RESEARCH

SAFETY EVALUATION OF CURVE WARNING SPEED SIGNS

Final Report

SPR 685
OTREC RR-11-18

RESEARCH ODOT/OTREC

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16. Abstract

This report presents a review of a research effort to evaluate the safety implications of advisory speeds at horizontal curve locations on Oregon rural two-lane highways. The primary goals of this research effort were to characterize driving operations at rural two-lane highway curve locations where advisory speed signs were present, and to determine to what extent these signs play a role in enhancing safety. Placement of advisory speed signs at horizontal curve locations in the State of Oregon is a practice aided by unique and specific state-level policies and, as such, may vary from nationally accepted procedures.

Speed data was collected at 16 sites and compliance with advisory speed signs determined. An evaluation of site crash data and how advisory speed relates to historic crash information is included along with a statistical model that identifies critical variables that are associated with the posted speed and how they ultimately relate to the expected crash frequency.
The research team developed a statistically based advisory speed model that assesses predicted crash outcomes based on a combination of geometric design, operations, and signage. The resulting advisory speed models were then contrasted to the expected advisory speeds based on the Oregon Policy as well as the *2009 MUTCD* thresholds. They determined that the safety-based model actually predicted advisory speeds that are not as conservative as those recommended using the ball-bank thresholds in the *2009 MUTCD* or those identified using the thresholds Oregon has been using.

Just prior to publication of this report, the Oregon Traffic Control Devices Committee (OTCDC) decided to adopt the *2009 MUTCD* without making an exception to advisory speed posting guidelines. ODOT has begun to transition to the *2009 MUTCD* advisory speed posting criteria. Actual adoption of the *2009 MUTCD* is expected to occur in August 2011.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
	NOTE: Volumes greater than 1000 L shall be shown in m^3.			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

SAFETY EVALUATION OF CURVE WARNING SPEED SIGNS

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EXECUTIVE SUMMARY

This report presents a review of a research effort to evaluate the safety implications of advisory speeds at horizontal curve locations on Oregon rural two-lane highways. The primary goals of this research effort were to characterize driving operations at rural two-lane highway curve locations where advisory speed signs were present, and to determine to what extent these signs play a role in enhancing safety. Placement of advisory speed signs at horizontal curve locations in the State of Oregon is a practice aided by unique and specific state-level policies and, as such, may vary from nationally accepted procedures.

This report includes a brief literature review of recent research regarding advisory speed signs. Although a widely-accepted standard procedure is often used to determine advisory speeds (the ball-bank indicator method), there are several different ball-bank thresholds commonly actively used in the United States. This summary only highlights the current Oregon threshold and the newly established *2009 MUTCD* threshold.

This report then presents a summary of the experimental design (Chapter 3) and the data collection phases (Chapter 4), with a special emphasis on Oregon safety conditions and their apparent associations with advisory speed signs. This report also presents findings based on observed operational speed data and compliance with advisory speed signs.

An evaluation of site crash data and how advisory speed relates to historic crash information is included in Chapter 5 along with a statistical model that identifies critical variables that are associated with the posted speed and how they ultimately relate to the expected crash frequency.

Chapter 6 reviews the expected safety implications if Oregon adopts the *2009 MUTCD* thresholds. Chapter 7 provides an alternative computational procedure that is based explicitly on predicted safety performance.

The report concludes with recommendations and supporting documentation (located in the report appendices).

The research team developed a statistically based advisory speed model that assesses predicted crash outcomes based on a combination of geometric design, operations, and signage. The resulting advisory speed models were then contrasted to the expected advisory speeds based on the current Oregon Policy as well as the *2009 MUTCD* thresholds. They determined that the safety-based model actually predicted advisory speeds that are not as conservative as those recommended using the ball-bank thresholds in the *2009 MUTCD*. The resulting advisory speed predictions were generally not as conservative as those identified using the current Oregon Policy thresholds.

Just prior to publication of this report, the Oregon Traffic Control Devices Committee (OTCDC) decided to adopt the *2009 MUTCD* without making an exception to advisory speed posting guidelines. ODOT has begun to transition to the *2009 MUTCD* advisory speed posting criteria. Actual adoption of the *2009 MUTCD* is expected to occur in August 2011.

1.0 INTRODUCTION

The use and placement of advisory speed signs at horizontal curve locations in the State of Oregon is determined by guidance in the Oregon Department of Transportation (ODOT) *Traffic Manual* and the *ODOT Sign Policy and Guidelines*. Currently, Oregon uses a 13-10-7 threshold (*ODOT, 2006*) as demonstrated in Table 1.1; however, little is known about the origin of these current values. These state guidelines are a supplement to the *Manual of Uniform Traffic Control Devices* (*MUTCD*). The *2003 MUTCD* included a change in recommended guidance for establishing advisory speeds on Exit, Ramp, and Curve Speed Signs. Traditionally, advisory speeds have been established by driving a vehicle equipped with a ball-bank indicator around a curve at a specified speed and noting the ball-bank indicator reading. Based on research from the 1930's, a 10 degree ball-bank indicator reading was formerly used in determining advisory speeds. The *2003 MUTCD* changed the 10 degree reading to a 16 degree ball-bank indicator reading, based on perceived performance of modern vehicles and speeds at which most drivers' judgment recognizes "incipient instability" along a ramp or curve.

Table 1.1: Oregon and National Advisory Speed Ball-Bank Thresholds

Oregon Thresholds	**_MUTCD_ 2009 Thresholds**
13 degrees (≤ 30 mph) 10 degrees (35 to 55 mph) 7 degrees (≥ 60 mph)	16 degrees (≤ 20 mph) 14 degrees (25 to 30 mph) 12 degrees (≥ 35 mph)

Posting Comparison Shown for Individual Speed Thresholds:

Speed	**Oregon Policy**	**_MUTCD_ 2009**
≤ 20 mph	13 degrees	16 degrees
25 to 30 mph	13 degrees	14 degrees
35 to 55 mph	10 degrees	14 degrees
≥ 60 mph	7 degrees	12 degrees

Source: ODOT, 2006 and FHWA, 2009

Subsequent to the publication of the 2003 Edition of the *MUTCD*, the Advisory Speed Task Force of the National Committee on Uniform Traffic Control Devices Regulatory and Warning Signs Technical Committee identified inconsistencies in the *MUTCD* text regarding the advisory speed issue and began re-evaluating this modified advisory speed posting guidance. Though historically the ball-bank thresholds have varied slightly at national level, the current recommendation for posting advisory speeds is a 16-14-12 threshold (*MUTCD, 2009*) as depicted in Table 1.1. This value is based on the assumption that drivers generally tend to exceed the posted advisory curve speed by as much as 7 to 10 mph. As a result, the recently adopted thresholds more closely reflect expected driver performance at horizontal curve locations. The Committee further recommended that the criteria for advisory speed engineering studies can be based on ball-bank criteria, accelerometer readings, or calculations using side friction factors. These recommendations are now reflected in the *2009 MUTCD*.

Since the Oregon posting procedures are different than the newly recommended values, the State of Oregon must determine if it is appropriate to adopt the new, somewhat less conservative values or to retain the current thresholds. As shown in Table 1.1, the posting thresholds between Oregon and *MUTCD* recommendations differ the greatest for speeds at or below 20 mph and for those above 35 mph. The safety implications associated with the Oregon and national posting procedures are, therefore, an ultimate focus of this research effort.

In 2008, researchers at Oregon State University (OSU) completed a research effort (State Planning and Research (SPR) Project 641, *Methodologies for Estimating Advisory Curve Speeds on Oregon Highways*) to evaluate the identification and marking of advisory speeds on Oregon highways. In particular, this research effort focused on the implications of modified advisory speed thresholds and identification procedures following the most recent and the upcoming *MUTCD* and the *Traffic Control Devices (TCD) Handbook* recommendations. The objectives of this research effort were to help identify the basis for the current and proposed advisory speed posting procedures (with specific attention to the horizontal curve location on rural two-lane roads), to evaluate Oregon placement strategies at a variety of locations, and to identify potential criteria for establishing advisory speeds for these curved sections on Oregon highways. Included with this evaluation was an assessment of associated costs for implementation of a modified advisory speed policy in Oregon. The research did not evaluate the associated safety of the various speed posting thresholds. Additionally it was found that the linkage between advisory speed signs and the road safety record at curve warning locations has never been identified (regionally or nationally), simply presumed.

This research, therefore, evaluated the safety record for the randomly sampled curve locations and contrasted this finding with sign compliance in an effort to determine the safety implications of various advisory speed signage treatments. This effort focused on the posted advisory speeds at 160 randomly selected rural highway locations in Oregon (80 on state-maintained highways and 80 on county highways). The project team contrasted the historic crash record at the 80 state-maintained locations with their companion posted advisory signs. This assessment included locations where advisory signs were posted but not in direct correlation with Oregon standards and locations where advisory speed signs were warranted but not posted. In addition, the research team studied a *targeted random sample* of sites to assess prevailing operating speed conditions and to aid in determining how the posted advisory speeds corresponded with driver selected operating speeds. This group of sites included a variety of companion horizontal curve radii so that the direct influence of road geometry could be included in the assessment. Chapter 3 describes in more detail the various data samples available for analysis in this project.

The 2009 edition of the *MUTCD* recommends modified thresholds for advisory speeds that vary from the current Oregon threshold. This research will help decision makers in Oregon determine if they want to adopt new *MUTCD* thresholds and invest in the placement of new advisory speed signs based on these modified thresholds. This research will aid Oregon decision makers by determining specific safety implications of current posted advisory speeds and the implications of either modifying the posting threshold or enforcing the current threshold. This research will also help identify priorities for sign upgrades by determining the safety implications of the various compliance levels.

The goal of this proposed research was to provide guidance so that advisory speeds are adequately posted in the State of Oregon in a manner that helps improve safety and with particular emphasis on higher speed rural horizontal curve locations. To accomplish this goal, this research project addressed two key objectives. These are summarized as follows:

- Use randomly selected curve locations including upstream and downstream regions of the typical two-mile study corridor to contrast the historic safety record with the advisory speeds posted, the proposed modified advisory speed thresholds, and the observed operating speeds (where applicable).

- Evaluate potential advisory speed posting assessment procedures that can be performed prior to or instead of the current ball-bank field evaluation. These alternative procedures may ultimately provide more consistent and cost effective advisory speed posting techniques.

Chapter 2 of this report presents a brief review of literature about advisory speed research or key information that has occurred since the completion of the previous ODOT advisory speed project.

Chapters 3 and 4 describe the procedures by which sites were selected, and speed data collected and evaluated. Chapter 3 reviews site selection and how the 180 site *statewide random sample* corresponds to the 16 site *targeted random sample*. Chapter 4 also presents some relevant characteristics of the measured operating speeds at the study sites.

Chapter 5 presents an assessment of the crash data contrasted to the speed data for the *targeted random sample* (16 corridors where the project team measured actual operating speed) and the state-maintained corridors in the *statewide random sample* (80 corridors where previous researchers measured physical geometric elements and surveyed the posted advisory speeds). This analysis provides observations regarding crash trends at sites with a variety of geometric and operational characteristics as well as a statistical assessment of the influential factors that affected the posted advisory speeds and anticipated safety performance.

Chapter 6 reviews the expected safety effects of adopting the *2009 MUTCD* thresholds for Oregon. Chapter 7 summarizes a proposed computational method developed by the project team that would not require the use of a ball-bank indicator and would permit more consistent posting of advisory speeds that are based on expected safety performance.

Chapter 8 provides concluding comments and recommendations and is followed by a list the cited references and seven appendix items that provide supporting documentation for the project report.

2.0 LITERATURE REVIEW

In 2008, researchers at OSU, in conjunction with the Oregon Department of Transportation (ODOT), completed a research project titled *Methodologies for Estimating Advisory Curve Speeds on Oregon Highways* (SPR 641). As part of that effort, the research team performed a comprehensive literature review to determine the science behind current advisory speed posting thresholds and procedures. At that time, five common thresholds were in use by the various state and local agencies. The purpose of this abbreviated literature review is to identify subsequent research efforts that have occurred, this summary includes two topics. First, the literature review briefly identifies the three common recommended methods for determining warrants for advisory speed posting. The literature review also provides information about a recent research project completed in Texas that recommended methods for evaluating the need for advisory speeds.

2.1 ADVISORY SPEED EVALUATION METHODS

A wide variety of non-traditional advisory speed evaluation methods exist, but the *MUTCD* (*2009*) acknowledges that there are three established procedures that are recommended for determining the appropriate advisory speed procedure at horizontal curve locations. These methods are:

- Use an accelerometer to directly determine side friction factors;
- Use a design speed equation; or
- Use a traditional ball-bank indicator.

The use of an accelerometer is a relatively new technology. This device is mounted on a vehicle's dashboard and can directly monitor the performance of the vehicle as it navigates horizontal curves. A common concern regarding the use of an accelerometer includes the fact that it is very sensitive to pavement imperfections. Since a perceived advantage of this device is that data can be collected by one person (who may also be the vehicle driver), the device records the extreme conditions so when a vehicle encounters a rough pavement location the recorded value may be used for the associated side friction factor. This value may not be representative of actual conditions for the length of a study section. Using a second person to monitor the incremental values as the vehicle traverses the curve or capturing a stream of data from the accelerometer that shows the intermittent values can address this concern.

The second method identified is the design speed equation. This equation can be found in the document *A Policy on Geometric Design of Highways and Streets (AASHTO, 2004)*. Inputs for the design speed equation include expected velocity, curve radius, and superelevation (the cross-slope within the horizontal curve). An advantage for this approach is that is can be applied based on calculations and does not require field testing; however, it may be appropriate to field verify values as there may be considerable fluctuation in the friction factor at a site over time as well as for the final construction of the superelevation and its associated rate of transition.

The third and final method for determining advisory speed posting is the more commonly used ball-bank approach. The use of a ball-bank indicator (also known as a slope meter) as a tool for determining safe operating speeds on curves in the United States occurred as early as 1937. Though electronic versions are now available, this simple tool is a curved level that is mounted in a test vehicle. The ball-bank reading, in degree units, represents the combined influences of vehicle body-roll, lateral acceleration angle, and superelevation. Figure 2.1 depicts the various values represented by a ball-bank angle reading.

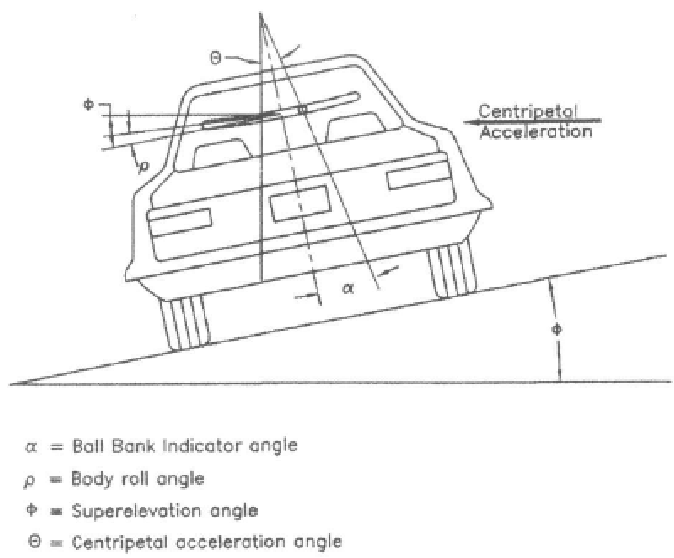


Figure 2.1: Geometry for the Ball-Bank (Source: *AASHTO 2004*)

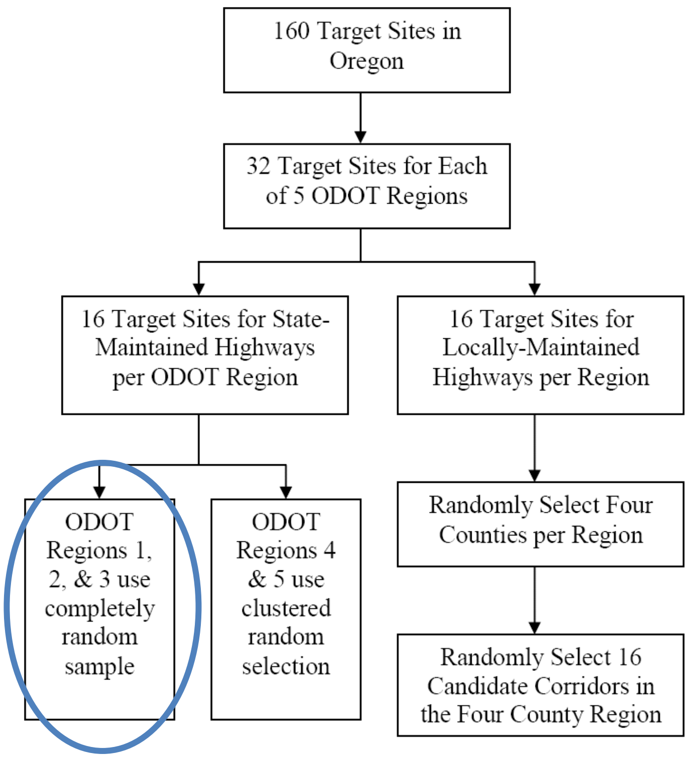
The ball-bank indicator displays an angular reading that represents the measurement from the vehicle centerline (perpendicular to the road) to a value representative of the forces acting on a vehicle in motion as it traverses a curve. For a vehicle parked on a level surface, the ball-bank indicator would display a 0 degree value. To assess a curve condition, a vehicle equipped with a ball-bank indicator traverses the curve at 5 mph intervals. For each test run the ball-bank value is recorded. The advisory speed is then defined as the maximum speed for which the ball-bank value does not exceed some predetermined threshold. Table 1.1 on page 3 summarized the Oregon and *MUTCD* recommended ball-bank thresholds.

2.2 RECENT ADVISORY SPEED RESEARCH

As previously indicated, the previous Oregon research effort (SPR 641) included a historic review of advisory speed literature. Since that report was completed, there has only been one additional relevant study that focused on this topic. The Texas Transportation Institute (TTI) performed research for the Texas Department of Transportation to assess methods for determining a need for posting advisory speed signs. The initial stages of the project were focused on developing a *Horizontal Curve Signing Handbook* to be used in the State of Texas (*Bonneson et al., 2008*); however, the TTI research team soon observed that there were considerable inconsistencies as to how advisory speed posting occurred. These differences resulted in considerable variability in selected advisory speed values. Upon additional investigation, the TTI team determined that they could not acquire consistent values for speeds when using the ball-bank procedure or the accelerometer approach. As a result, they ultimately recommended that the most effective way to determine the appropriate advisory speed is to use the design speed equation approach (they referred to this as the compass method). This approach resulted in more consistent and unbiased speed values that were directly associated with the curve length, the deflection angle, and the superelevation rate. The TTI team further modified the approach to also incorporate a speed variable. They recommended that the basis for the speed could be the average speed selected by trucks on a corridor. In general they found that this speed is 2 to 3 mph lower than that of passenger cars and so is a conservative value (*Bonneson et al., 2009*). The TTI team members ultimately recommended the use of the compass method for providing more reliable and repeatable signing results combined with the corridor truck speeds as indicated above.

3.0 SAMPLE DESIGN FOR OPERATING SPEED EVALUATION

To successfully accomplish the objectives of this research effort, the project team first acquired data for a randomly selected sample of sites representative of two-lane rural highway advisory speed curve locations in the State of Oregon. Initial site selection occurred as part of a previous study titled *SPR 641: Methodologies for Estimating Advisory Curve Speeds on Oregon Highways,* by Dixon and Rohani (2008). Figure 3.1 demonstrates the site sampling procedure developed for this previous research effort.



Source: Dixon and Rohani (*2008*)

Figure 3.1: Stratified Sampling Procedure

For this new research effort, the project team used the previous study sample as an initial data set and then collected supplemental operating speed data at curve locations posted with advisory speed signs. This chapter presents an overview of the statistically based sample design used to gather the speed data. For the purposes of reference, the larger SPR 641 data sample from this point forward is referred to as the *statewide random sample*. Reference to the smaller study sample for Regions 1, 2, and 3 used in this extended analysis is referred to as the *targeted random sample*.

3.1 SITE SELECTION CRITERIA

Based on statistical projections, the research team estimated that speed data from approximately 15 sites should be acquired. However, due to randomly selected sites in close proximity to each other, the research team was able to collect data from 18 sites. Only 16 of these sites resulted in suitable quality data for use in this research effort.

