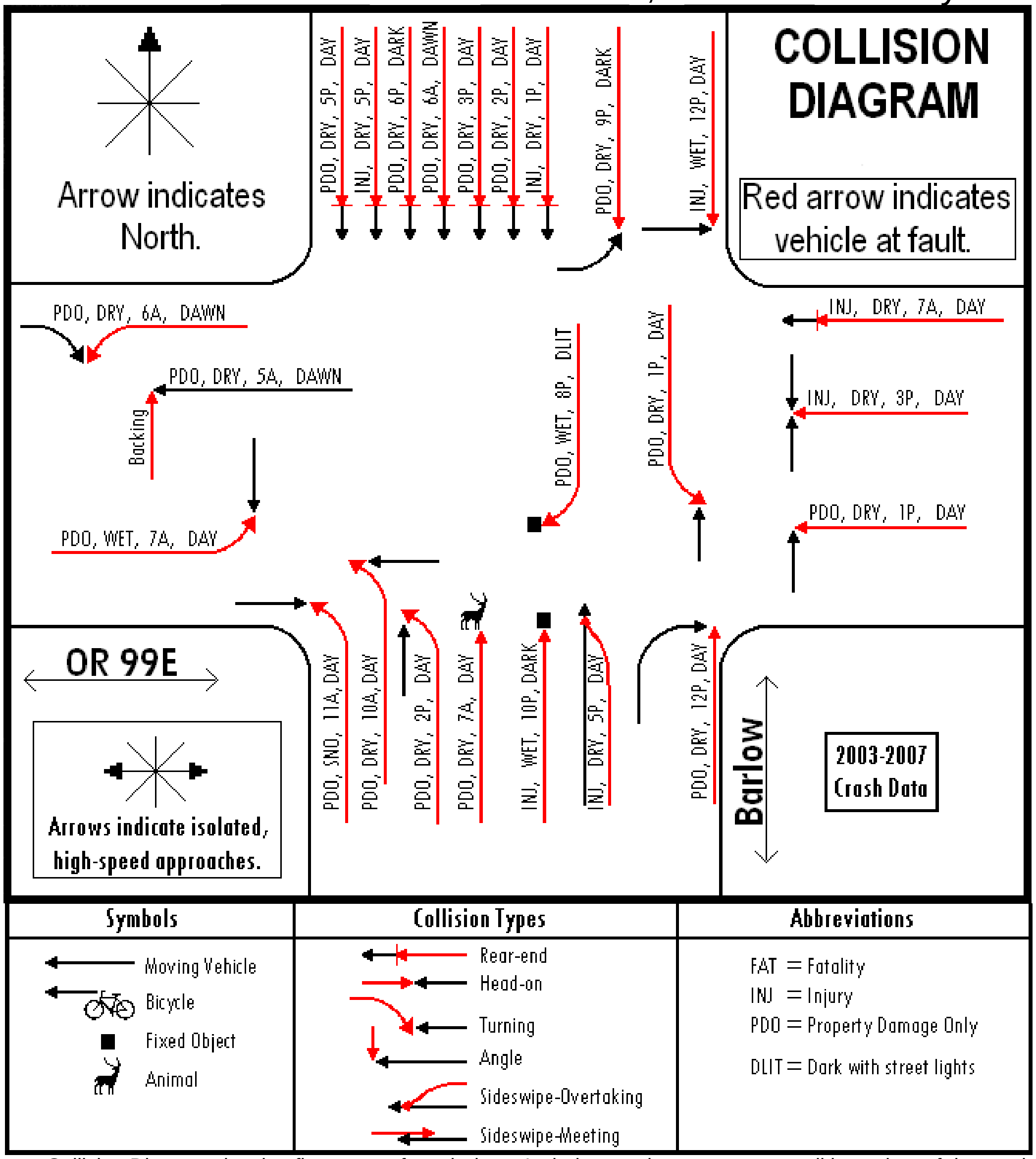
Graphs of speed data for high-speed approaches

		Volumes between 2:30pm and 3:00pm on 9/23/09 Su M T W R F Sa			
Direction	AADT	% left turns	% right turns	% total turns	Total # of Vehicles
Northbound	unknown	5.3	53.3	58.6	75
Southbound	unknown	66.3	6.3	72.6	175
Eastbound	11000	5.6	0.5	6.1	213
Westbound	21400	13.3	30.2	43.5	398

Other notes: Northbound and southbound signal heads have extra long visors to block view from minor approaches. Railroad tracks parallel 99E on the north.