The research team utilized the following three basic site selection strategies:

- The first step was to design a statistical procedure to gather complementary data for the 160 statewide random sample corridors used for the 2008 ODOT study. By using this approach, the sample for this project became a subsample of the larger set of sites from the 2008 study.
- The second step established a geographic boundary for the data collection sites. Candidate sites were selected from ODOT Regions 1, 2 and 3.The research team used two criteria to determine this targeted random sample of sites: (1) due to the large number of candidate sites in these regions, the research team could develop probability sampling; and (2) the majority of the Oregon population is located in these three ODOT Regions, so conclusions can be expected to be relevant at a policy making level.
- The third and final step was to only select sites from state-maintained corridors. This site selection strategy was based on the expectation that the advisory speed posting practices at these sites are generally consistent with ODOT standards and would therefore be more uniform than those of locally-maintained roads.

3.2 SAMPLE DESIGN

As indicated in Section 3.1, the research team executed a site sampling procedure based on the 160 *statewide random sample* corridors. Since the average corridor length at the sites was approximately two-miles, the 160 corridors resulted in 210 study curve locations. The circled region in Figure 3.1 depicts the subset of sites that served as a pool from which to draw the *targeted random sample* for this project.

Using the information available from the previous effort, the research team designed a probability sample that incorporated both sampling procedures: the one followed by Dixon and Rohani and the approach subsequently performed for this research effort. The selection of the estimated number of potential sites is reviewed in Section 3.3. First, the project team estimated the total number of candidate rural two-lane highway curves. That number was then used as input to determine a statistically representative number of sites appropriate for the extended operating speed analysis. The resulting sample size for this *targeted random sample* equated to a minimum of 15 locations.

3.3 ESTIMATION OF TOTAL NUMBER OF POTENTIAL SITES

For each of the three ODOT study regions, the researchers required a reasonable estimate of the total number of curve locations on state-maintained corridors where there is a posted advisory speed sign. This estimate could then be used as a basis for a reasonable probability sample (to further identify proposed data collection sites for the targeted random sample).

The research team used a computer simulation method to estimate how many potential two-lane rural state-maintained curve sites, based on the previous advisory speed study, exist in each of the three Oregon western regions. Table 3.1 shows the estimates for the number of candidate sites that resulted from this simulation-based approach. Figure 3.2 is a graphic display of the simulation results for Region 3. More details on the simulation results are available in Appendix D.

Table 3.1: Simulation-Based Estimates for Total Number of Sites

Region (k)	Upper Tail Alpha	Probability that Estimate is Above Actual Value	Estimate of Candidate Total Number of Sites per Region
1	0.005	99.5%	53
2	0.005	99.5%	435
3	0.005	99.5%	185
Total for Regions 1, 2, and 3:		98.5%	673

Upon development of the estimates of potential sites for each of the three ODOT Regions, the next step was to design a probability sample of sites. This effort included a combination of three sampling procedures at different stratification levels: (1) stratified sampling, (2) double sampling, and (3) cluster sampling. Figure 3.3 schematically depicts the structure under which the research team selected the sample of sites for speed data collection. Initially, the research team estimated speeds would be accurate within about ten miles per hour. This value does not reflect expected speed collection performance, but rather is a goal used for developing the probability estimate for actual speed and refers to a plus or minus five mile per hour target. Examination of field speed data later confirmed this estimate to be appropriate.

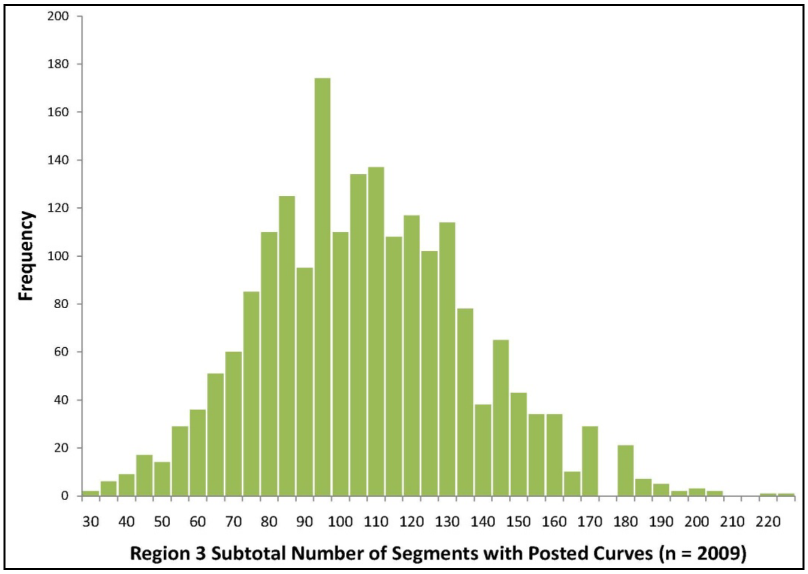


Figure 3.2: Simulation Graphic Output for Region 3

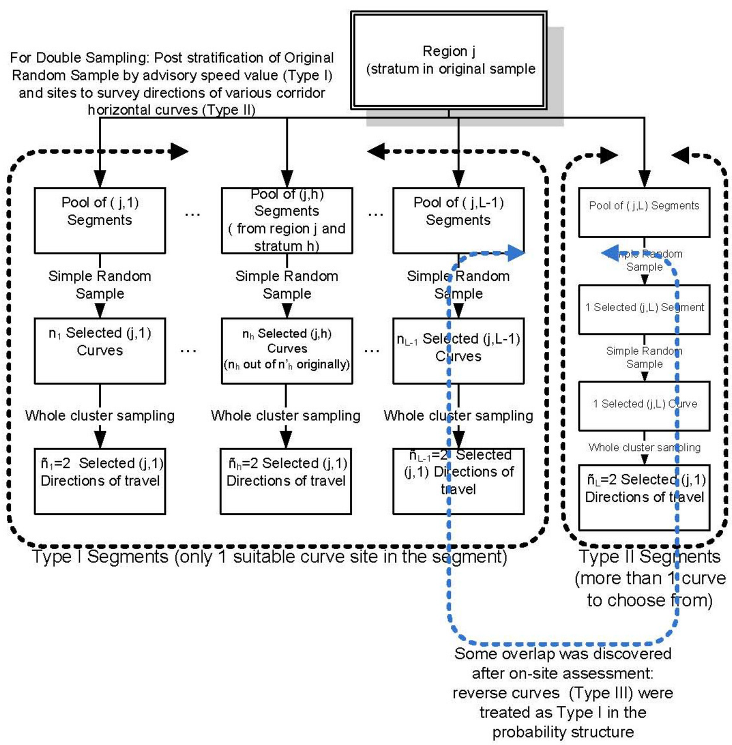


Figure 3.3: Sample Structure Design for Speed Data Collection

Table 3.2 shows a complete list of the sites selected as candidates for the final *targeted random sample*. The research team initially identified 20 potential sites for speed data collection. This oversampling technique (20 sites identified when 15 sites are required) helped to ensure that ultimately at least 15 usable curve locations could be identified for analysis. The term “usable” refers to representative sites where speed data could be safely acquired. Ultimately the project team selected 16 usable sites. Figure 3.4 depicts the geographic spread in the 20 site sample. The "push pins" on the map indicate sites and these locations are also color coded by ODOT Region (1=blue, 2=green, 3=red). Appendix C provides additional information for the sites ultimately used for analysis.

Table 3.2: List of Final Study Sites to Consider for the *Targeted Random Sample*

Site ID	Posted Advisory Speed	Curve Site Designation	Region
1	30	Clackamas 10 WB*	1
2	35	Odell 0 WB	1
3	35	Clackamas 13 WB	1
4	40	Mt Hood 62 NB	1
5	45	Mt Hood 80 NB	1
6	20	Three Rivers 22 WB	2
7	30	Yamhill-Newberg 2*	2
8	35	Santiam 55 WB	2
9	40	McKenzie 36 WB	2
10	45	Oregon Coast 58*	2
11	45	Wilson River 24 WB*	2
12	45	Kings Valley 6 NB	2
13	30	North Umpqua Hwy 37 WB	3
14	40	Elkton Sutherlin 4 WB	3
15	45	Umpqua 36 WB	3
16	45	Coos Bay-Roseburg 48 WB	3
17	45	Jacksonville 14 EB	3
18	Varies	Woodburn Estacada 31 SB	1
19	Varies	Kings Valley 22 SB	2
20	Varies	Green Springs 29 EB	3

*Site Not Included in Final Analysis

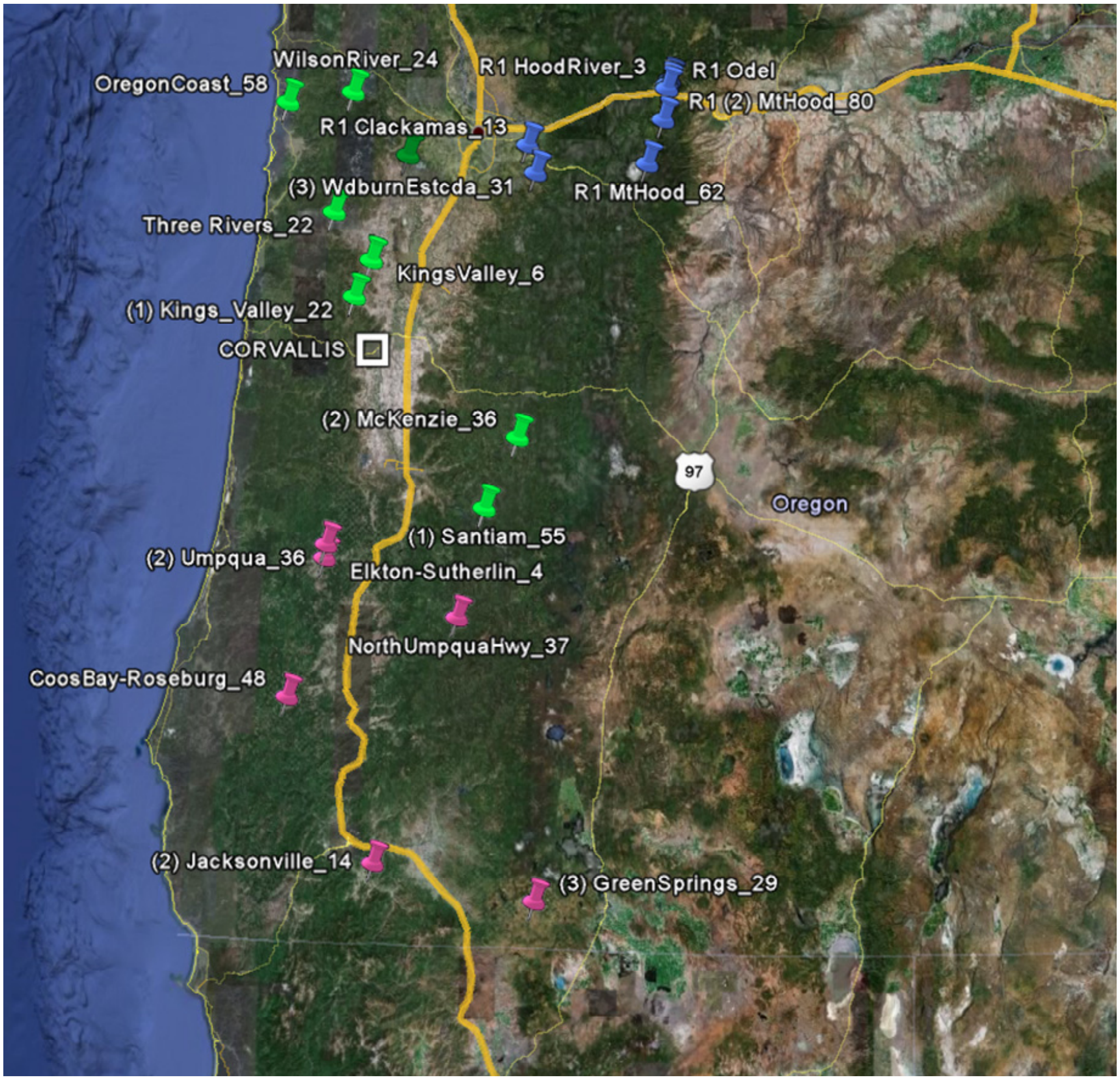


Figure 3.4: Geographic Distribution of Selected Sites for the *Targeted Random Sample*

3.4 DATA COLLECTION EQUIPMENT

Since pneumatic tubes are highly visible and have limited accuracy at curve locations, they were not considered as acceptable data collection devices for this research effort. As a result, the research team used NC-200 HiStar ® Traffic Analyzers for speed data collection. See Appendix G for a summary of the process used to calibrate these devices.

Figure 3.5 shows a sample NC-200 device and its protective cover. Figure 3.6 shows the installed devices. In the photo, the protective cover is nailed directly into the pavement; however, for this research effort the research team installed the cover by using a tape coat that completely obscured the cover and, as a result, resembled a patch in the pavement. The NC-200 devices monitor the earth's magnetic field and identify disruptions, in the form of approaching speed, as vehicles enter and therefore interrupt the magnetic field.

In addition to the collection of speed data, the research team also acquired physical site data including the orientation (distance) of the devices relative to the curve and signs. The data collection team acquired this distance information with the use of a measuring wheel.

Source: Quixote Transportation Technologies, Inc.

Figure 3.5: NC-200 Traffic Analyzer

Source: Quixote Transportation Technologies, Inc.

Figure 3.6: Placement of NC-200

3.5 DATA COLLECTION DEVICE LAYOUT AT SITES

The typical placement of the speed data collection equipment included the positioning of eight devices. Four devices were placed in each direction of travel with one device located upstream of the curve, two devices along the curve, and one device downstream of the curve. A generic layout of this configuration is depicted in Figure 3.7. Due to unique site conditions, some of the sites did not conform to the typical layout and so required variations of this generic layout. For example, locations with reverse curvature and multiple, closely spaced curves required an alternative device configuration that reflected the unique geometry. Figure 3.8 shows an example of device placement at a reverse curve location.

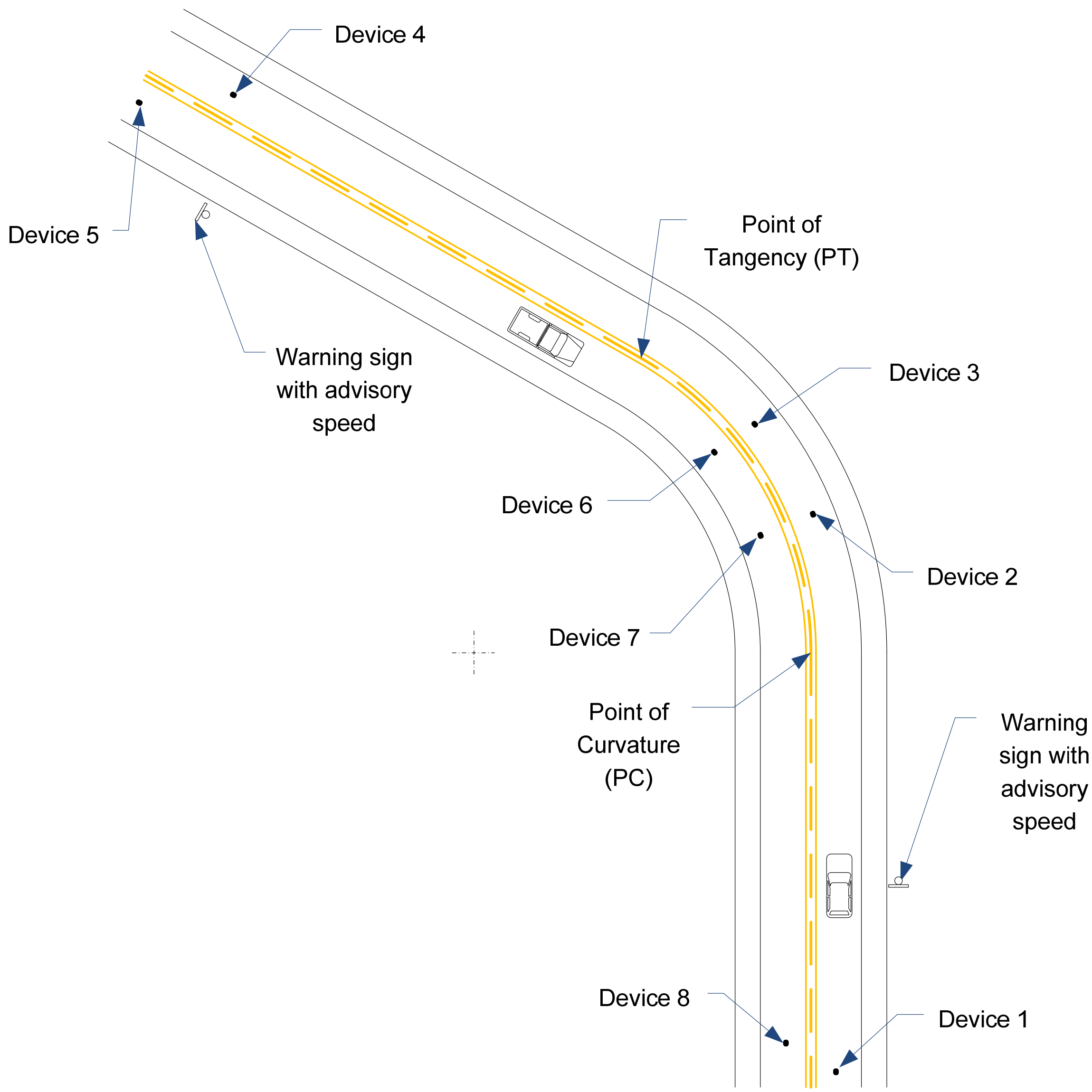


Figure 3.7: Speed Data Collection Layout

At other locations, advisory speed signs were present (warranted) in only one direction of travel. When this occurred, the data collection team located the first device (Device 1) upstream of the sign and placed Device 5 at a similar distance from the point of curvature for the opposing direction of travel.

In addition to the speed data collected at each site, the data collection team also noted recent pavement improvements, driveways with unusually high traffic volumes, and other items of note that could influence speed choices. The research team also took photographs of the general and special conditions at every site.

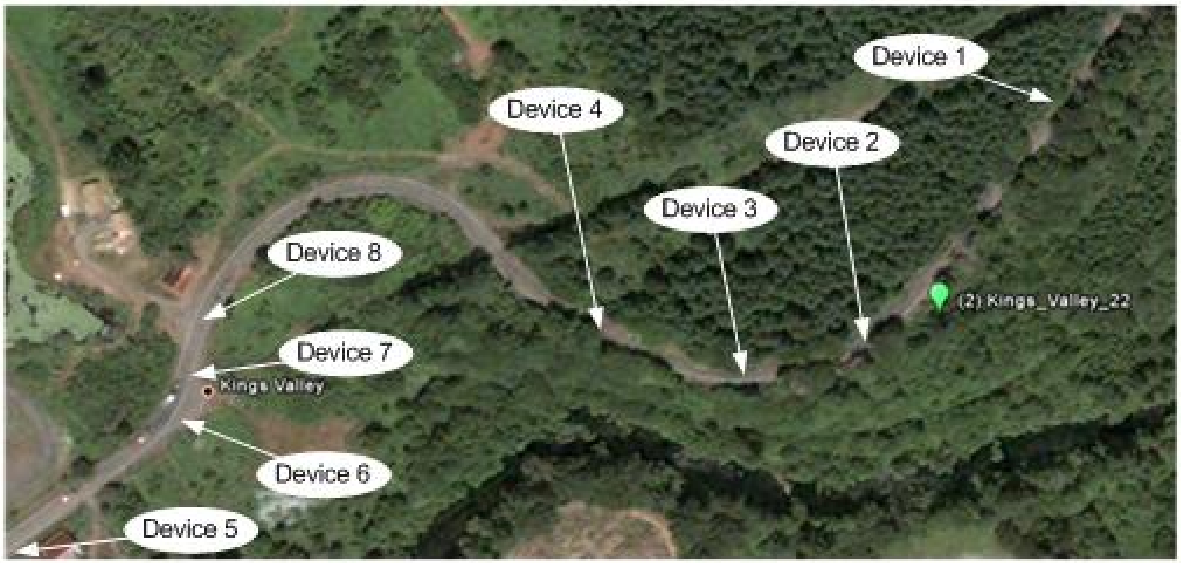


Figure 3.8: Example Layout for a Site with Reverse Curves

3.6 DETERMINING A MINIMUM NUMBER OF RECORDS PER SITE

In order to achieve the expected precision in the operating speed statistics, the research team determined the number of hours required for operating speed data collection at each site in the *targeted random sample*. To determine this data collection duration, the OSU team used traffic volume data (Average Annual Daily Traffic (AADT)) information available on ODOT's website (*ODOT, 2007*) and established a minimum desired level of precision for speed estimates at each site. The researchers set this target precision as 0.5 mph since this threshold enables the measurement error of the speed data to be within 1 mph (± 0.5 mph).

As determined using 3-1, to account for a 1 mph measurement error with a 5 mph standard deviation (a typical value for spot speed studies), it would be necessary to collect speed data for at least 300 individual trips. Since this equation assumes well-spaced trips, the level of precision might be compromised if the vehicles follow each other too closely.

Equation 3.2 shows an alternative method to model this type of co-dependence (vehicles that follow closely and so do not maintain free-flow speeds) using the lag-1 autocorrelation coefficient r_1. For instance, if the data from a particular site is determined to have a value of $r_1 = 0.7$, a minimum of 575 individual trips would be necessary in order to maintain the desired precision.

Equation 3-1: Operating Speed Variance for Well-Spaced Trips

$$Var\left(\overline{S}_i\right) = \frac{\sigma_i^2 + \varepsilon^2}{n_i} \qquad \textbf{(3-1)}$$

Equation 3-2: Operating Speed Variance for Close-Following Trips

Adapted from Ramsey and Schafer, 2002

$$Var\left(\overline{S}_i\right)=\frac{\left(\frac{1+r_1}{1-r_1}\right)\sigma_i^2+\varepsilon^2}{n_i} \qquad \textbf{(3-2)}$$

Where:

$Var\left(\overline{S}_i\right)$ = variance of the average spot speed for Site *i*,

σ_i^2 = standard deviation of speed for Site *i*,

ε^2 = measured error,

n_i = number of vehicles at Site *i*, and

r_1 = first serial correlation coefficient.

In an attempt to evaluate free-flowing speeds, the research team filtered out vehicles with time gaps of seven seconds or less. This value is a conservative threshold since five seconds is a more common value found in the literature.

As a result, the researchers attempted to acquire between 500 and 600 sample vehicle speeds at a site with a goal of no less than 300 for any one location. Since some sites were characterized by very low traffic volumes, it was difficult to acquire these target speed samples at all locations. One extreme case was the Green Springs Highway site where in eight hours of data collection, approximately 60 vehicles were recorded in each direction of travel. Other sites, however, yielded over 1000 records per direction of travel.

4.0 DATA COLLECTION PLAN AND SPOT SPEED EVALUATION

The OSU research team collected speed data during dry, daylight conditions. As previously indicated, the targeted random sample included 16 final sites with usable data. The data collection primarily occurred on weekdays. The number of hours of collected speed data at each site ranged from 3.5 up to 9 hours. Weekday data collection was preferred because traffic volumes can generally be expected to be lower at rural locations resulting in a greater opportunity to record more independent trips. For most of the sites, the data collection included both morning and afternoon time periods. Example data collection forms are available in Appendix B.

4.1 SITE SPEED CHARACTERISTICS

A preliminary inspection of the speed data validates the general assumptions that most speed distributions are normally distributed (symmetrical around the mean) and that the time gaps between vehicles suggest independent trips. Table 4.1 shows an example of speed statistics for one site. Figure 4.1 and Figure 4.2 show speed and time gap histograms, respectively.

Table 4.1: Sample Statistics for a Typical Site

Statistic		Value
Sample Size (Vehicles)		302
Speed (mph)	Mean	52.95
	Mode	53.00
	Median	53.00
	85^{th} Percentile Value	59.00
	95^{th} Percentile Value	62.00
	Standard Deviation	5.90

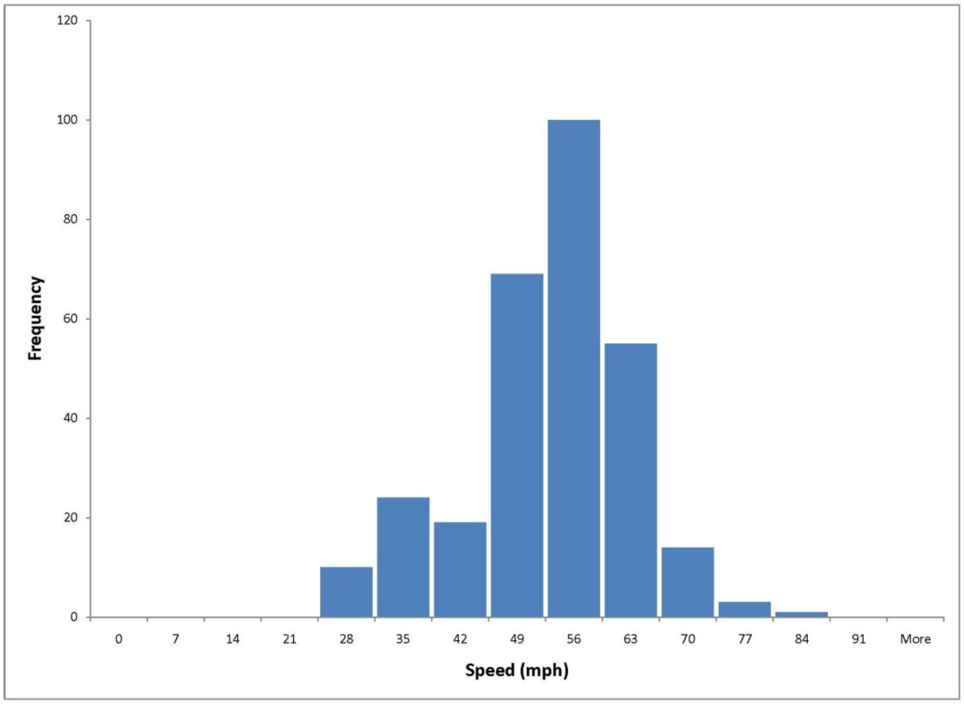


Figure 4.1: Histogram of Sample Speed (mph)

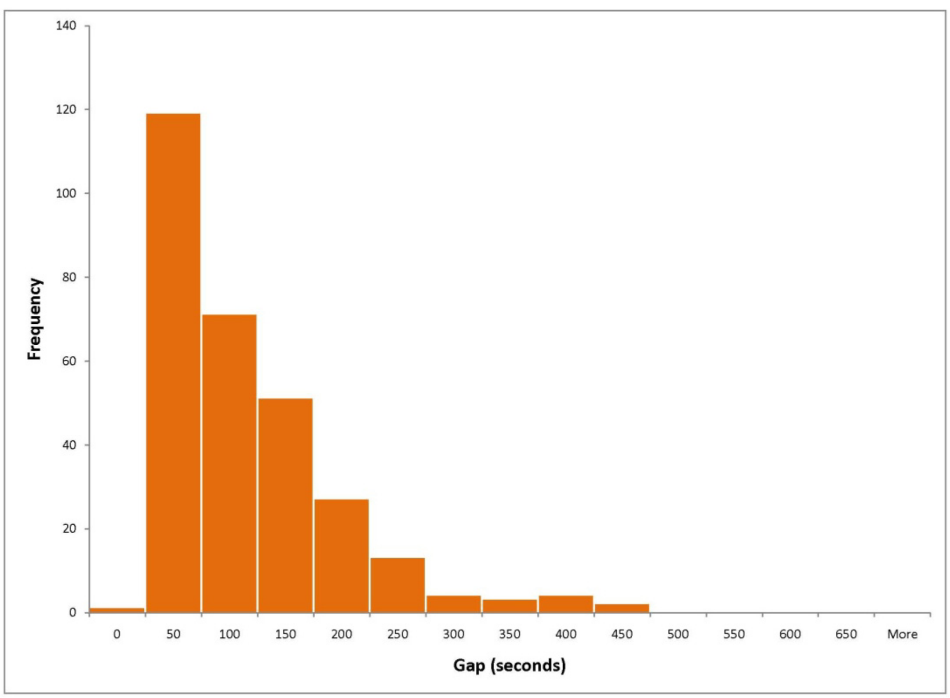


Figure 4.2: Histogram of Sample Gaps (seconds)

The speed histograms and distribution-shape statistics in general suggest that a large proportion of the vehicles (with varying free-flow speeds on the tangent) slow down to a more uniform operating speed as they enter the curve. A typical example is shown in Figure 4.3 where the frequency in the center speed bins tends to increase, while the number of speed observations in the higher speed bins tends to decrease, and the lower speed bins tend to remain the same.

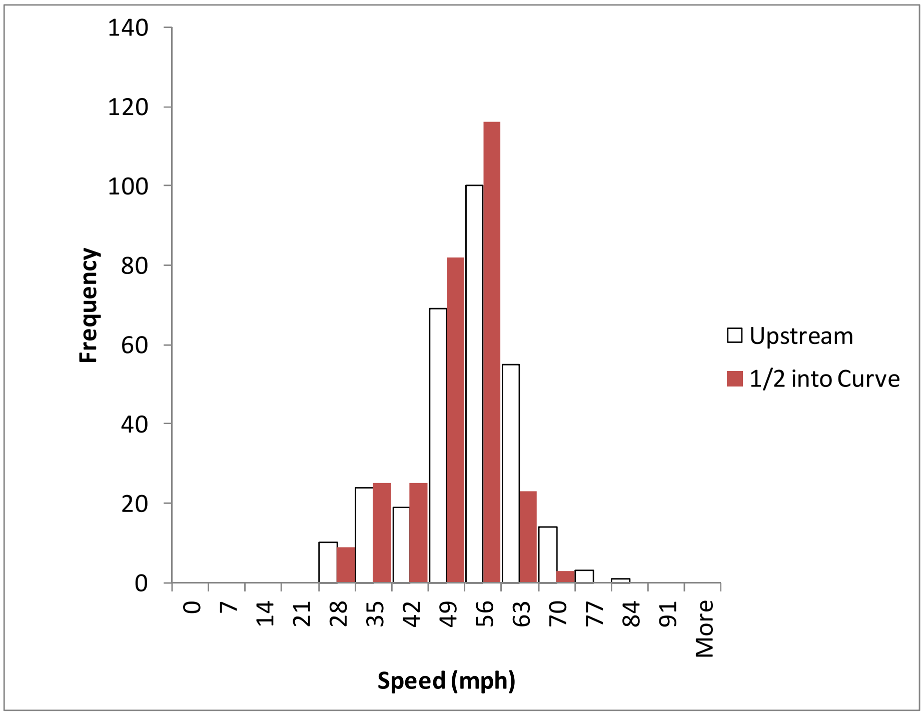


Figure 4.3: Typical Speed Distribution Change from Tangent to Curve

4.2 SPOT SPEED DATA OVERVIEW

As part of the preliminary analysis, the members of the OSU team computed descriptive statistics using the sample design explained in Chapter 3. Although it is a straightforward process to construct confidence intervals for the mean operating speed, a more relevant task for this research effort was to find reliable estimates for other operating speed characteristics. For this assessment the project team placed particular attention on the 85th percentile speed, since this value is typically used as one common “design” value for road geometry (since design speed is often associated with this value). Because of its relevance, the analysis approach required the creation of confidence intervals for the 85th percentile speed that on average represent ODOT Regions 1, 2 and 3. Standard error creation conformed to a procedure derived from the work of Evans (*1942*).

Table 4.2 shows the 85th percentile speeds for the ODOT Regions. Table 4.3 shows an approximate value for the 85th percentile speeds minus the companion speed limits at a location immediately upstream of the studied curves. The large confidence intervals, though, make it challenging to infer conclusive speed information regarding observed speed differences between the 85th percentile and posted speeds.

Table 4.2: 85th Percentile for Observed Operating Speeds (Upstream of Curve)

Region	Estimate for 85th Percentile Speed Upstream of the Curve (mph)	Standard Error	Expected Range of Values (95% Confidence)	
			Lower Boundary (mph)	Upper Boundary (mph)
1	60.3	5.36	49.83	70.84
2	58.7	5.69	47.53	69.84
3	62.7	5.31	52.24	73.07
All Three Regions	60.1	3.89	52.48	67.72

Table 4.3: 85th Percentile for Observed Operating Speeds Minus Posted Speed Limits (Upstream of Curves)

Region	Estimate for 85th Percentile Above Speed Limit Upstream of the Curve (mph)	Standard Error	Expected Range of Values (95% Confidence)	
			Lower Boundary (mph)	Upper Boundary (mph)
1	7.6	5.36	-2.95	18.06
2	3.7	5.69	-7.47	14.84
3	7.7	5.42	-2.97	18.28
All Three Regions	5.2	3.90	-2.41	12.89

As previously indicated, the variation in the observed speed distributions tended to diminish as vehicles entered the curve. This apparent trend toward the mean may help to explain the smaller standard errors shown in Table 4.4, which displays the 85th percentile speeds at a point one-third of the way into the curves. The estimate for Region 3 depicts a slightly higher standard error. This region includes three sites with unique geometric characteristics: two sites with passing lanes present in the curve and one with extremely low traffic volumes on a mountainous road.

Table 4.5 shows estimates of the 85th percentile speed for passenger vehicles only. The research team assumed a vehicle of 30 ft or longer to be a heavy vehicle. As expected, the estimates in Table 4.5 are slightly larger than the overall ones from Table 4.4. Unfortunately, this separation of vehicle types based on length did not substantially enhance the associated degree of uncertainty when compared to a subgroup of similar vehicles (passenger vehicles, in this case).

Table 4.4: 85th Percentile for Operating Speeds One-Third into the Curve

Region	Estimate for 85th Percentile One-Third Into the Curve (mph)	Standard Error	Expected Range of Values (95% Confidence)	
			Lower Boundary (mph)	Upper Boundary (mph)
1	56.7	5.31	46.24	67.07
2	53.4	3.74	46.05	60.71
3	58.1	7.26	43.85	72.31
All Three Regions	55.1	3.31	48.65	61.63

Table 4.5: 85th Percentile Estimates for Passenger Vehicles One-Third into Curve

Region	Estimate for Passenger Car 85th Percentile One-Third Into the Curve (mph)	Standard Error	Expected Range of Values (95% Confidence)	
			Lower Boundary (mph)	Upper Boundary (mph)
1	58.3	5.24	47.99	68.52
2	54.5	4.04	46.60	62.43
3	59.1	6.56	46.24	71.94
All Three Regions	56.3	3.28	49.82	62.69

Table 4.6 shows estimates of the 85th percentile speed for trucks only. These estimates are smaller than those shown in Table 4.5 and have a higher degree of associated uncertainty (i.e. larger standard errors).

Table 4.6: 85th Percentile for Trucks One-Third into the Curve

Region	Estimate for Truck 85th Percentile One-Third Into the Curve (mph)	Standard Error	Expected Range of Values (95% Confidence)	
			Lower Boundary (mph)	Upper Boundary (mph)
1	55.8	7.36	41.39	70.23
2	50.6	5.90	39.00	62.14
3	55.9	10.92	34.48	77.30
All Three Regions	52.7	5.10	42.67	62.65

Table 4.7 shows estimates for the difference in 85th percentile speeds between passenger vehicles and trucks. Although these estimates are all positive, all of the confidence intervals contain the value of zero, so there is no statistically significant evidence of a difference between these two vehicles types at a 95 percent confidence level).

Table 4.7: Difference between Passenger Vehicles and Truck 85th Percentiles One-Third into the Curve

Region	Estimate for 85th Percentile Difference Between Cars and Trucks One-Third Into the Curve (mph)	Standard Error	Expected Range of Values (95% Confidence)	
			Lower Boundary (mph)	Upper Boundary (mph)
1	2.4	8.36	-13.95	18.84
2	3.9	4.60	-5.08	12.96
3	3.2	4.82	-6.25	12.66
All 3 regions	3.6	3.26	-2.78	9.98

Similar to Table 4.3, Table 4.8 shows estimates for the 85th percentile speed values minus their associated advisory speeds at a location approximately one-third of the way into the horizontal curve. In this case, however, the expected range of values does not contain zero, strongly suggesting that this trend of the 85th percentile speed above the advisory speed is positive and significant for all of the studied regions. As an additional observation, all of the 85th percentile speeds in the collected sample were substantially greater than their corresponding advisory speed.

Table 4.8: 85th Percentile Estimates for Observed Speeds Minus Advisory Speeds One-Third into Curve

Region	Estimate for 85th Percentile above Advisory Speed One-Third Into the Curve (mph)	Standard Error	Expected Range of Values (95% Confidence)	
			Lower Boundary (mph)	Upper Boundary (mph)
1	18.0	3.57	11.01	24.99
2	10.1	2.99	4.27	15.99
3	17.2	6.01	5.37	28.94
All Three Regions	12.9	2.69	7.67	18.23

Table 4.9 shows estimates for the percent of vehicles driving faster than the advisory speed at a location approximately one-third into the horizontal curve. About 92 percent of the drivers exceeded the advisory speeds in Regions 1 and 3. Conversely, Region 2 exhibited fewer drivers exceeding the advisory speed (60 percent on average). Table 4.10 shows estimates corresponding to a location approximately two-thirds into the horizontal curve.

Table 4.9: Percentage of Vehicles Driving Faster than the Advisory Speeds (One-Third into the Curve)

Region	Estimate of Vehicle Percentage over Advisory Speed (%)	Standard Error (%)	Lower Boundary for Percentage of Vehicles Faster than Advisory Speed (95% Confidence)
1	92.4	3.8	86.2
2	60.6	10.0	44.1
3	92.2	10.8	74.4
All Three Regions	73.0	7.1	61.4

Table 4.10: Percentage of Vehicles Driving Faster than the Advisory Speeds (Two-Thirds into Curve)

Region	Estimate of Vehicle Percentage over Advisory Speed (%)	Standard Error (%)	Lower Boundary for Percentage of Vehicles Faster than Advisory Speed (95% Confidence)
1	89.6	7.5	77.3
2	64.9	8.1	51.6
3	91.4	17.1	63.3
All Three Regions	75.2	7.5	62.9

4.3 SPEED PROFILES ALONG THE CURVES

Constructing speed profiles is a useful way to assess the operation of the surveyed curves. A speed profile consists of a consecutive plot of speed values for the four different locations along the curve. Figure 4.4 and Figure 4.5 show the two most distinctive speed profile patterns at the sites studied. These typically occurred at moderately sharp curve locations and in the absence of significant vertical grades.

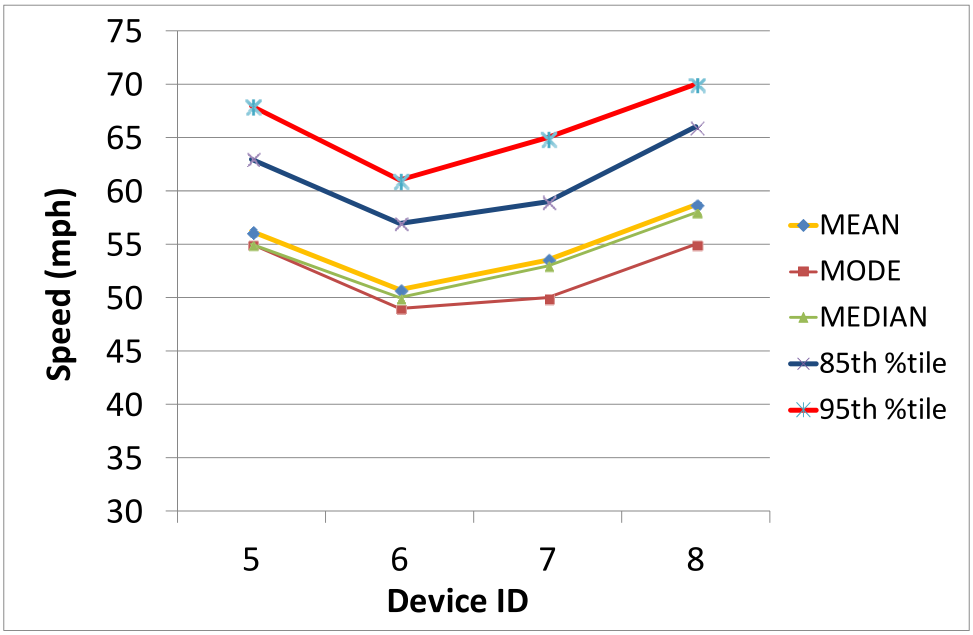


Figure 4.4: Typical Speed Profile A

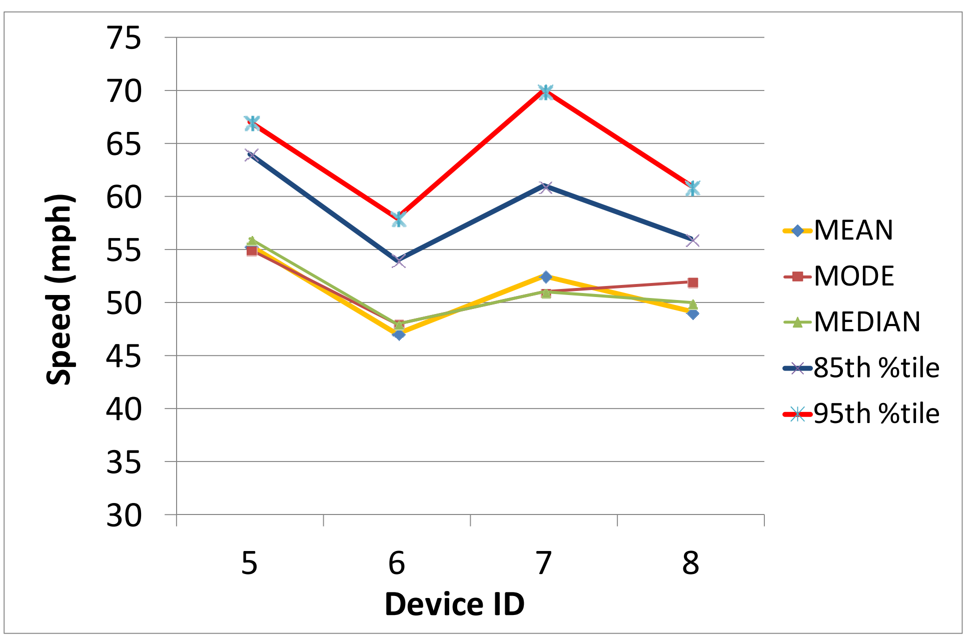


Figure 4.5: Typical Speed Profile B

Both Figure 4.4 and Figure 4.5, though distinctly different as the vehicle travels within the curve, demonstrate a speed reduction from the warning and advisory signs upstream of the curve to the data collection location approximately one-third of the way into the horizontal curve. Both figures also demonstrate an increase in speed just prior to the vehicle exiting the curve. This common pattern suggests that the driving population might, on average, overestimate the curve hazard, but as they drive through it adjust their speed to a more comfortable pace.