Figure C.4: Safety Evaluation Template, Barlow and OR 99E (Continued)

Intersection of Barlow and OR 99E, Clackamas County (Page 3)



Collision Diagram showing five years of crash data. Include severity, pavement conditions, time of day, and light conditions. Indicate vehicle at fault with red arrow. Include description of symbols/abbreviations.

Feedback from users familiar with intersection:

Figure C.4: Safety Evaluation Template, Barlow and OR 99E (Continued)

4-leg, Signalized Oregon Intersections with at Least One High-Speed, Isolated Approach

Barlow and OR 99E

Average Crash Percentages

speed limit (mph)	# Lanes	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged
45	1	57.7	22.2	9.9	5.7	0.7	2.1	1.7	100	4	48.8	29.6	11.8	3.8	0.7	2.0	3.3	100	16
	2	45.8	32.1	12.4	3.2	0.7	1.9	3.8	100	12									
55 to 45	1	52.6	10.5	15.8	15.8	0.0	5.3	0.0	100	1	50.0	21.2	14.4	5.6	1.3	3.3	4.2	100	9
	2	46.9	24.9	16.8	2.9	1.2	3.3	4.0	100	6									
	1→2	58.1	15.4	6.5	8.9	2.2	2.2	6.7	100	2									
50	2	54.6	19.1	16.1	2.6	3.3	0.0	4.3	100	5	54.6	19.1	16.1	2.6	3.3	0.0	4.3	100	5
55	1	50.5	26.4	10.1	1.3	3.3	4.4	4.1	100	5	41.3	24.4	12.0	8.5	1.9	6.4	5.7	100	15
	2	36.7	23.4	12.9	12.0	1.1	7.4	6.4	100	10									
										OVERALL	46.8	25.2	13.0	5.7	1.4	3.4	4.5	100	44

Fill in data for specific intersection. Circle applicable averages listed above.

55	**2**	**33.3**	**29.2**	**16.7**	**4.2**	**0.0**	**8.3**	**8.3**	**100**	Crash % = (# of one type of crash) / (# total crashes)

Average Crash Rates (#Crashes in 5 year period x 10000 / AADT)

speed limit (mph)	# Lanes	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged
45	1	8.6	3.1	1.2	0.6	0.2	0.3	0.3	14.3	4	6.3	3.5	1.4	0.5	0.1	0.3	0.4	12.6	16
	2	5.6	3.7	1.5	0.5	0.1	0.2	0.5	12.1	12									
55 to 45	1	10.9	2.2	3.3	3.3	0.0	1.1	0.0	20.7	1	5.4	2.1	1.3	0.7	0.2	0.5	0.3	10.6	9
	2	4.5	2.1	1.1	0.2	0.2	0.4	0.3	8.8	6									
	1→2	5.5	2.1	1.1	1.0	0.4	0.4	0.6	11.0	2									
50	2	6.7	2.6	2.2	0.5	0.3	0.0	0.5	12.6	5	6.7	2.6	2.2	0.5	0.3	0.0	0.5	12.6	5
55	1	5.3	2.7	0.9	0.2	0.2	0.6	0.4	10.3	5	4.2	2.2	1.3	0.6	0.1	0.6	0.4	9.4	15
	2	3.7	1.9	1.5	0.8	0.1	0.5	0.4	8.9	10									
										OVERALL	5.4	2.7	1.4	0.6	0.1	0.4	0.4	11.1	44

Fill in data for specific intersection. Circle applicable averages listed above.