Other patterns are present in addition to those depicted in Figure 4.4 and Figure 4.5. In order to better understand the factors that influence these patterns, it is necessary to account explicitly for geometric characteristics such as superelevation, radius, etc. The relationship between the observed operating speeds, site characteristics, and historic crash data is further explored in Chapter 5 of this report.

5.0 CRASH DATA ANALYSIS

In addition to an assessment of the observed operating speed at advisory curve locations, this research project also includes an analysis of the crash data available for the *statewide random sample* used in the 2008 study. Since speed data is readily available for the *targeted random sample*, the research team developed a procedure by using the following three stages:

1. Analysis of the relationship between operating speed and crash data for the 16 sites where speed data is now available (i.e. *targeted random sample)*;
2. Crash data analysis using the *statewide random sample*; and
3. Thorough model-based analysis using the *targeted random sample*.

Each of these three stages of analysis is reviewed in detail in the following sections.

5.1 RELATIONSHIP BETWEEN OPERATING SPEED AND CRASH DATA

A crash might result from isolated events in which a combination of events or potentially unsafe conditions might occur. In some cases, crashes might be related to hazardous behavior by drivers and their response to geometric features of the road. This section looks at the characteristics of crashes in order to determine how they relate to the associated speed and road characteristics at the *targeted random sample* study locations.

To check for a potential link between crash frequency and speed, the research team used crash data for the 16 sites in the *targeted random sample* to contrast the crash frequencies and associated speed characteristics. The team collected speed information for both directions of travel for 15 of the sites, and similar speed data for one direction of travel at the remaining site. Figure 5.1 depicts example data at one site that is typical of information available to perform this exploratory analysis. It includes speed statistics for both directions of travel, data collection device placement along the corridor, and incident frequency by type. Appendix C includes a similar site summary for each of the *targeted random sample* sites.

Table 5.1 shows a Pearson's correlation that evaluates associations between speed statistics and crash rates for the *targeted random sample* sites. It is somewhat surprising to notice a slight negative correlation between the 85th percentile speed minus the advisory speed when compared to the related crash rate, since one would expect that higher crash rates are associated with higher speeds.

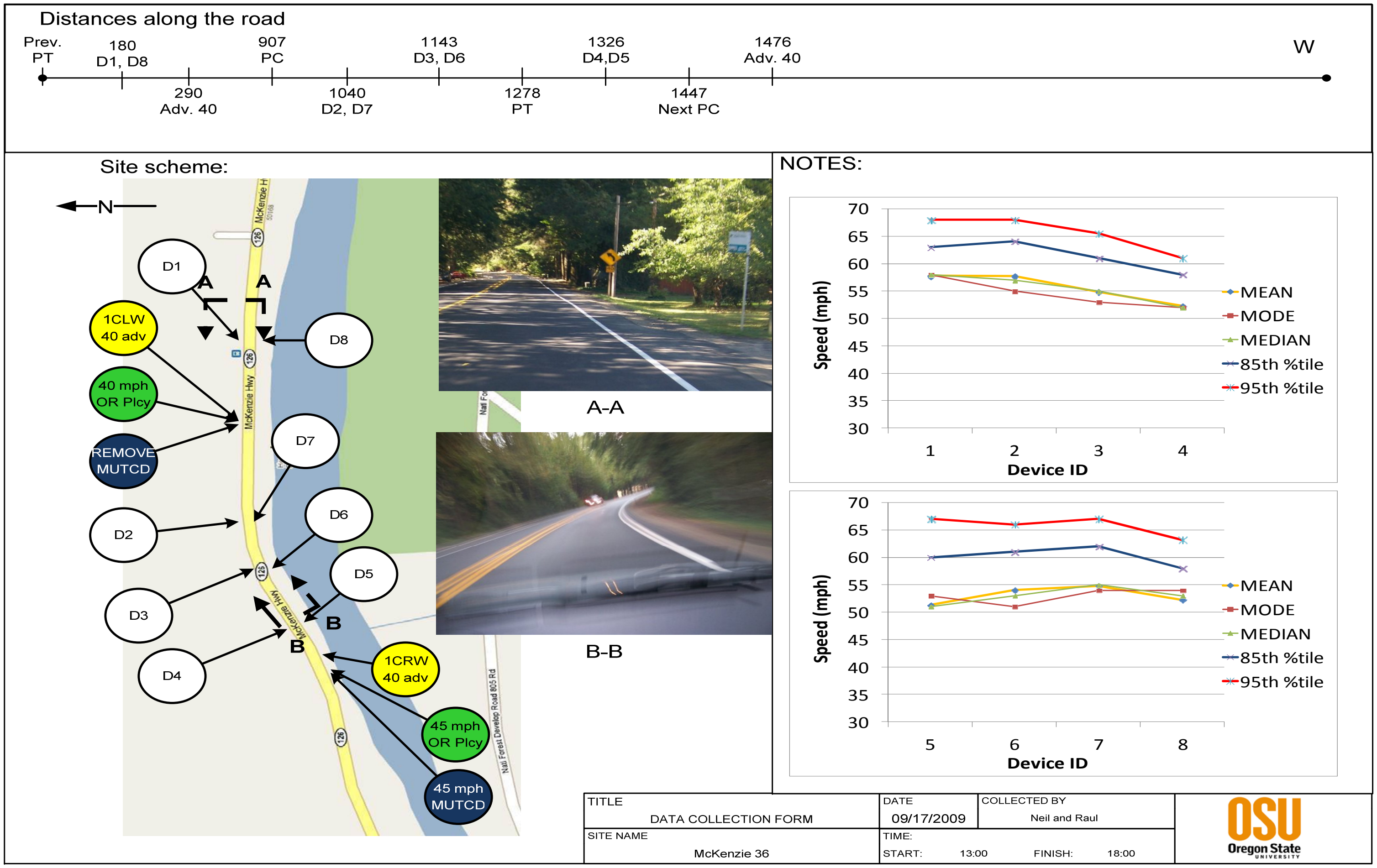


Figure 5.1: Graphic Display of Data Used for Speed-Crash Analysis

Table 5.1: Pearson's Correlation between Speed Statistics and Crash Rates for the *Targeted Random Sample* Sites

	Total Crashes / 10,000 AADT	**Advisory**	**Speed Limit**	**85th Percentile Speed Minus Advisory Speed**
Total Crashes / 10,000 ADT	1.00			
Advisory	-0.34	1.00		
Speed Limit	0.07	0.09	1.00	
85th Percentile Speed Minus Advisory Speed	-0.14	0.22	-0.15	1.00

Figure 5.2 shows the possible underlying trends between operating speed and crashes. The researchers subdivided the *targeted random sample* sites into three groups based on their crash rates per 10,000 AADT:

1. Sites without crashes in the database (five sites with two directions of travel and one site with one direction of travel) or sites where crash information is unclear (two sites with one direction of travel affected) for a total of seven sites and 13 associated directions of travel;
2. Sites with crash rates below nine incidents per 10,000 AADT and referred to as "Low" in Figure 5.2 (three sites with two directions of travel and two sites with one direction of travel) for a total of eight associated directions of travel; and
3. Sites with crash rates above nine incidents per 10,000 AADT and referred to as "High" in Figure 5.2 (four sites with two directions of travel and two sites with one direction of travel) for a total of ten associated directions of travel.

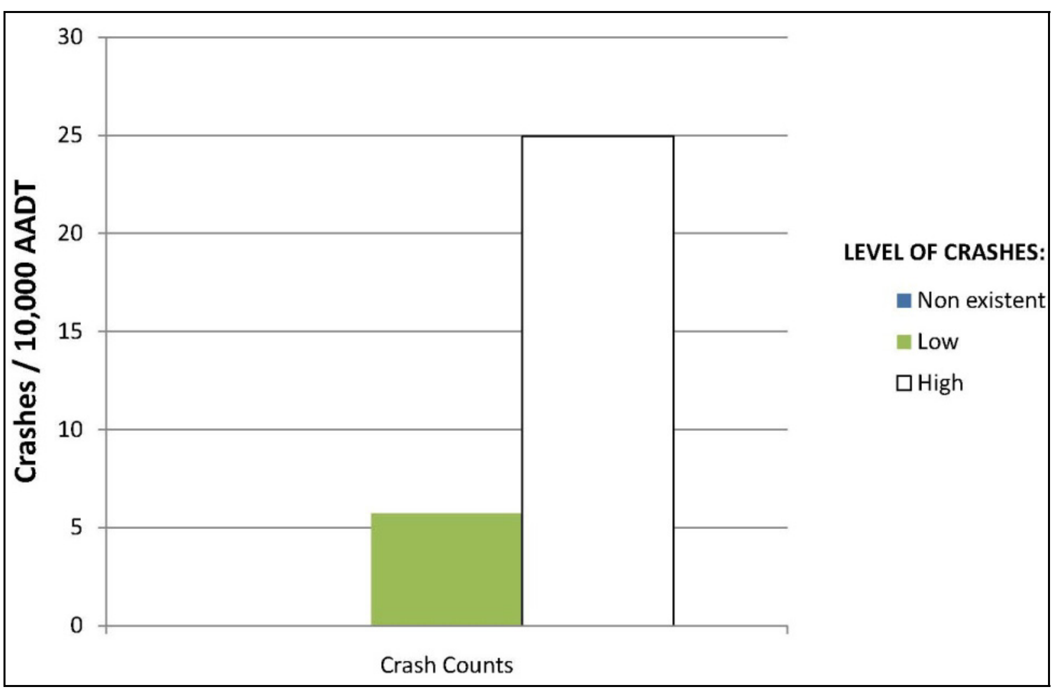


Figure 5.2: Average Crash Characteristics for Sites by Crash Level Category

Figure 5.3 displays the average associated advisory speeds and operating speeds for the same three crash categories (nonexistent, low, and high). From this figure it appears that the crashes at posted advisory speeds for “High” crash sites tend to be lower than for the other two categories (“Low” and “Nonexistent”). Advisory speeds for these last two categories tend to be, on average, approximately the same. Since the “High” sites are clearly sites with lower advisory speeds and higher crashes, it is clear now why the correlation coefficient in Table 5.1 (as previously identified) appears to underestimate the strength of the relationship between these variables. However, it is still not possible to attribute an effect to the advisory speed plaques, since it is well known that lower advisory speeds are also correlated with sharper curves, a factor that is itself more likely to increase the likelihood of a crash occurrence.

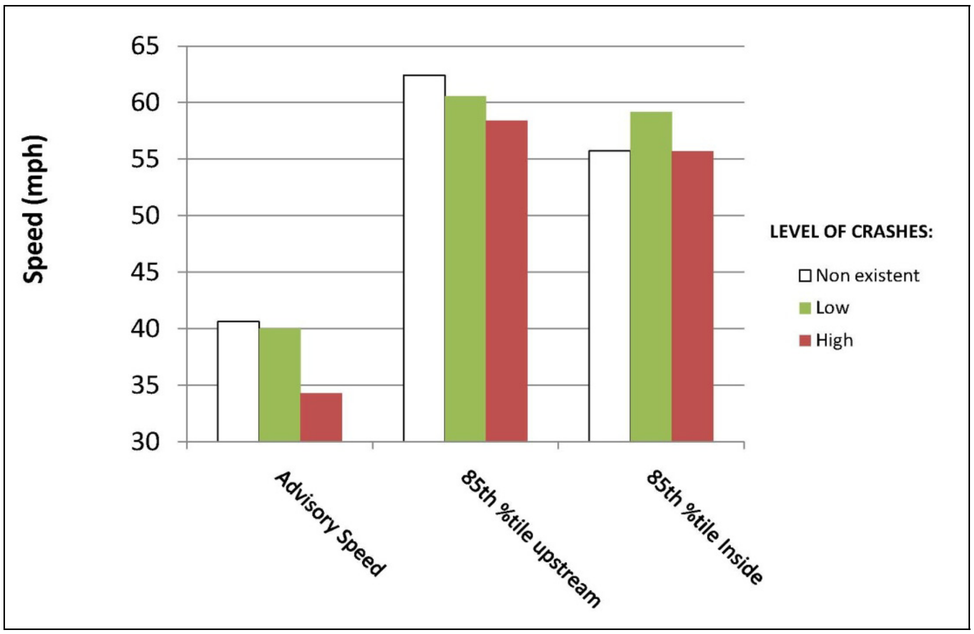


Figure 5.3: Average Advisory Speed and 85th Percentile Speeds by Crash Level Category

Figure 5.3 shows that, on average, speeds upstream of the curves were highest for the “No Crash” category and lowest for the “High” category. These data suggest that even though drivers appear to approach the curves at slower speeds for the “High” crash level category, they might be underestimating the risk posed by the curve. The data collection team generally placed the speed measuring devices upstream of the advisory speed signs, so the approach speeds may be indicative of the overall nature of the road.

Figure 5.4 and Figure 5.5 further demonstrate that the sharpest curves and the lowest AADTs were associated with the locations with the highest crash rates.

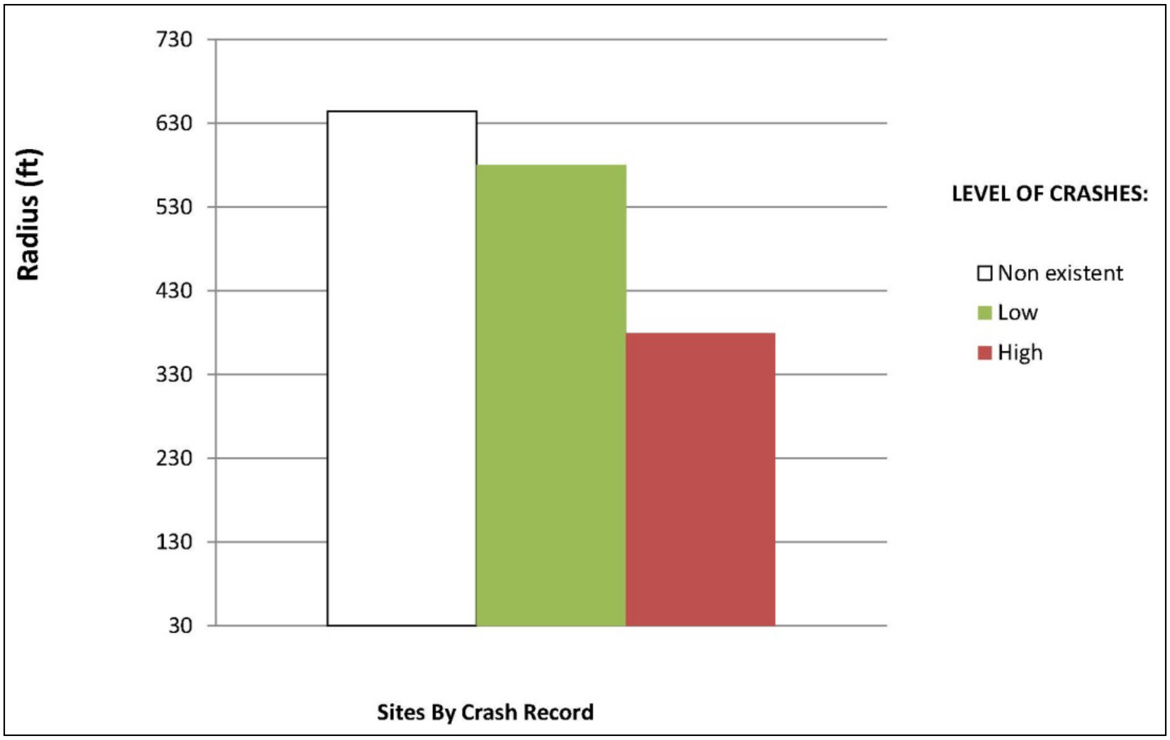


Figure 5.4: Average Radius by Crash Level Category

Figure 5.5: Average AADT by Crash Level Category

Figure 5.6 demonstrates the differences in observed 85th percentile speed at the study sites and contrasts these values to the differences between this value and the posted advisory speed. From this analysis, it appears that the operating speed has two clear links with crash frequencies: (1) upstream operating speeds are on average slower at "High" crash sites, and (2) speed reductions are on average larger at sites where crashes are "Nonexistent." This observation suggests that geometric design may have a strong influence on operating speeds as well as crash rates. Sites at locations without crashes appear to have the largest radii and higher advisory speeds. These sites, as a group, displayed the largest reduction in the 85th percentile speed within the curve region.

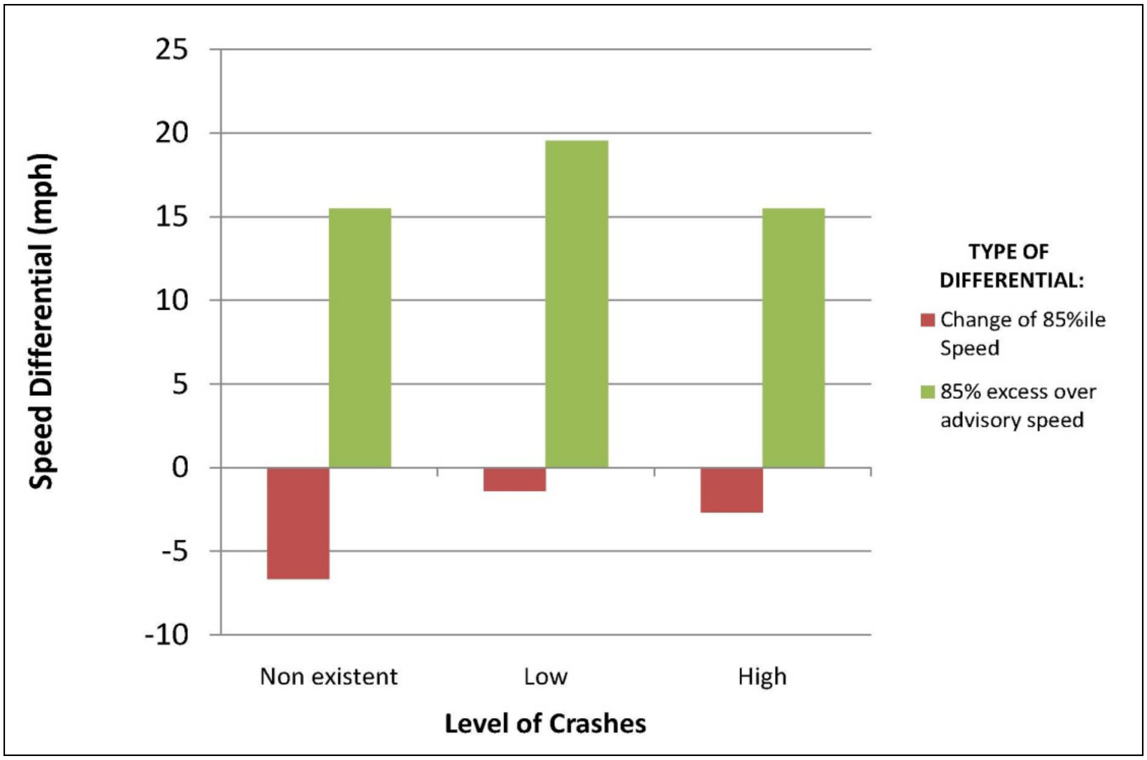


Figure 5.6: Change of 85th Percentile and Excess over Advisory Speed by Crash Level Category

The influence of shoulder width, superelevation, and vertical grade for the three levels of crash categories is depicted in Figure 5.7, Figure 5.8, and Figure 5.9, respectively. These figures demonstrate that higher crashes are associated with narrower shoulders, adverse superelevation in the curve, and downhill vertical grades approaching the horizontal curve.

The crash level category with the highest crash rates, as depicted in Figure 5.7, is associated with significantly narrower shoulder widths than the other categories. Sites with "Low" crashes or no crashes typically had shoulders that ranged from one to feet wider than those at "High" locations.

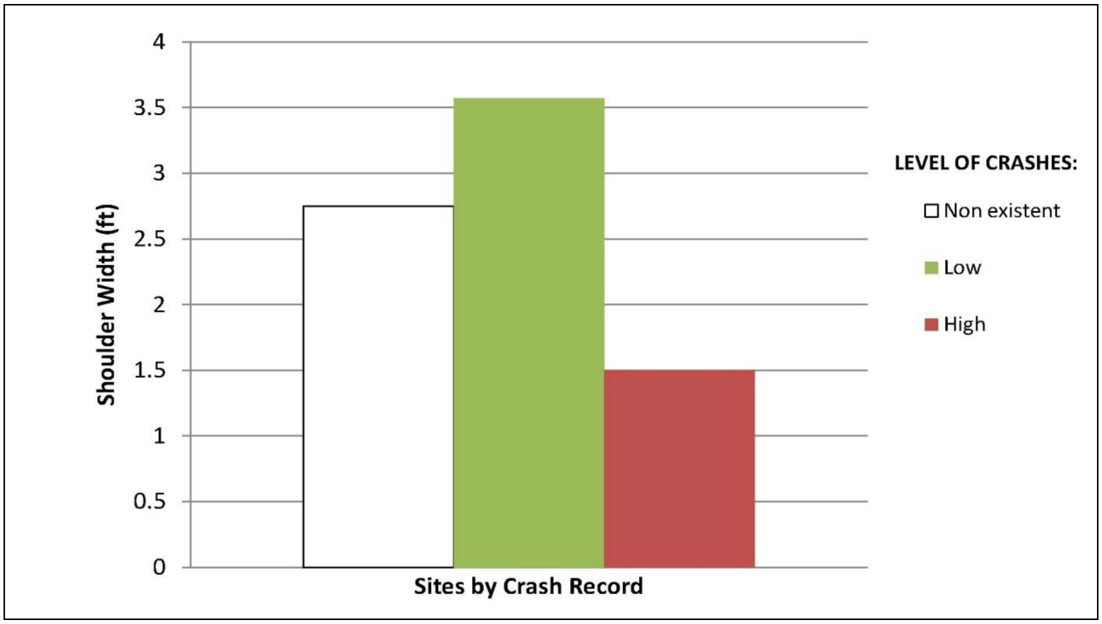


Figure 5.7: Average Shoulder Width by Crash Level Category

The cross-slope of a road and transition into superelevation (SE) at a horizontal curve is purposefully designed to counteract centripetal acceleration; therefore, the project team assessed the safety performance at curve locations with respect to the SE. At a curve approach and departure, the typical cross-section is a "roof top" configuration. At this location there were no apparent differences between the levels of crash category for the study sites (based on directions of travel). An obvious difference emerges, however, when comparing the crash level categories to the associated full SE values. The SEs displayed with negative values occurred in the direction of travel with the longest SE transition (extended rotation length). That is, the direction of travel for which the SE rate first decreases, reaches zero, reaches the SE of the opposite direction of travel, and then both directions increase together until attaining the design SE. The common location where this type of SE transition occurs is at a horizontal curve to the left.

It is also clear from Figure 5.8 that the "no crash" sites show a reverse trend for the SE. SEs in the "Low" category also, on average, were associated with positive values. This rather clear trend in crash rates on particular regions of curve SE transitions may indicate a disconnect between the tangent-to-curve transition as assumed in the design and the actual operating characteristics.

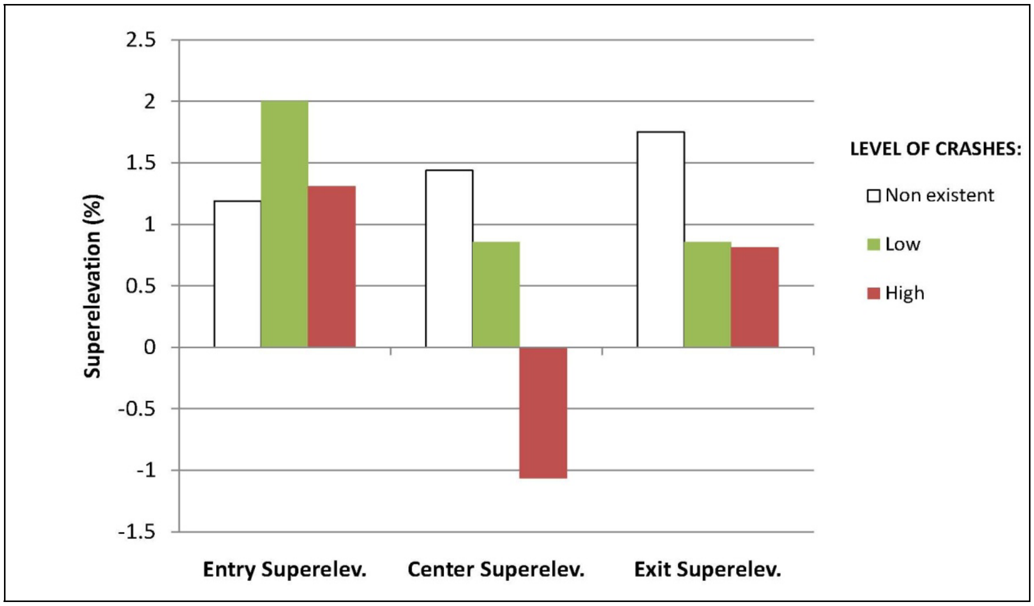


Figure 5.8: Average Superelevation by Crash Level Category

Figure 5.9 depicts the relationship between the crash level categories and the vertical grade of the facilities. For both the approach and inside-the-curve locations, the “High” crash level category is associated with, on average, downhill vertical grades (i.e. sites with downhill slopes larger than their uphill counterparts). It is similarly clear that the vertical grade is generally positive for the no crash sites, roughly zero for the “Low” sites, and negative for the “High” sites.

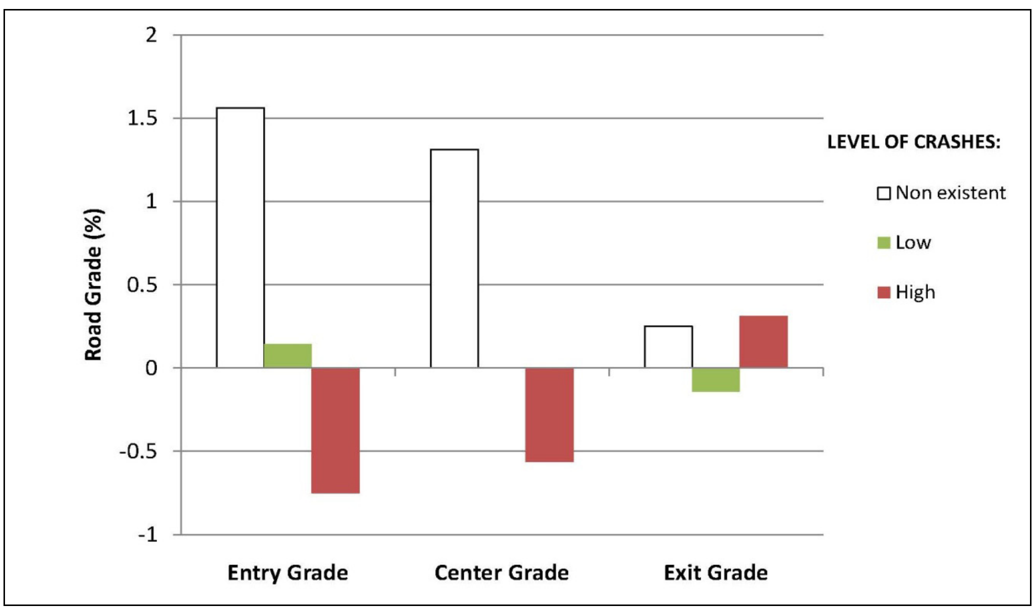


Figure 5.9: Average Road Grade by Crash Level Category

Finally, Figure 5.10, which shows the side friction demand at the 85th percentile speed for each crash level category, summarizes the discussion regarding Figure 5.4, Figure 5.6, and Figure 5.8

which indicates a potential mismatch between operating characteristics and the horizontal curve design components. The side friction demand (SFD) is a quantity that measures the lateral friction needed by the tires of a vehicle in order to follow the curvilinear path of a horizontal curve. It takes into account the vehicle speed, the radius, and the superelevation of the curve. It is apparent from Figure 5.10 that the sites with higher crash frequencies exhibited higher SFDs for the locations where speed data was collected.

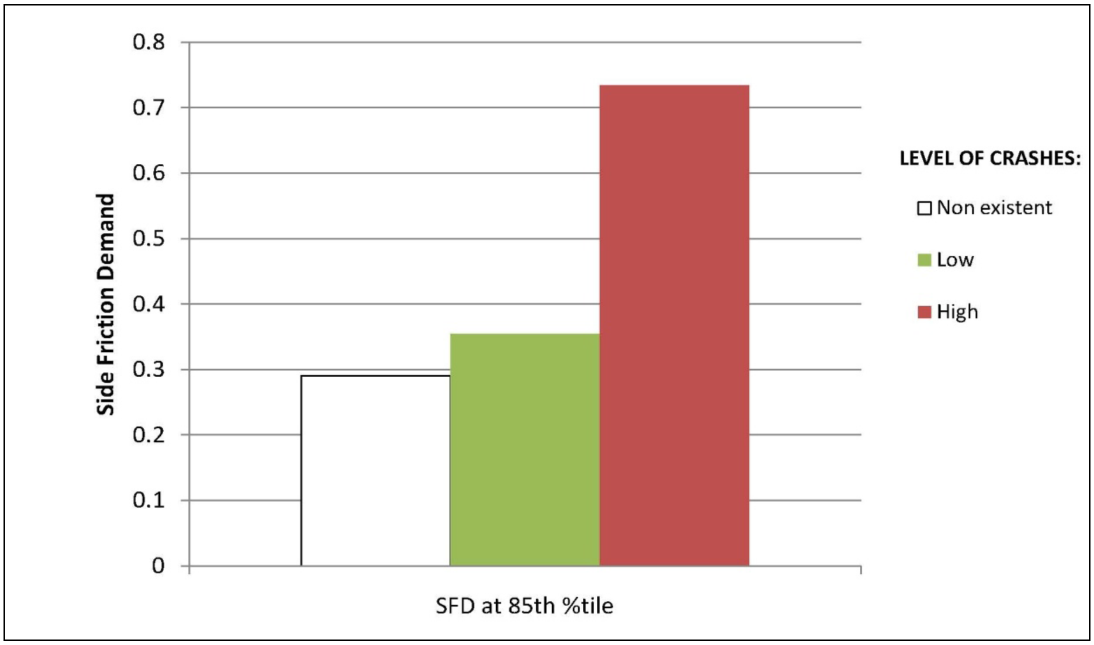


Figure 5.10: Side Friction Demand at the 85th Percentile Speed by Crash Level Category

Based on this analysis, it is clear that strong trends are evident between the geometric design and crash rates. It is not clear from this exploratory analysis if the apparent relationship between advisory speeds and crash rates is a direct cause-effect response. Generally, the operating characteristics seem to indicate a mismatch between design and operation of the sites. This comparison among speeds, crashes, and site characteristics suggest that the geometric features may individually or collectively influence the level of crashes at a site.

5.2 LARGER SAMPLE DESCRIPTIVE STATISTICS AT THE SITE LEVEL

Since the project team had a substantial database of geometric elements available for analysis from the *statewide random sample* and the content previously observed in Section 5.1 suggests that the physical geometry appears to have a strong influence on the overall crash expectations, the project team assessed the crash history for the 80 state-maintained sites included in the *statewide random sample*. These 80 sites were the 16 target sites for each of the five ODOT regions as depicted in Figure 3.1. The project team focused on these state-maintained sites because crash data was readily available at these locations for the target years.

For the 80 state maintained two-mile corridors segments, which included a total of 105 distinct curves, the project team determined that 72 of the 80 two-mile long corridor locations experienced crashes during the years 2000 through 2005. In total, 1104 crashes were reported for these locations.

Figure 5.11 depicts the distribution of the 1104 crashes for the five ODOT regions. A majority of the observed crashes occurred in ODOT Regions 1 and 2, where a large portion of the Oregon population is concentrated. The proportion of crashes in Regions 1 and 2 equates to approximately 75 percent of the observed crashes.

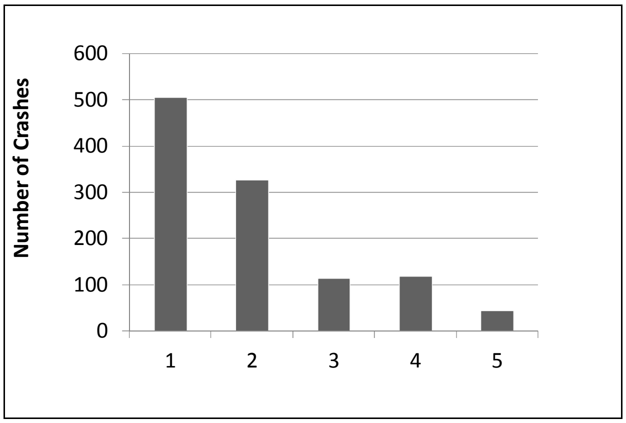


Figure 5.11: Total 2000-2005 Crashes at Corridor Locations, by ODOT Region

Figure 5.12 demonstrates the relationship of number of crashes versus AADT values. As expected, the corridors with a higher number of crashes are also those with higher traffic volumes. It is worth noting that as the crash frequency and AADT increase, the crash frequency variability also increases. Because of this, the research team, in the exploratory phase of this project, determined that crash rates were of limited value since they assume a simple linear relationship between these two variables and do not account for the distributed behavior observed in the figure. Figure 5.12 suggests a possible concave curvature between both variables. The research team tested and verified this trend and determined it to be significant. This analysis is reviewed in Section 5.3 of this report.

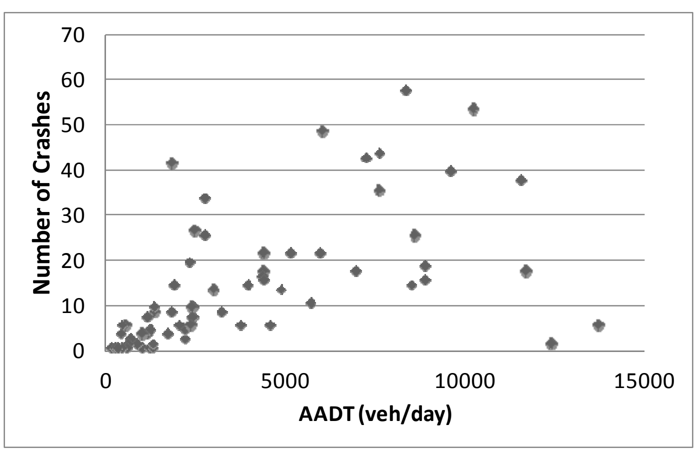


Figure 5.12: Crash Frequency vs. AADT for Corridor Locations

Figure 5.13 shows crash frequencies for different crash types. Fixed-object (FIX) crashes occurred frequently followed by rear-end (REAR) and turning (TURN) crashes. Typically, rear-end and turning crashes are associated with intersection locations. The fixed-object crashes, on the other hand, are more common to non-intersection locations. Head-on (HEAD) and sideswipe-meeting (SS-M) and sideswipe-overtaking (SS-O) crashes often occur at horizontal curve locations.

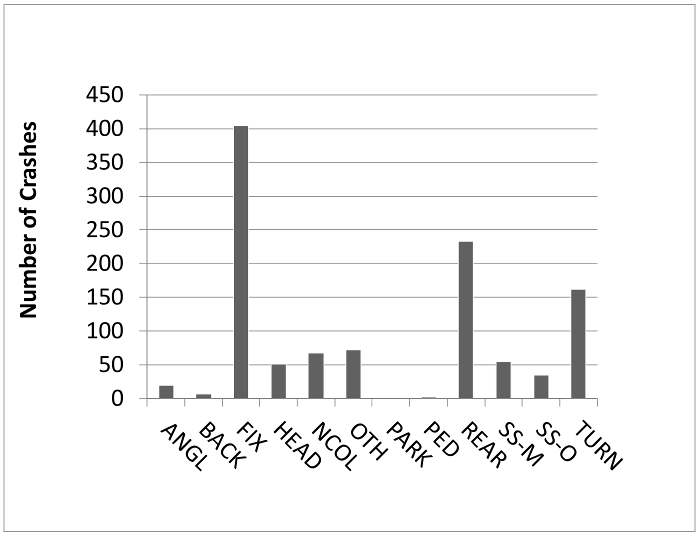


Figure 5.13: Crash Frequency vs. Crash Type

Figure 5.14 displays crash frequency for various AADT thresholds and the crash types associated with these traffic conditions for the study sites. The proportions of crash types are distributed differently for sites with AADTs larger than or equal to 4000 vehicles per day (vpd). The frequency of typical intersection crashes (TURN+REAR+ANGL) is particularly noticeable at these locations. It appears from this figure that crashes commonly associated with intersections are substantially higher at these high volume locations.

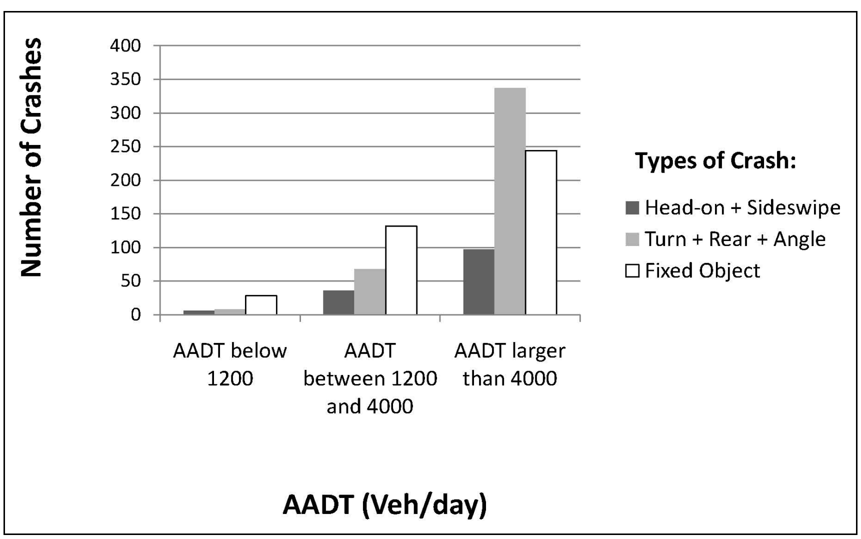


Figure 5.14: Crash Frequency by AADT (vpd) and Relevant Crash Types

Figure 5.15 shows overall crash densities by AADT. The number of crashes per mile at the study curve locations is smaller than the overall segment crash density. The team developed these values by assigning the crashes to their respective mile points and then determining the boundaries of the individual study curves along with their associated lengths. Since the research team did not collect comprehensive geometric data for the entire segment length (approximately two-miles in length), it is not possible to fully explain why crashes located in a horizontal curve with advisory speed signs occurred less often than crashes located along the entire corridor (which included the curve locations as well as surrounding segments and curves located within the two-mile corridor boundaries). One reasonable explanation may be because the segment may include intersections where the turning, rear-end, and angle crashes are introduced.

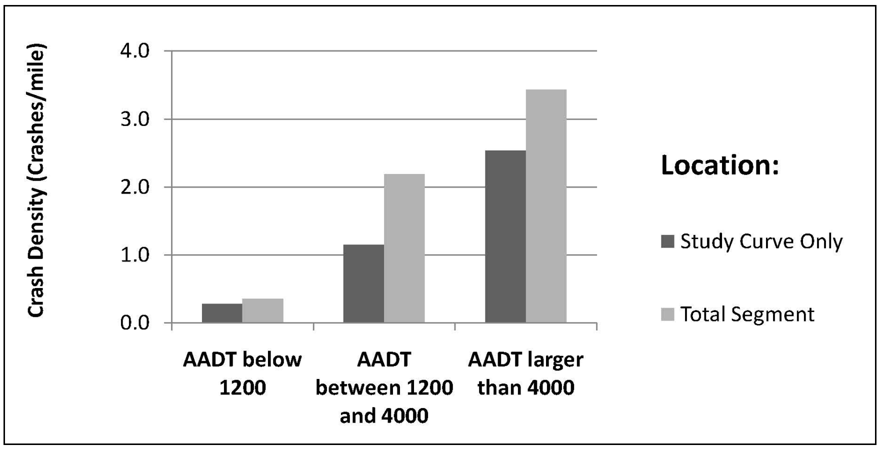


Figure 5.15: Total Crash Densities by AADT

Figure 5.16 shows crash densities for the various AADT thresholds for the types of crashes often observed at non-intersection locations (i.e. head-on plus sideswipe crashes). Though the numeric values for crash densities are different from those depicted in Figure 5.15, the trend is consistent in that the total segment crash density is greater than the specific study curve crash density suggesting more segment-related crashes per mile occur at locations along the corridor than those located within the study curves. Without comprehensive geometric design information for the entire two-mile corridor, it is not feasible to fully explain this observation.