55	**2**	**4.9**	**4.3**	**2.5**	**0.6**	**0.0**	**1.2**	**1.2**	**14.8**	Crash rate = (#crashes in 5yr period)x(10,000)/(AADT)

Comments: **All crash rates appear high (except 'Sideswipes'). Percentages look reasonable.**

'Fixed Object' seems high - 2 crashes from minor approaches (both while wet and dark).

Other' section based on 1 'Backing' and 1 'Animal' Collision.

Figure C.4: Safety Evaluation Template, Barlow and OR 99E (Continued)

Potential Countermeasures for Isolated, High-Speed, Signalized Intersections

Rear End

- Create turn lanes
- Install advanced warning devices
- Remove sight obstructions
- Install 12 inch signal lenses
- Install visors
- Install/enhance backplates
- Improve location/number of signal heads (e.g. near-side)
- Adjust/extend amber/all-red
- Provide progression (if not isolated approach)
- Adjust signal timing
- Improve skid resistance
- Reduce speeds - traffic calming or lower speed limit (after study)
- Lengthen mast arms
- Install additional loops
- Check equipment for malfunction
- Install transverse pavement markings
- Install extension of green time systems (Advance Detection Control Systems)
- Remove signal (see MUTCD)

Turning

General treatments

- Remove sight obstructions
- Adjust signal timing
- Adjust/extend amber/all-red
- Reduce speeds - traffic calming or lower speed limit (after study)

If turning vehicle at fault

- Add protected phase (remove permitted phase)
- Increase/add turn lane
- Provide channelization
- Increase curb radii

If through vehicle at fault refer to Angle treatments

Angle

- Remove sight obstructions
- Install advanced warning devices
- Install 12 inch signal lenses
- Install visors
- Install/enhance backplates
- Improve location/number of signal heads (e.g. near-side)
- Reduce speeds - traffic calming or lower speed limit (after study)
- Adjust/extend amber/all-red
- Adjust signal timing
- Provide progression (if not isolated approach)
- Improve skid resistance
- Channelize intersection
- Check equipment for malfunction
- Install transverse pavement markings
- Install extension of green time systems (Advance Detection Control Systems)

Sideswipe

General treatments

- Install/improve pavement markings
- Channelize intersection

Overtaking Sideswipe

- Provide turning bays
- Install acceleration/ deceleration lanes
- Install/improve directional signing
- Restrict driveway access near intersection
- Reduce speeds - traffic calming or lower speed limit (after study)

Meeting Sideswipe

- Install median divider/barrier
- Widen lanes
- Install no passing zone signage

Fixed Object

- Remove/relocate obstacles
- Install barrier curbing
- Install breakaway features
- Reduce number of utility poles
- Relocate islands
- Widen lanes
- Install/improve pavement markings (include edgeline delineation)
- Install edgeline rumble strips
- Protect objects with guardrail or attenuation device
- Re-align intersection
- Check vertical alignment
- Upgrade roadway shoulders
- Improve channelization
- Close curb lanes
- Install advanced warning devices
- Reduce speeds - traffic calming or lower speed limit (after study)

Wet Pavement Treatments

- Overlay/groove existing pavement
- Reduce speeds - traffic calming or lower speed limit (after study)
- Provide "slippery when wet" signs
- Improve skid resistance
- Provide adequate drainage
- Upgrade pavement markings
- Install chip seal
- Install open graded asphalt concrete

Night Accident Treatments

- Install/improve street lighting
- Install/improve pavement markings
- Install/improve warning signs
- Upgrade signing
- Provide illuminated signs
- Install pavement markings
- Provide raised markers
- Upgrade advance warning signs

Figure C.4: Safety Evaluation Template, Barlow and OR 99E (Continued)

Intersection of Circle Blvd and OR 99W; Benton County, OR

Basic site characteristics:

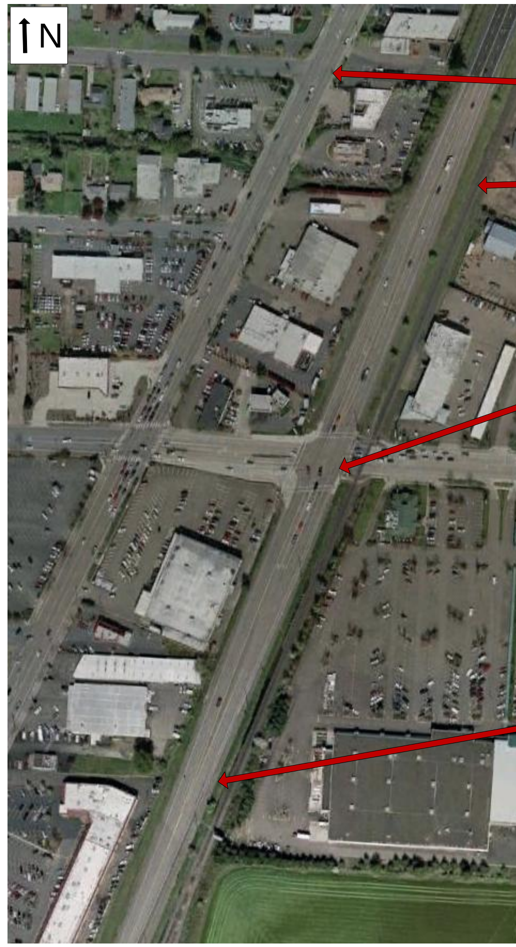
- Posted speed of 50 mph on major approach
- 2 lanes of traffic in each major direction (N/S). 2 lanes in each minor direction (E/W)
- Exclusive left turn lanes
- Intersection has slight skew (70 degrees)
- No sight distance restrictions
- Northbound approach is isolated
- Signal Ahead Sign on northbound approach

9th Street parallels OR 99W on the west.
The railroad tracks parallel OR 99W on the east.

Unknown site characteristics:

- Signal phasing
- Actual travel speeds
- Turning Volumes

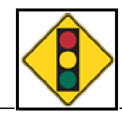
↑N



Signalized intersection located ~1800 ft to the north

9th Street

Traffic signal has good visibility



SAS located 700 ft before stop bar

TITLE	DATE	PREPARED BY
Circle and 99W Intersection	11/2009	OSU Research Team
DESCRIPTION	FILE	
Site Characteristics	CIRCLE AND OR 99W, HISTORIC EVAL DEMO.VSD	