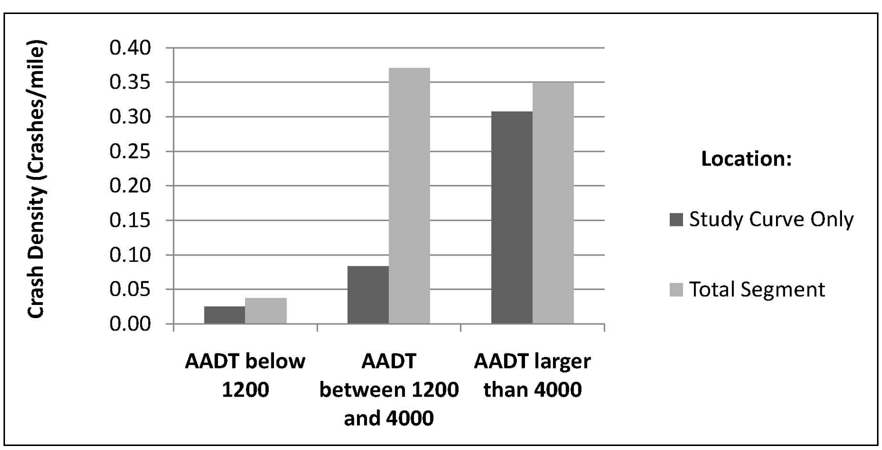


Figure 5.16: Head-on Plus Side-Swipe Crash Densities by AADT

Figure 5.17 shows crash frequency as it relates to run-off-road (ROR) crashes. The crashes shown represent a subset of the total crashes at these sites and do not include the crash types commonly associated with intersections since the research team, from this point forward, will focus the analysis on crashes that are linked to non-intersection locations with specific attention to crashes at horizontal curve locations. As demonstrated in Figure 5.17, approximately 65 percent of the non-intersection crashes were ROR at the study sites.

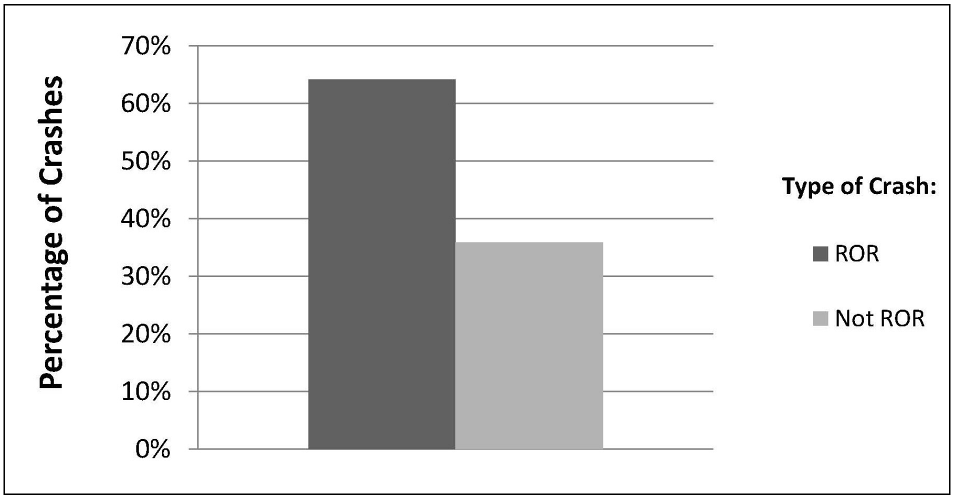


Figure 5.17: Proportion of Non-Intersection Crashes by Run-Off-Road Status

Many of the approximately two-mile long segments included multiple curve locations. As a result, some of the curves located within the corridors were not a direct focus for the advisory speed sign analysis. In Figure 5.18, the term "Study Curve" refers to the curves where the project team collected detailed geometric information. The corridors were then identified as "In Study Curve" representing the curves that are the focus of the advisory speed assessment and "Out of Study Curve" signifying curves or tangent sections located within the total corridor length but that were not subjected to the detailed advisory speed analysis. This "Out of Study Curve" portion of the corridor can be considered as the entire corridor length minus study curve lengths. It is important to contrast the study curve characteristics to those surrounding the curve to assess if the crashes associated with the study curves are consistent with those in the corridor region.

Figure 5.18 presents the crash trend in Figure 5.17 at the "In Study Curve" and "Out of Study Curve" locations and depicts the proportion of crashes by their relative location as a percentage of this overall proportion. For example, a value of 100-percent would mean that the proportion of crashes at that location is the same proportion observed in Figure 5.17. This percentage appears to be approximately 100 percent for crashes out of study curves, suggesting similar proportions to those shown in Figure 5.17. Alternatively, the percentage of the ROR crashes at the studied curves was approximately 8 percent higher than the expected proportion, and the proportion of non-ROR crashes was moderately low (about 15 percent less than the expected proportion). Though this information does not directly provide insights into the relationship between the studied curve locations, it does suggest that locations that are only curves tended to have more ROR crashes than the locations that included both curves and tangent sections.

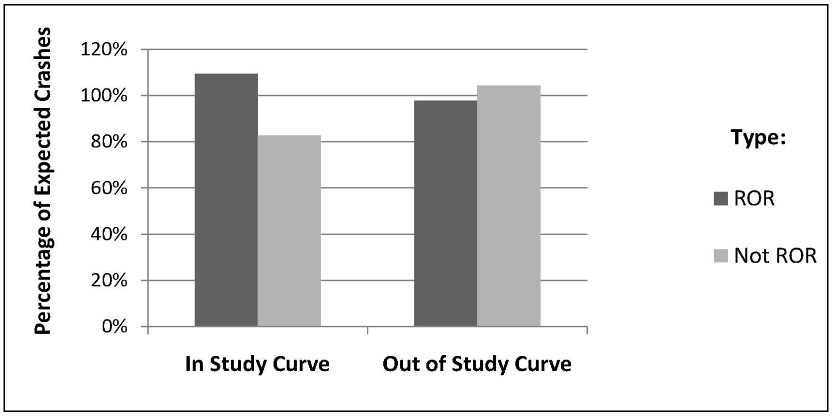


Figure 5.18: Percent of Curve-Related Crash Proportion by Run-Off-Road Status

Even though ROR crashes appear to be pervasive at rural highway locations, a moderately higher number of these crashes can be expected at sharp curve locations. Figure 5.18 provides strong evidence that filtering out crash types commonly associated with intersections may enhance understanding of expected crash types at non-intersection locations such as these rural curve sites. To evaluate this hypothesis, the research team verified a similar scheme using the crash types expected primarily at the intersection locations.

Figure 5.19 provides information in a format similar to that of Figure 5.18 but with a focus on intersection-related crashes. This figure shows percentage of expected proportions of crash records typical to intersection locations (TURN + REAR + ANGLE crashes). One clear difference between this figure and Figure 5.18 is the observed proportion of ROR crashes. These ROR crashes, as shown in Figure 5.19, appear significantly lower than expected at study curve locations, indicating that intersection-like crashes are notably less common at these locations (by approximately 38 percent). This finding is not surprising since the study curve locations were selected for their predominant horizontal curve geometry. This observation confirms the research team’s decision to remove the crash types common to intersections from the remaining corridor safety analysis as these turning, rear-end, and angle crashes are not expected to occur frequently at the non-intersection locations and are more likely associated with intersections or driveways (locations that are not a target for this analysis).

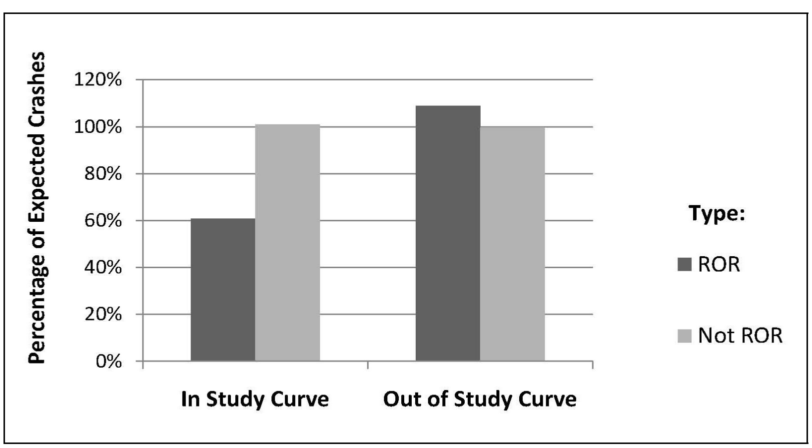


Figure 5.19: Percent of Intersection-Related Crash Proportion by Run-Off-Road Status

Figure 5.20 shows the overall proportion based on crash severity for the non-intersection crash types. Property-damage-only crashes (PDO) accounted for approximately 54 percent of the total crashes. About 43 percent of all crashes included injury (INJ) crashes (where at least one occupant in the crash was injured) and about three percent included fatality (FAT) crashes (distinguished by the death of at least person involved in the crash within 30 days of the crash occurrence).

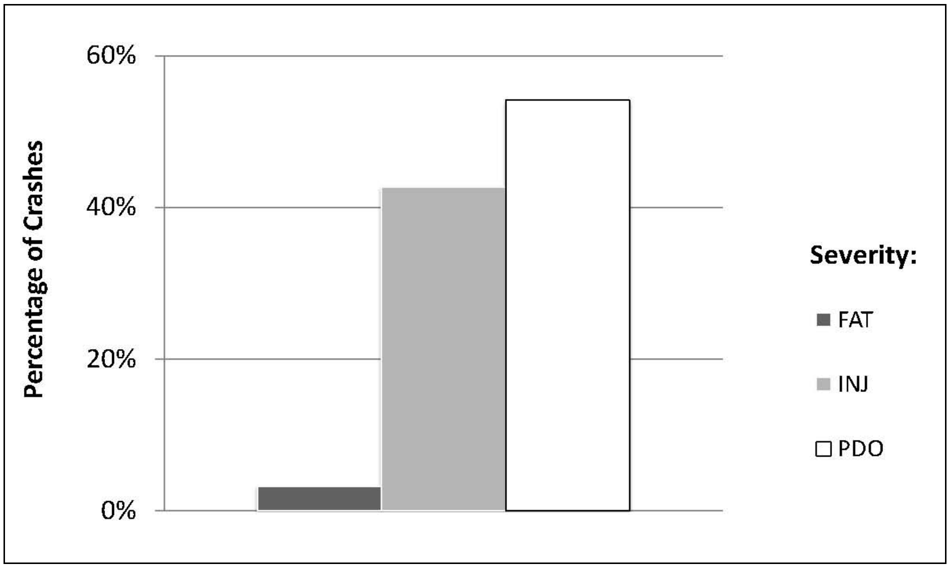


Figure 5.20: Proportion by Severity of Non-Intersection Crashes

Figure 5.21 shows percentages based on severity proportions shown in Figure 5.20. A value of 100 percent would indicate that proportions for horizontal curvature locations (referred to as "In Study Curve" in the figure) and proportions for locations that are not within the limits of a study curve (referred to as "Out of Study Curve") are consistent with overall corridor, non-intersection crashes as indicated in Figure 5.20. It is clear that fatal crashes are disproportionately high at study curves (more than two times the expected value). Injury crashes are moderately higher at study curve locations (approximately 19 percent more than for the corridor sample). As a reminder, the "Out of Study Curve" includes the total for all *targeted random sample* crashes within the various two-mile corridor segments that are not located within the limits of the studied horizontal curves.

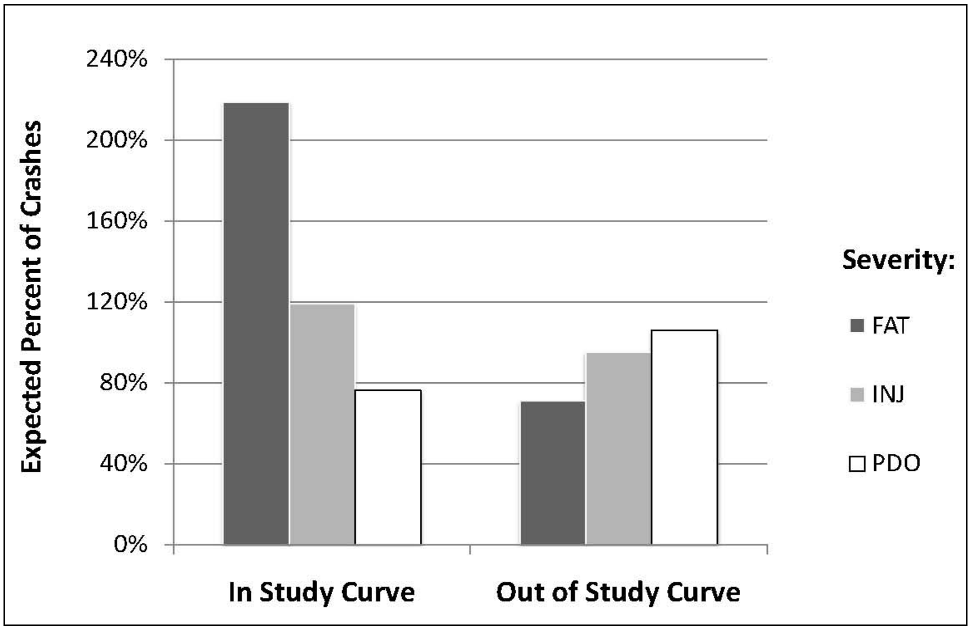


Figure 5.21: Crashes by Relative Location and Severity as Percentage of Total Sample Proportion

Figure 5.22 demonstrates the relationship of traffic volume, in the format of AADT, to study location using a proportion comparison similar to that in Figure 5.21. Crash proportions are once again larger than expected at the study curves even though Figure 5.16 demonstrated that the total crash density for the segment is greater than for the study curve locations. Figure 5.22 shows that the proportion of crashes was 44 percent more than expected at curves with AADTs smaller than 1200 vpd. For curve locations with AADT values greater than 4000 vpd, the proportion of crashes was 21 percent more than expected. This finding suggests that, for the study locations, curves with either low or high traffic volumes tended to have more associated crashes than one would expect based on the overall crashes observed for the two-mile study corridors.

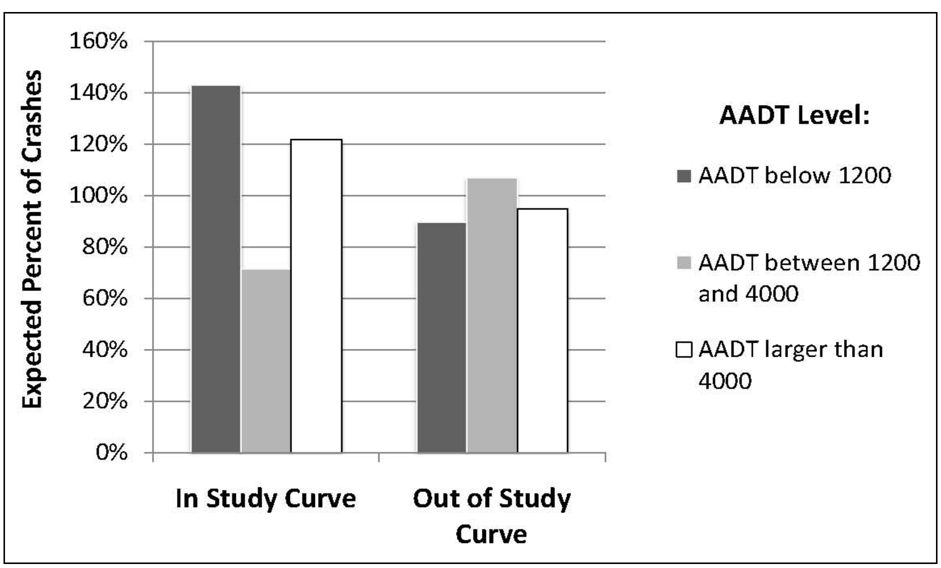


Figure 5.22: Percentage of Expected Crash Proportion by Relative Location and AADT

This initial analysis characterizes the sample sites in terms of general trends. After the research team filtered out crash types more common to intersection locations, it became clear that, on average, crash densities (depicted as crashes per mile) are smaller at the study curves as they compare to their surroundings possibly suggesting that the posted advisory speeds do help improve safety. However, for sites with AADT values below 1200 vpd and sites with AADT values greater than 4000 vpd, the proportion of crashes at curve locations substantially exceeded the expected values. Although these study site level estimates are informative, they do not directly address a relationship to specific posted advisory speeds (e.g. some study sites were posted with different advisory speeds per direction, some sites did not have posted advisory, and some sites has advisory speeds posted only for one direction of travel).

Section 5.3 explores safety trends as they relate to more specific geometry and signage at the study sites. Since there were some advisory speed posting differences in the various directions of travel, Section 5.3 also explores crash statistics based on curve direction of travel.

5.3 DESCRIPTIVE STATISTICS AT THE STUDY CURVE LEVEL

This section reviews the crash conditions observed at the study curve locations to help identify how they related to the geometry and signage of their respective curves. At the 80 state-maintained highways in the *statewide random sample*, it was possible to identify 118 crashes that occurred at or very close to the curves. After a close examination of the specific site and crash characteristics for these 80 corridors, the research team identified 41 crashes with imprecise mileage indicators suggesting that these crashes could be also located at the study curves. This distribution is shown in Figure 5.23. In this figure, three categories of crashes are depicted: curve located crashes; possibly curve located crashes; and undetermined location crashes. The "curve located" crashes are known to occur within the limits of the study curve and/or in immediately proximity of the curve (defined as a distance within 0.2 miles of the beginning or end of the curve). Crashes referred to as "possibly curve located" are crashes common to curve locations such as a run-off-road or sideswipe crash, but their mileage indicator appears to be rounded to a whole number and this rounded milepoint location occurs within the boundaries of the study curves. Finally "undetermined location" crashes also appear to have a milepoint value that was rounded to a whole number but this value did not occur within the study curve limits. It is possible that some of these "undetermined location" crashes did occur within the limits of the curve, but it is not possible to determine this based on the available crash data.

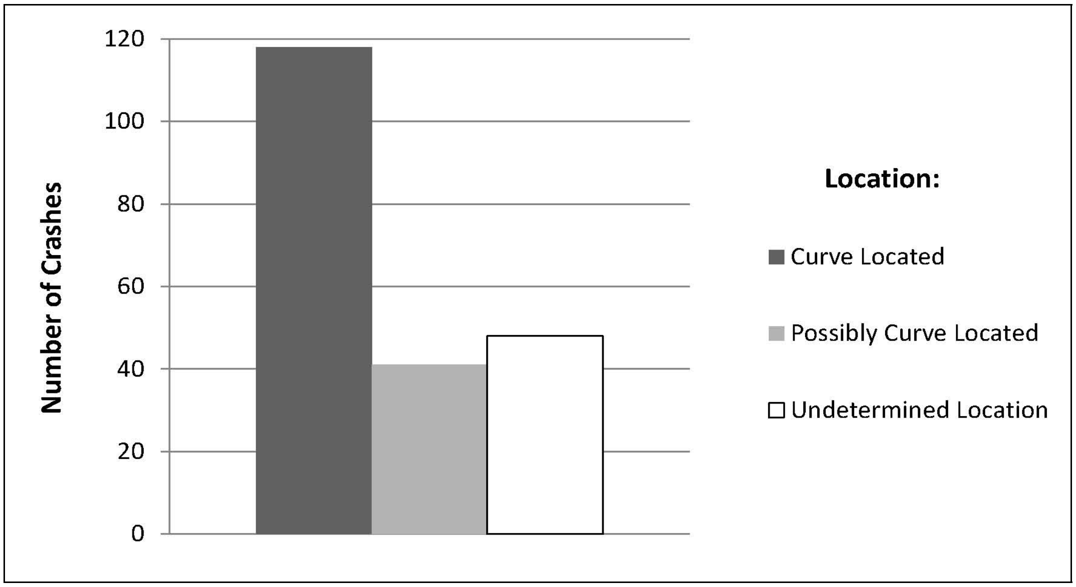


Figure 5.23: Crash Frequency by Curve-Located Status

The “curve located” crashes occurred at 65 of the 105 study curves, or at 98 of the 210 curve directions of travel (each curve included two directions of travel).

The research team performed a preliminary statistical test to determine whether to include crashes identified as “possibly curve located.” Figure 5.24 shows crash frequency for posted advisory speed locations at the "curve located" sites as well as the "possibly curve located" sites. A Pearson’s independence test for these values suggests that the variables are not independent (chi-square statistic of 4.308, with a p-value of 0.038) and may introduce a bias when accounting for advisory speed signs. As a result, these sites with imprecise mileage were excluded from subsequent analysis.