OSU Oregon State UNIVERSITY

Figure C.5: Example Case Study, Circle and 99W (Site Information

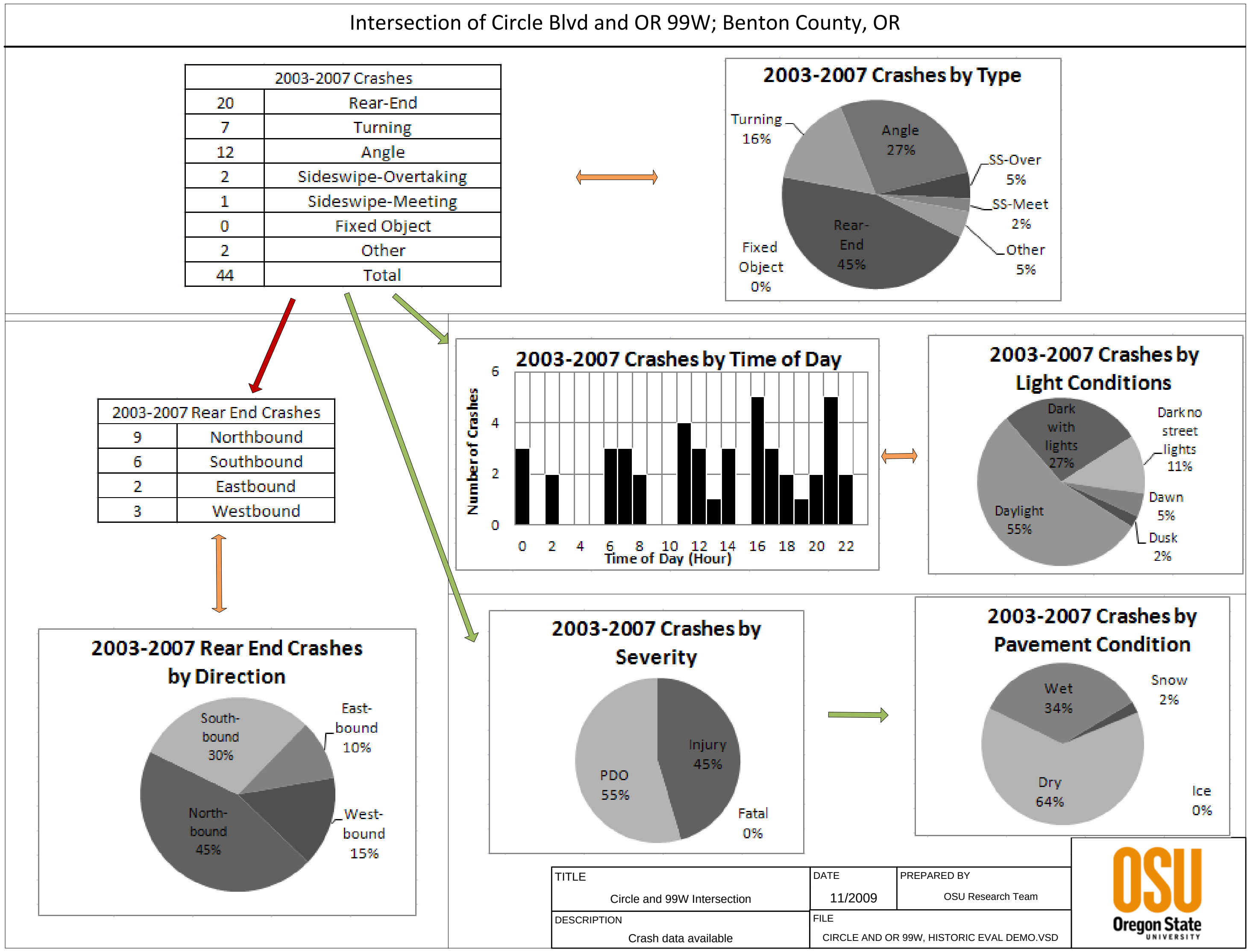


Figure C.6: Example Case Study, Circle and OR 99W (Crash Data)

Intersection of Circle and OR 99W , Benton County (Page 1)

	Northbound	Southbound	Eastbound	Westbound
Speed Limit	50 mph	50 mph	35 mph	35 mph
Isolated Major Approach (>1mile Isolation)	Yes	No	No	No
Advanced Intersection Warning*	SAS	--	--	--
Other	--	--	--	--

*SAS = Signal Ahead Sign
CFSSA = Continuous Flashing Symbolic Signal Ahead
PTSWF = Prepare to Stop when Flashing

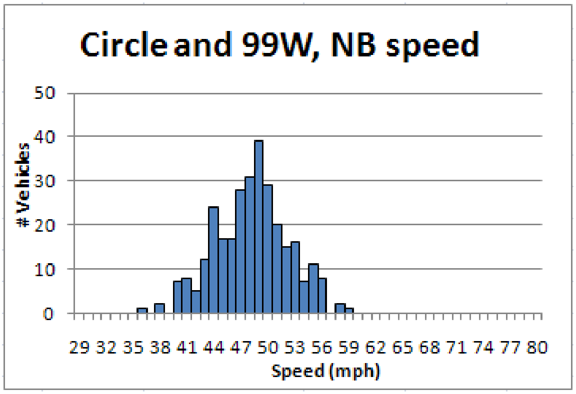
Aerial photograph or diagram indicating intersection geometry and lane configurations

Figure C.7: Safety Evaluation Template, Circle and OR 99W

Intersection of Circle and OR 99W , Benton County (Page 2)

Image shows northbound approach.

Picture showing typical arrangement and number of signal heads



Average northbound speed = 48.7 mph

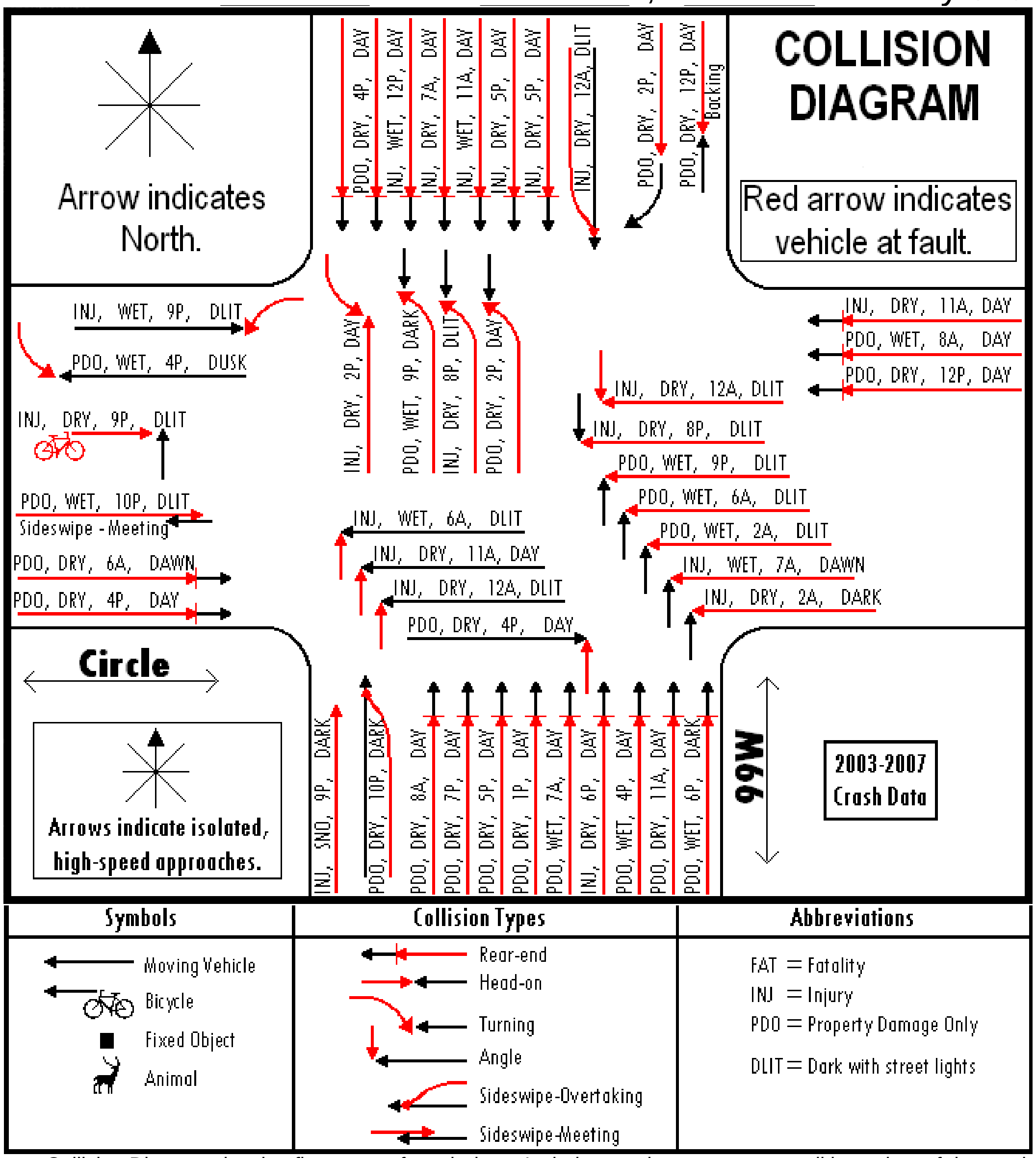
Graphs of speed data for high-speed approaches