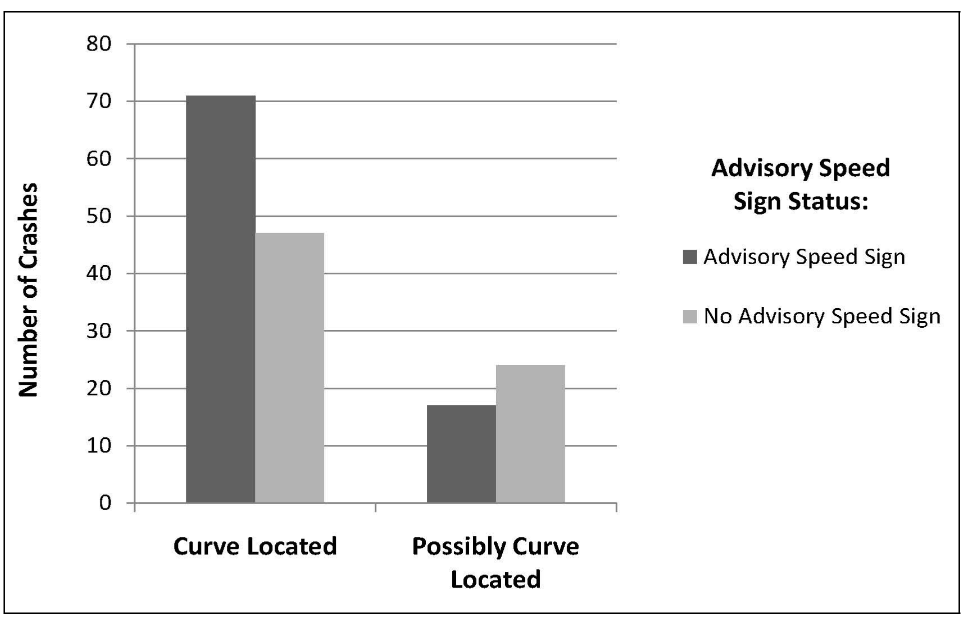


Figure 5.24: Crash Frequency for Posted Advisory Speed

Figure 5.25 shows the proportions corresponding to the "curve located" crashes previously depicted in Figure 5.24. These proportions were then used as a baseline for the data in Figure 5.26 and Figure 5.27. As previously indicated, of the 80 corridors there were 72 with crashes with a total of 1104 crashes. For the study curve locations only, however, approximately 118 known crashes occurred within the limits of the study curve.

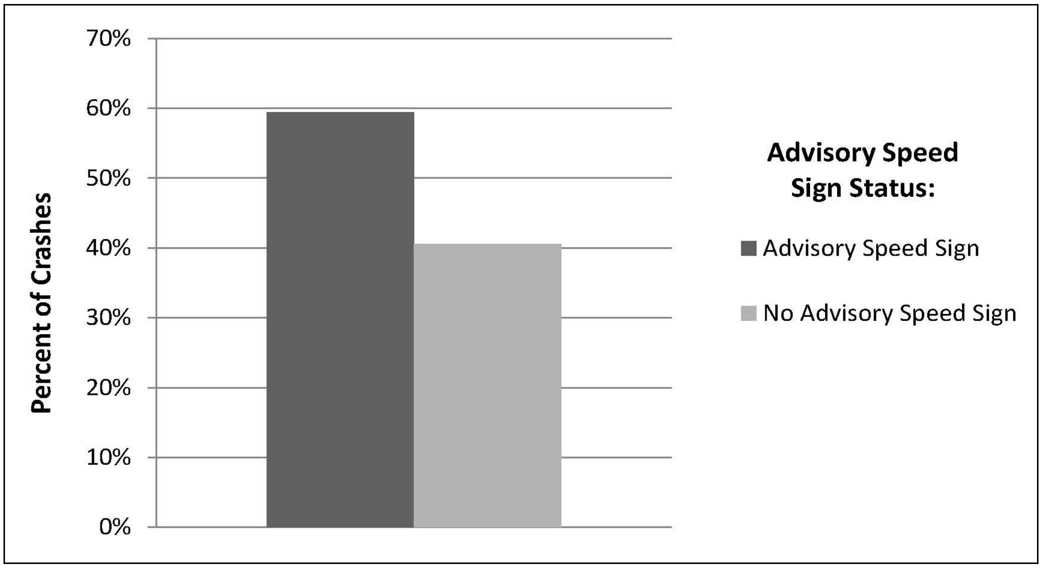


Figure 5.25: Total Proportion of Crashes by Presence of Advisory Speed Signs

The research team would have preferred to analyze the differences in crash frequencies at locations with a variety of curve radii; however, this was not possible due to the small sample size for various radii thresholds. In fact, only one radius threshold had an adequate number of data points with and without posted advisory speed signs (radii ranging from 350 to 875 ft.) as shown Figure 5.26.

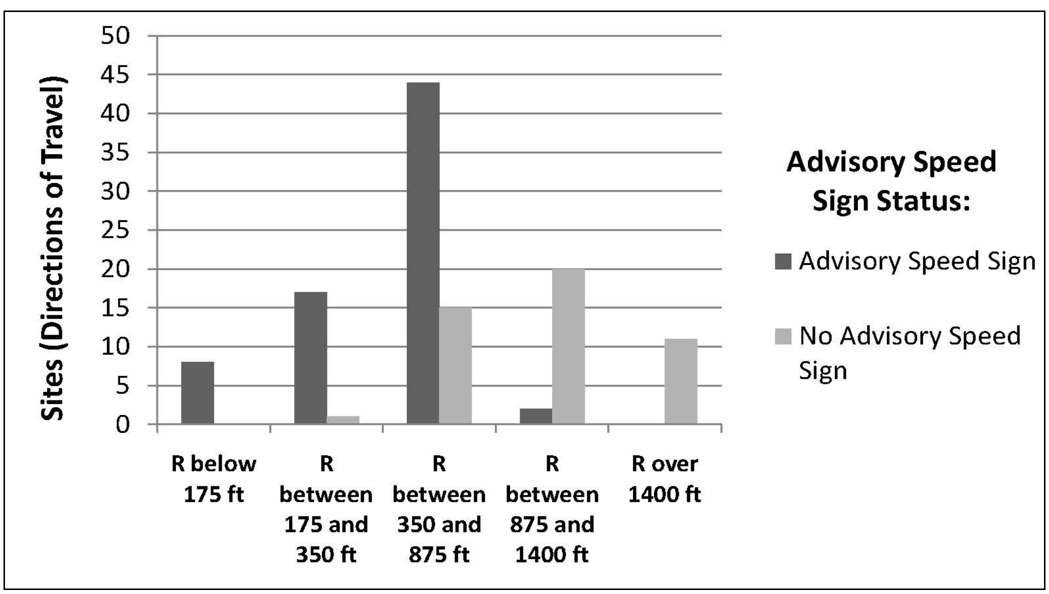


Figure 5.26: Number of Curve Directions of Travel by Radius

Figure 5.27 depicts the percentage of crashes for the expected proportion by AADT. A value of 100 percent suggests that the proportion of crashes at a particular AADT threshold is the same as the proportions shown in Figure 5.25. As indicated above, only sites with radii ranging from 350 to 875 ft are shown as only this radii range included an adequate sample size. Figure 5.27 indicates that different AADT levels are associated with different safety trends relative to the advisory speed signs. One obvious example is the large number of crashes shown for sites without advisory speed signs and when the AADT values are larger than 4000 vpd (resulting in approximately 40 percent more than the expected proportion). This observation implies that if there is an influence due to advisory speed signs on crash frequency, this trend may vary as a function of AADT.

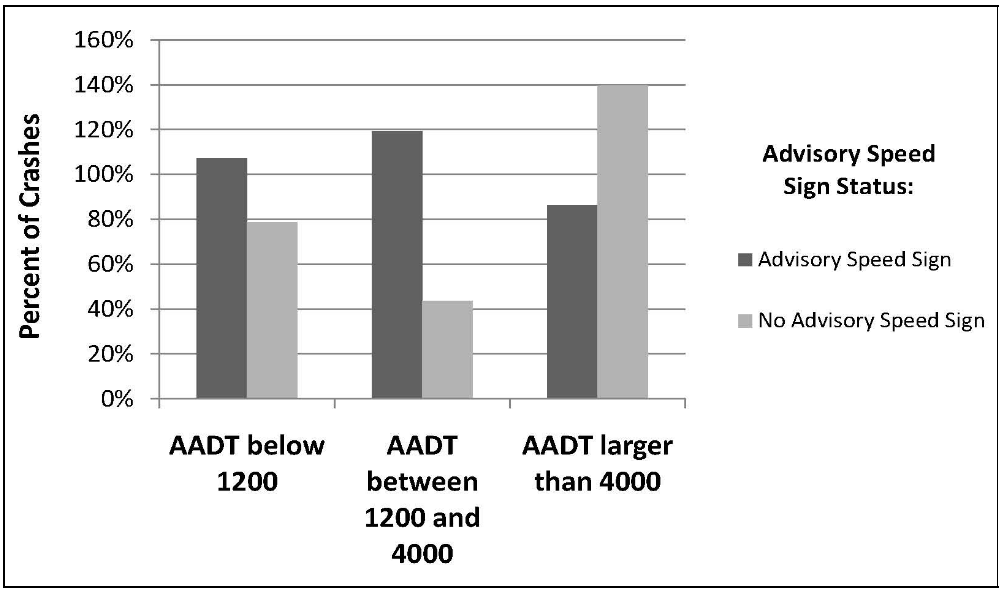


Figure 5.27: Advisory Speed Sign Status for Percent of Crashes by AADT for Curves with Radius between 350 and 875 feet

Figure 5.28 shows the required side friction demand (SFD) for speeds at the posted advisory speed or 5 mph lower than the speed limit (a level where advisory speed signs are not required). Figure 5.29 shows average crash densities for each advisory speed. The contrast with Figure 5.28 appears obvious: higher crash densities occur at locations posted with lower advisory speeds even though the SFD was roughly equal for the various advisory speeds (see Figure 5.28). One explanation may be that Oregon drivers consistently travel at speeds greater than the posted advisory speeds.

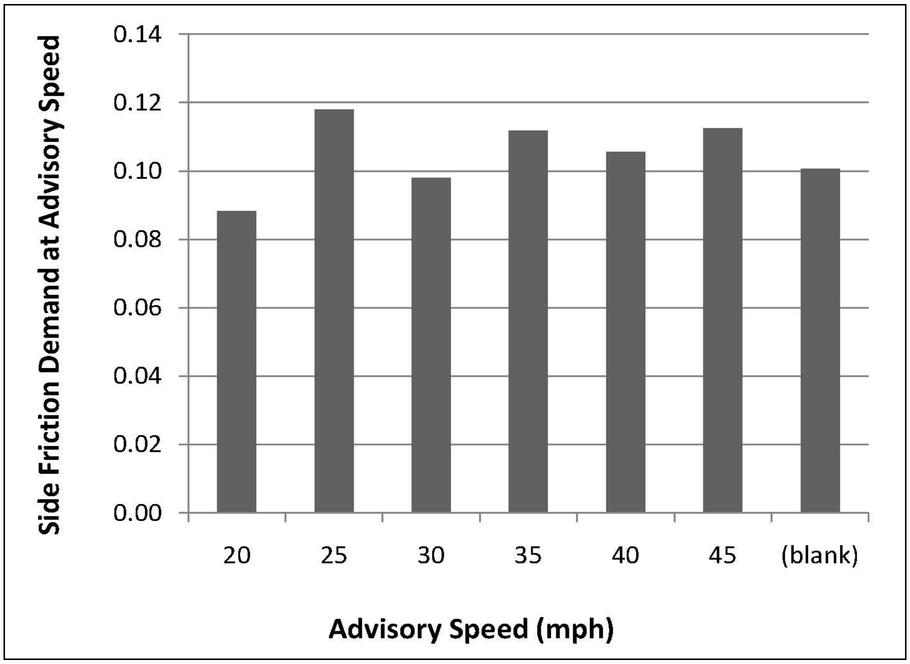


Figure 5.28: Side Friction Demand by Posted Advisory Speed

Six of the study sites (or 10 studied directions of travel for these sites) had a 25 mph posted advisory speed. For these 10 curve directions of travel, Figure 5.29 indicates an average crash density of zero (or no crashes during the study period). The research team performed a statistical assessment (p-value of 0.988, see Appendix E, Section E.1) to determine if these sites should be treated differently and could not find evidence to support excluding them from the larger data set during the subsequent statistical analysis.

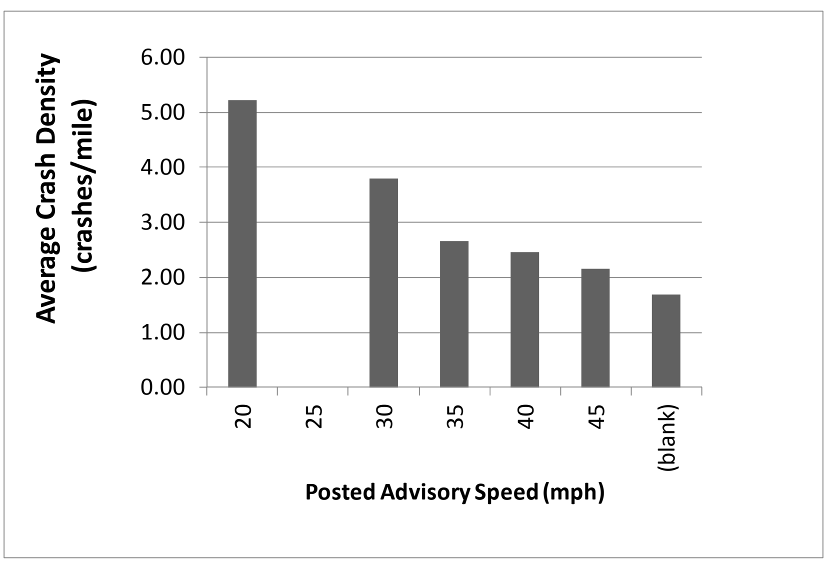


Figure 5.29: Crash Density by Posted Advisory Speed

Figure 5.30 depicts the average crash density as it relates to the advisory speed differential (ASD) which is the value that results from subtracting the posted advisory speed from the speed limit. For example, if a facility has a posted speed limit of 55 mph but an advisory speed of 40 mph, the associated speed differential shown in this figure would be 15 mph. Since an agency is not required to post an advisory speed if it is within 5 mph of the speed limit, it is not a surprise that for the 96 curve directions of travel which have a 5 mph speed differential only one site included a posted advisory speed. As the speed differentials become larger, the number of sites (curve directions of travel) dramatically decreases. For the 25, 30, and 35 mph speed differentials there were 10, zero, and four curve directions of travel respectively. The fluctuations depicted in Figure 5.30 suggest a non-linear relationship between the crash density and the speed differential. The research team tested this non-linear trend and determined that it is not statistically significant (p-value of 0.1613 for a quadratic term, see Appendix E, Section E.2 for a detailed computer output).

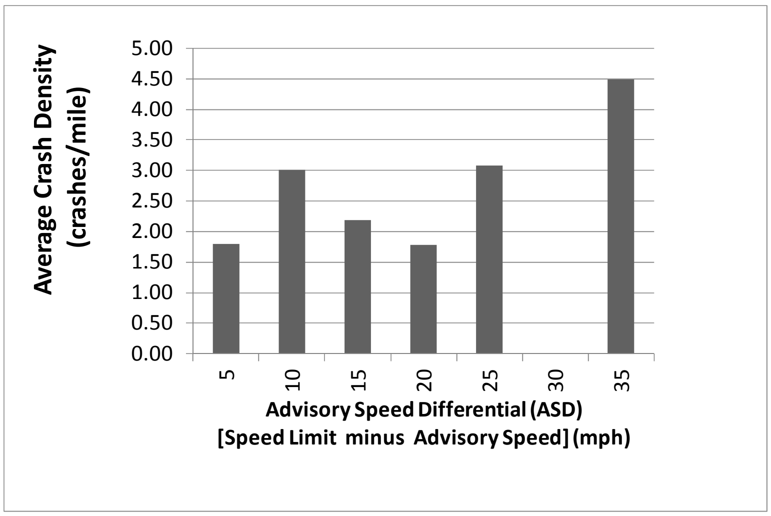


Figure 5.30: Crash Density by Advisory Speed Differential

Figure 5.31 shows the associated crash density for posted advisory speed conditions based on the current Oregon policy. This figure includes the following four conditions: (1) not warranted but posted; (2) not warranted and not posted; (3) warranted but not posted; and (4) warranted and posted. On average, sites where posted advisory speeds were not warranted experienced more crashes per mile than sites where posted advisory speeds were warranted. The purpose of a warranted posted advisory speed sign is to inform the driver that he or she should slow down to successfully negotiate the curve, In most cases the sites where the signs were not warranted have higher speed conditions.

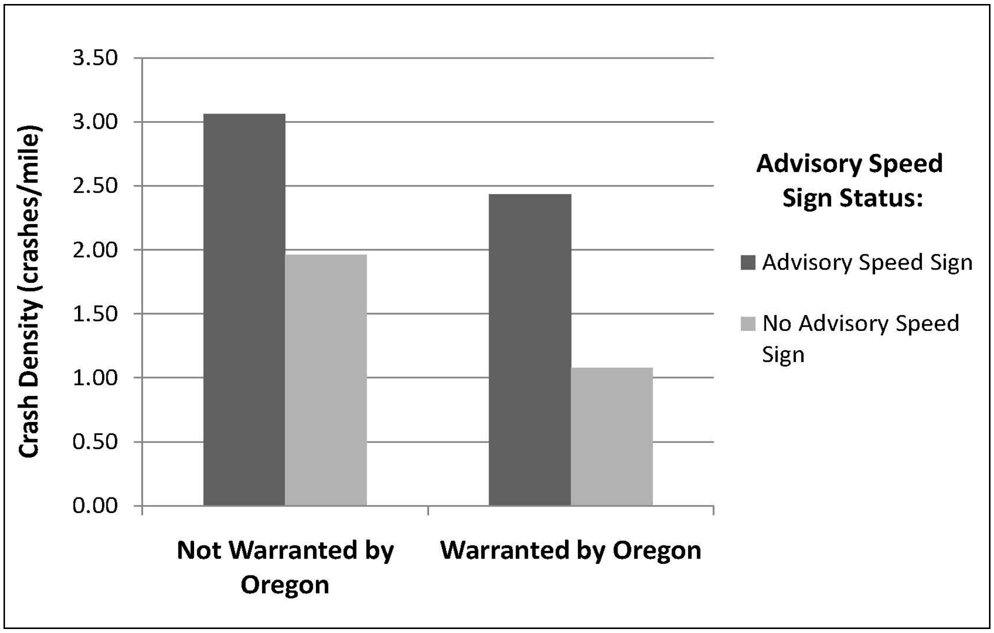


Figure 5.31: Crash Density Based on Oregon Policy and Existing Advisory Speeds

Another important note is that the group of sites where advisory speeds were not warranted but posted appear to have a notably higher crash density compared to their companion group (not warranted and not posted); however, this group of sites includes only seven curve directions of travel (a very small sample size). The research team assessed this difference using the statistical model presented in Section 5.4. The modeled effect is, as shown in Figure 5.31, an increase in expected crashes, but this increase was not statistically significant (p-value of 0.517, see Appendix E, Section E.3 for the detailed statistical model output).

The sites where advisory speeds were warranted but not posted experienced, on average, fewer crashes per mile than their comparison group (warranted and posted). The research team also statistically evaluated this trend and determined that this effect is a decrease in the number of crashes; however, this finding was also determined not to be statistically significant (p-value of 0.993, see Appendix E, Section E.4 for the detailed statistical output).

Following the descriptive statistics phase of the data analysis, the project team performed statistical analysis to explore if an appropriate predictive model may be developed that can help link advisory speed associated issues directly to crash history. Section 5.4 summarizes this detailed analysis.

5.4 MODEL-BASED STATISTICS

In an effort to further test for the statistical significance of the trends observed in Section 5.3 of this report, the project team discarded the use of direct single variable (univariate) statistical tests, since these tests consider only one factor at a time and do not capture the interaction of various factors that may contribute to the crash. Initially, the research team developed a single statistical model to include all of the expected factors based on observations from the descriptive statistics analysis.

The literature suggests the use of Poisson and Negative Binomial (NB) models for the assessment of crash data. The research team used both model methods at various points when comparing the candidate models. Ultimately, a Poisson regression model provided the best explanatory power and fit to the study data.

The research team constructed a model based on the Akaike Information Criterion (AIC). This approach can be used to estimate the impact of including potential explanatory variables, one at the time, towards the overall quality of information in the model. The resulting model from this procedure is shown in Equation 5-1 (see Appendix E, Section E.5 for a detailed computer output). In Chapter 7 the authors demonstrate how this statistical model can also serve as an alternative method for posting advisory speeds that enhance safety.