		Volumes between 3:00pm and 3:30pm on 9 /14 / 09 Su M T W R F Sa			
Direction	AADT	% left turns	% right turns	% total turns	Total # of Vehicles
Northbound	18,200	22.5	16.1	38.6	378
Southbound	14,500	13.2	9.2	22.4	304
Eastbound	unknown	11.0	23.8	34.8	374
Westbound	unknown	15.0	12.6	27.6	293

Other notes: Stop bar for westbound traffic is ~30 ft past railroad tracks. Stop bar for eastbound traffic is ~400 ft past signalized intersection of Circle and 9th. Northbound approach changes from 1 to 2 lanes ~700 ft before stop bar.

Figure C.7: Safety Evaluation Template, Circle and 99W (Continued)

Intersection of Circle and OR 99W, Benton County (Page 3)



Collision Diagram showing five years of crash data. Include severity, pavement conditions, time of day, and light conditions. Indicate vehicle at fault with red arrow. Include description of symbols/abbreviations.

Feedback from users familiar with intersection:

Figure C.7: Safety Evaluation Template, Circle and 99W (Continued)

4-leg, Signalized Oregon Intersections with at Least One High-Speed, Isolated Approach

Circle and OR 99W

Average Crash Percentages

speed limit (mph)	# Lanes	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged
45	1	58	22	9.9	5.7	0.7	2.1	1.7	100	4	49	30	12	3.8	0.7	2.0	3.3	100	16
	2	46	32	12	3.2	0.7	1.9	3.8	100	12									
55 to 45	1	53	11	16	16	0.0	5.3	0.0	100	1	50	21	14	5.6	1.3	3.3	4.2	100	9
	2	47	25	17	2.9	1.2	3.3	4.0	100	6									
	1→2	58	15	6.5	8.9	2.2	2.2	6.7	100	2									
50	2	55	19	16	2.6	3.3	0.0	4.3	100	5	55	19	16	2.6	3.3	0.0	4.3	100	5
55	1	50	26	10	1.3	3.3	4.4	4.1	100	5	41	24	12	8.5	1.9	6.4	5.7	100	15
	2	37	23	13	12	1.1	7.4	6.4	100	10									
										OVERALL	47	25	13	5.7	1.4	3.4	4.5	100	44

Fill in data for specific intersection. Circle applicable averages listed above.

50	**2**	**46**	**16**	**27**	**4.5**	**2.3**	**0.0**	**4.5**	**100**	Crash % = (# of one type of crash) / (# total crashes)

Average Crash Rates (#Crashes in 5 year period x 10000 / AADT)

speed limit (mph)	# Lanes	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged	REAR-END	TURNING	ANGLE	SS-OVER	SS-MEET	FIXED OBJ	OTHER	TOTAL	# Intersections Averaged
45	1	8.6	3.1	1.2	0.6	0.2	0.3	0.3	14	4	6.3	3.5	1.4	0.5	0.1	0.3	0.4	13	16
	2	5.6	3.7	1.5	0.5	0.1	0.2	0.5	12	12									
55 to 45	1	11	2.2	3.3	3.3	0.0	1.1	0.0	21	1	5.4	2.1	1.3	0.7	0.2	0.5	0.3	11	9
	2	4.5	2.1	1.1	0.2	0.2	0.4	0.3	8.8	6									
	1→2	5.5	2.1	1.1	1.0	0.4	0.4	0.6	11	2									
50	2	6.7	2.6	2.2	0.5	0.3	0.0	0.5	13	5	6.7	2.6	2.2	0.5	0.3	0.0	0.5	13	5
55	1	5.3	2.7	0.9	0.2	0.2	0.6	0.4	10	5	4.2	2.2	1.3	0.6	0.1	0.6	0.4	9.4	15
	2	3.7	1.9	1.5	0.8	0.1	0.5	0.4	8.9	10									
										OVERALL	5.4	2.7	1.4	0.6	0.1	0.4	0.4	11	44

Fill in data for specific intersection. Circle applicable averages listed above.

50	**2**	**12**	**4.3**	**7.3**	**1.2**	**0.6**	**0.0**	**1.2**	**27**	Crash rate = (#crashes in 5yr period)x(10,000)/(AADT)

Comments: **All crash rates are high (except Fixed Object). Percentages appear average.**

Angle collisions stand out as most overrepresented (followed by Overtaking Sideswipes and Rear-End).

Figure C.7: Safety Evaluation Template, Circle and 99W (Continued)

Potential Countermeasures for Isolated, High-Speed, Signalized Intersections

Rear End

- Create turn lanes
- Install advanced warning devices
- Remove sight obstructions
- Install 12 inch signal lenses
- Install visors
- Install/enhance backplates
- Improve location/number of signal heads (e.g. near-side)
- Adjust/extend amber/all-red
- Provide progression (if not isolated approach)
- Adjust signal timing
- Improve skid resistance
- Reduce speeds - traffic calming or lower speed limit (after study)
- Lengthen mast arms
- Install additional loops
- Check equipment for malfunction
- Install transverse pavement markings
- Install extension of green time systems (Advance Detection Control Systems)
- Remove signal (see MUTCD)

Turning

General treatments

- Remove sight obstructions
- Adjust signal timing
- Adjust/extend amber/all-red
- Reduce speeds - traffic calming or lower speed limit (after study)

If turning vehicle at fault

- Add protected phase (remove permitted phase)
- Increase/add turn lane
- Provide channelization
- Increase curb radii

If through vehicle at fault refer to Angle treatments

Angle

- Remove sight obstructions
- Install advanced warning devices
- Install 12 inch signal lenses
- Install visors
- Install/enhance backplates
- Improve location/number of signal heads (e.g. near-side)
- Reduce speeds - traffic calming or lower speed limit (after study)
- Adjust/extend amber/all-red
- Adjust signal timing
- Provide progression (if not isolated approach)
- Improve skid resistance
- Channelize intersection
- Check equipment for malfunction
- Install transverse pavement markings
- Install extension of green time systems (Advance Detection Control Systems)

Sideswipe

General treatments

- Install/improve pavement markings
- Channelize intersection

Overtaking Sideswipe

- Provide turning bays
- Install acceleration/ deceleration lanes
- Install/improve directional signing
- Restrict driveway access near intersection
- Reduce speeds - traffic calming or lower speed limit (after study)

Meeting Sideswipe

- Install median divider/barrier
- Widen lanes
- Install no passing zone signage

Fixed Object

- Remove/relocate obstacles
- Install barrier curbing
- Install breakaway features
- Reduce number of utility poles
- Relocate islands
- Widen lanes
- Install/improve pavement markings (include edgeline delineation)
- Install edgeline rumble strips
- Protect objects with guardrail or attenuation device
- Re-align intersection
- Check vertical alignment
- Upgrade roadway shoulders
- Improve channelization
- Close curb lanes
- Install advanced warning devices
- Reduce speeds - traffic calming or lower speed limit (after study)

Wet Pavement Treatments

- Overlay/groove existing pavement
- Reduce speeds - traffic calming or lower speed limit (after study)
- Provide "slippery when wet" signs
- Improve skid resistance
- Provide adequate drainage
- Upgrade pavement markings
- Install chip seal
- Install open graded asphalt concrete

Night Accident Treatments

- Install/improve street lighting
- Install/improve pavement markings
- Install/improve warning signs
- Upgrade signing
- Provide illuminated signs
- Install pavement markings
- Provide raised markers
- Upgrade advance warning signs

Figure C.7: Safety Evaluation Template, Circle and 99W (Continued)