Equation 5-1: Poisson Regression Model for Expected Number of Crashes (5-1)

$$
\begin{aligned}
\#Crashes = \exp[&-3.678 \\
&+\{0.0005(AADT) - 0.0005\,(Higher\ AADT \times AADT) \\
&+2.007\,(HigherAADT)\} \\
&+\{0.0004(Radius) - 0.0045\,(AdvSpdPresent \times Radius)\} \\
&+4.644(AdvSpdPresent) \\
&+\{0.0008(CurveLength) - 0.0026(AdvSpdPresent \times CurveLength)\} \\
&+\{7.711(SFD) - 0.8625\,(ASD \times SFD) + 0.049\,(ASD)\} \\
&-1.301\,(LowAdv)\ ]
\end{aligned}
$$

Where:

AADT = Annual Average Daily Traffic (vpd);
SFD = Side Friction Demand at Advisory Speed (no units);
CurveLength = Length of the Curve (ft);
Radius = Horizontal Radius (ft);
ASD = Advisory Speed Differential, defined as speed limit minus posted advisory speed (mph);
HigherAADT = Indicator variable equal to one if AADT > 6000, zero otherwise;
LowAdv = Indicator variable equal to one when the posted advisory speed is below 30 mph, otherwise the value is zero; and
AdvSpdPresent = Indicator variable equals to one when advisory speed signs are present, otherwise the value is zero.

The statistical model includes operational, geometric, and signage variables. In addition, the model also incorporates interaction terms. These interaction terms capture how some of the explanatory variables directly influence (or interact with) a variable's effect on crash frequency. An undesirable model attribute known as multicollinearity is likely to appear when interaction terms are part of the model. Although the effect of multicollinearity does not involve bias of the estimates, it does decrease the significance of terms involving the interacting variables because the variables do not behave independently. The research team found that interactions between variables were present and that the resulting model provides statistically significant information regarding the relevant trends of interest important for this research effort.

Table 5.2 depicts the coefficients and their statistical significance. The alternating shadowing is provided to facilitate visualization of the interacting variables as they are grouped by brackets in Equation 5-1.

Table 5.2: Model Coefficients and their Statistical Significance

Term	Estimate	Standard Error	z-value	p-value	Significance
(Intercept)	-3.678	0.692	-5.314	1.07×10^{-7}	***
AADT	5.097×10^{-4}	6.399×10^{-5}	7.966	1.64×10^{-15}	***
AADT:HigherAADT	-4.578×10^{-4}	9.134×10^{-5}	-5.011	5.41×10^{-15}	***
HigherAADT	2.007	0.678	2.960	0.003	**
Radius	4.430×10^{-4}	3.172×10^{-4}	1.396	0.163	
Radius:AdvSpdPresent	-4.459×10^{-3}	1.052×10^{-3}	-4.237	2.26×10^{-5}	***
AdvSpdPresent	4.644	0.745	6.237	4.47×10^{-10}	***
CurveLength:AdvSpdPresent	-2.557×10^{-3}	6.965×10^{-4}	-3.671	2.42×10^{-4}	***
CurveLength	8.485×10^{-4}	3.170×10^{-4}	2.677	7.431×10^{-3}	**
SFD	7.711	2.381	3.239	1.198×10^{-3}	**
ASD:SFD	-0.863	0.201	-4.152	3.300×10^{-5}	***
ASD	4.926×10^{-2}	2.594×10^{-2}	1.899	5.760×10^{-2}	
LowAdv	-1.301	0.504	-2.584	9.759×10^{-3}	***

Although Equation 5-1, upon initial examination, appears complex, its use is relatively straightforward. To demonstrate how this and similar equations can be used, Figure 5.32 demonstrates an example application of the model. Note the sample application predicts crashes for an approximate five year period. The current recommendation, as presented in the AASHTO *Highway Safety Manual,* is three to five years.

Sample Data:

Site Name	Mt. Hood Highway MP 70	Comments
AADT (vpd)	1320	
Higher AADT	0	This variable is equal to one when the AADT is larger than 6000; otherwise, this value is equal to zero.
Radius (ft)	1425	
AdvSpd Present	0	This variable is equal to one when posted advisory speed signs are present; otherwise, this value is equal to zero.
Curve Length (ft)	300	
Speed Limit (mph)	55	
Advisory speed (mph)	50	Recall this speed is not required to be posted as it is within 5 mph of the speed limit.
Superelevation (%)	4.0%	
LowAdv	0	This variable is equal to one when the posted advisory speed is either 20 mph or 25 mph; otherwise, this value is equal to zero.
SFD	0.11697	Computed as the squared advisory speed divided by 15 times the radius.
ASD (mph)	5	Speed limit minus the advisory speed

In order to use Equation 5-1 to estimate the expected number of crashes in the study period, substitute the corresponding values into the equation as follows:

$$
\begin{aligned}
\#Crashes = \exp[&-3.678+\{0.0005(1320) - 0.0005\,(0 \times 1320)+2.007\,(0)\} \\
&+\{0.0004(1425) - 0.0045\,(0 \times 1425)\}+4.644(0) \\
&+\{0.0008(300) - 0.0026(0 \times 300)\} \\
&+\{7.711(0.11697) - 0.8625\,(5 \times 0.11697) + 0.049(5)\} - 1.301\,(0)\,]
\end{aligned}
$$

Performing the indicated operations, the equation further reduces to:

$$\#Crashes = \exp[-1.5655\,]$$

The predicted number of crashes in 5 years would be approximately 0.21 crashes. This extremely small number of crashes coincides with the crash record for this site, which does not indicate any crashes during the study period.

Figure 5.32: Example Use of Equation 5-1

The research team further assessed the trends described in Section 5.3 and modified the model to incorporate the trend-associated variables. This model includes three variables associated with advisory speeds: ASD (the difference between the speed limit and the posted advisory speed), AdvSpdPresent (binary variable indicating the presence of posted advisory speeds), and LowAdv (a binary variable indicating advisory speeds of 20 or 25 mph). Based on the AIC model comparison approach, these variables improved the information quality of the model. For instance, the specific posted advisory speed values were not included during the model selection procedure because these variables would have resulted in redundant information within the model. The advisory speed variable was highly correlated with the horizontal curve radius (Pearson correlation of 0.67), so this relationship resulted in exclusion of the advisory speed variable in favor of the more significant radius variable.

The variables shown in the first bracket in Equation 5-1 correspond to the influence of the daily traffic volume. This AADT relationship to crash frequency is presented in the form of a natural logarithm as depicted in Figure 5.33. It is clear from this figure that the relationship between crashes and AADT has a curvilinear shape (or non-linear). The research team evaluated alternative ways to include this non-linear effect, and the AIC criterion strongly favored modeling AADT as a concave parabola. However, this functional form significantly increased the multicollinearity as previously discussed. To develop a more stable estimate, the research team approximated this non-linear behavior with two lines instead of a parabola. Figure 5.34 schematically displays this approach. The mathematical form for these two lines is shown in the first bracket of Equation 5-1 as the AADT term, the HigherAADT indicator variable term, and the interaction term for these two variables (HigherAADTx AADT). An AADT value of 6000 is the lower boundary for the HigherAADT variable and so serves as a “break point” between the two lines.

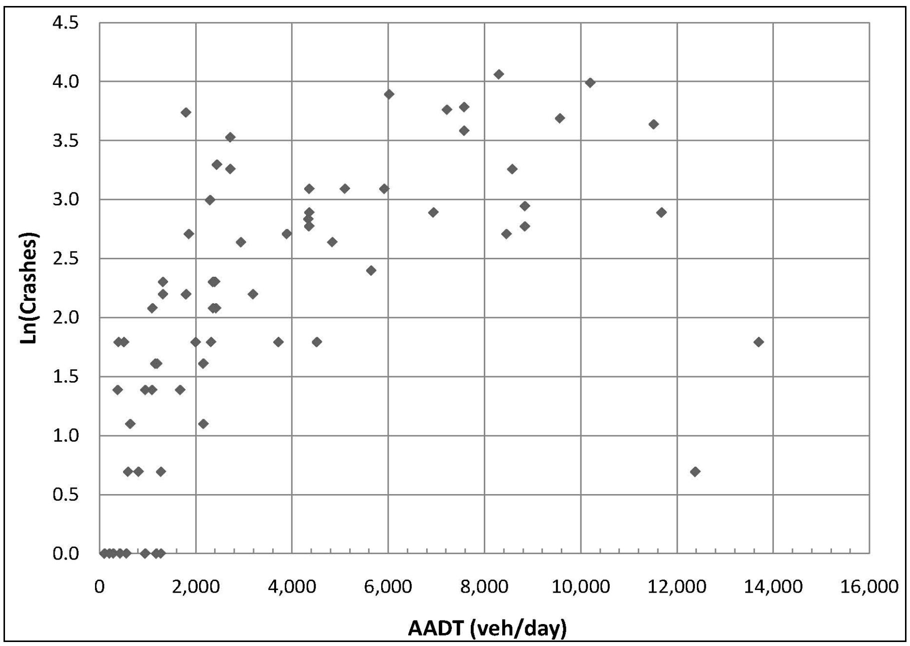


Figure 5.33: Natural Logarithm of Crash Frequency versus AADT

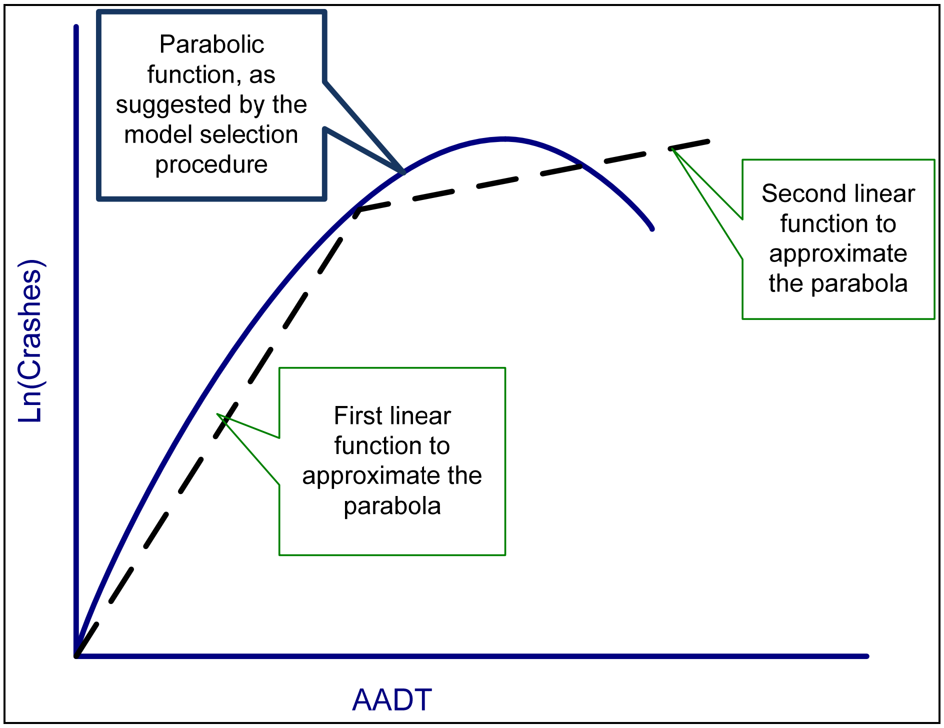


Figure 5.34: Two-line Approximation of the AADT Effect on Number of Crashes

The schematic in Figure 5.35 represents the statistical model variables in terms of the larger categories of Geometry, Signage, and Operations. In some cases, overlap between these categories can be expected. For instance, the SFD is a factor of speed, radius, and superelevation, so this candidate variable incorporates components of the Operations and the Geometry categories. There are, of course, relevant safety-related variables such as operating speed that have been excluded from the diagram. The diagram only displays the variables available from the statistical model.

The interaction between these various factors was confirmed for four of the interaction terms during the model selection procedure. The research team adopted a basic hierarchy to help explain the combined effects of interacting variables. For example, combined influences of the geometric design and signage can directly impact safety. The combined influence of warning signs and changes in the horizontal curve radius or highway cross-slope directly influence the crash frequency. In some cases, changing both elements can more significantly affect the anticipated number of crashes.

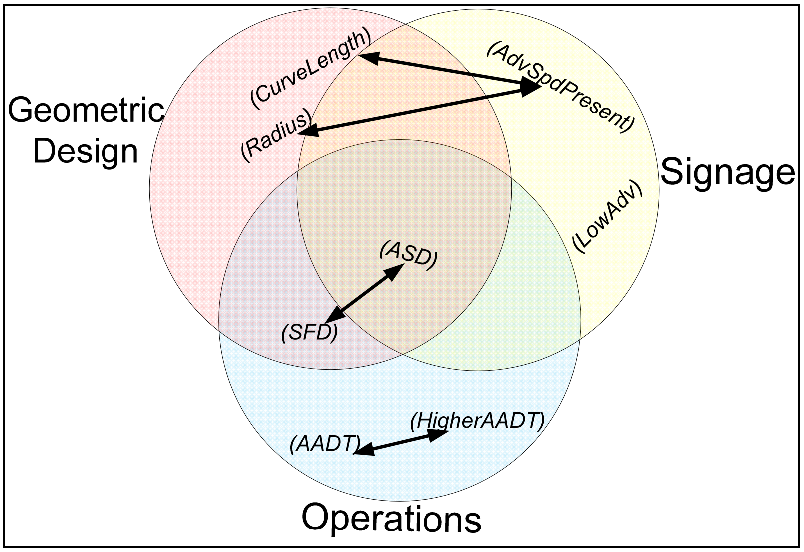


Figure 5.35: Conceptual Relationships among Statistical Model Variables

The interaction between a signage variable and an operations variable can be interpreted as the signage variable potentially shifting the effect of the operations variable. Under this approach, an interaction between signage and geometric design implies that the signage variable affects the "previously existing" influence of geometry which in turn will affect operations. As a result, the direct impact of an advisory speed plaque, as included in the statistical model, does not specifically influence the expected crash frequency. The safety effect of the posted advisory speeds, instead, influences the operations and geometric design variable interactions and these variables then influence the expected safety performance resulting from the model.

As shown in Figure 5.35, the side friction demand (SFD) is directly associated with the geometric design and operations categories. Since this variable is based on vehicle dynamics and the interactions between the vehicle and the road, it plays an important role in establishing the appropriate advisory speed at a curve location. It is not, however, a value that a driver would estimate when navigating the corridor.

The ASD (recall this is the speed limit minus the posted advisory speed value) is associated with the signage and operations categories. Since both the advisory speed and the speed limit are functions of the geometric design, this variable is logically associated with the geometric design category. Since the driving population can directly estimate and assess this value, it is also associated with the operations and signage category. As a result, the ASD variable is directly associated with all three model variable categories depicted in Figure 5.35.

The second bracket variable set in Equation 5-1 includes the horizontal curve radius and the presence of advisory speed signs. The isolated functional form of this combination of variables is shown in Equation 5-2 for convenience.

Equation 5-2: Total Effect on Crashes Due to Both Advisory Speeds and Curve Length

$$\alpha(\#Crashes) = \exp[\{0.0004(Radius) - 0.0045(AdvSpdPresent \times Radius)\}] \qquad (5\text{-}2)$$

Where:

α(#Crashes): Multiplicative joint effect of horizontal radius and advisory speed presence on number of crashes;

All other variables as previously defined.

Notice that when a posted advisory speed is not present (AdvSpdPresent = 0), the resulting effect is based primarily on the influence of the curve radius (a shift in number of crashes that is proportional to the radius). Since the radius effect is, in this case, only the fourth coefficient (excluding the intercept) as shown in Table 5.2, the corresponding p-value indicates it is not statistically significant (p-value of 0.163). Upon a closer inspection, the research team found that the average radius for horizontal curve locations that did not have posted advisory speeds was 1115 ft (more than double the 536 ft average radius at horizontal curve locations with posted advisory speeds). Because of this obvious difference, the research team concluded that, although the variable AdvSpPresent was included in the model to indicate the presence of advisory speed signs, it is confounded with radius-related information. As a result, this variable more likely conveys information about geometric characteristics and this information is then translated to indicating the presence or absence of advisory speed signs. In other words, the model suggests that at locations where posted advisory speed signs were not present, the horizontal curve radius does not significantly affect crash frequency.

When posted advisory speed signs are present (AdvSpdPresent = 1), Equation 5-2 then reduces to a summation of two constants multiplied by the horizontal curve radius. To determine if the radius is statistically significant at horizontal curve locations with posted advisory speeds, the research team performed an additional analysis to evaluate the associated regression estimates. Table 5.3 shows the data resulting from this assessment. As shown in this table, the horizontal curve radius has an inverse relationship to the crash frequency (determined by the negative value) and it is statistically significant (p-value of 0.00011). For curves with posted advisory speeds, the model predicts fewer crashes at curves with larger radii.

Table 5.3: Radius Effect at Sites with Posted Advisory Speeds

Radius effect when AdvSpPresent=1	-0.00402
Variance of Radius Coeff	1.006×10^{-07}
Variance of Radius: AdvSpPresent Coeff	1.108×10^{-6}
Covariance of Radius and Radius: AdvSpPresent Coeff	-1.350×10^{-8}
Standard Error	0.0011
z-value	-3.695
p-value	0.00011

The statistical model also includes an interaction term between the AdvSpPresent and CurveLength variables. Similar to the interaction with the horizontal radius, these coefficients are characterized by opposing signs and similar relative magnitudes. In this case, however, both terms are statistically significant so it was not necessary to perform additional significance analysis in a manner similar to that for Table 5.3. The model supports the finding that the number of crashes is proportional to the length of the horizontal curve at locations without posted advisory speeds, but this value is then inversely proportional to curve length at locations with posted advisory speeds. This latter finding suggests that, according to the statistical model, shorter curves with posted advisory speeds are more hazardous than longer curves. These observations do not, however, provide conclusive information about the effectiveness of advisory speed signs.

Since a primary goal of this research effort is to determine if the use of advisory speed signs has a direct influence on crash frequency, the LowAdv variable previously presented in Table 5.2 may be useful. Recall that this variable indicates the presence of advisory speed plaques that display a 20 or 25 mph advisory speed value. The model attributes a relevant safety effect at these sites (a 73-percent decrease in the number of crashes due to a multiplicative effect of 0.2723 derived from $e^{-1.301}$). The model also provides evidence that this effect is statistically significant. Although this variable is also associated with smaller radii (the radii at these sites ranged from 100 to 410 ft), the statistical significance would likely decay with the inclusion of more variables associated with this single factor (radius in this case) in the model. It is likely, for example, that the radius value is also addressed intrinsically by the additional variables for AdvSpPresent, Radius:AdvSpPresent, CurveLength:AdvSpPresent, and LowAdv. The fact that all of these variables are statistically significant suggests that they likely indicate the influence of other relevant significant factors. The research team expects that most of the explanatory power of the radius is distributed among these variables with the favorable effect of the LowAdv variable directly indicating a particular safety benefit associated with the advisory speed plaques.

As shown in Equation 5-1, an interaction occurs for the SFD and ASD variables. It is possible that this may represent the influence of the horizontal curve radius since a larger value for SFD and for the ASD is typically associated with a smaller curve radius. It appears that this interaction between the SFD and the ASD may indicate a potential safety benefit as a result of the posted advisory speeds. Since this interaction involves the combination of a continuous variable (SFD) with a discrete one (ASD), describing their joint effect can be challenging. This is because both the marginal effect and the statistical significance of one variable will vary with the other variable.

Table 5.4 shows the marginal effect of the ASD at different levels of the SFD. As previously indicated, the SFD is representative of the combined Geometric Design and Operations site categories rather than as a Signage variable. This association is because drivers do have a sense of their side friction needs simply as a result of the value displayed on the advisory speed plaques. Computationally we know that a higher SFD requires more friction from the vehicle wheels if drivers negotiate a horizontal curve at the advisory speed. As the value of the SFD increases, therefore, it is reasonable to assume that a higher SFD value is more likely a hazard when compared to a similar curve with a smaller SFD.

Table 5.4: ASD Marginal Effect at Sites with Different SFD

SFD	Marginal Effect of ASD	Ln(MargEff)	Std. Err.	z-stat	p-value
0.07	0.989	-0.011	0.025	-0.453	6.51×10^{-1}
0.14	0.931	-0.071	0.031	-2.314	2.07×10^{-2}
0.21	0.876	-0.132	0.042	-3.170	1.52×10^{-3}
0.28	0.825	-0.192	0.054	-3.553	3.82×10^{-4}
0.35	0.777	-0.253	0.067	-3.745	1.80×10^{-4}
0.42	0.731	-0.313	0.081	-3.855	1.16×10^{-4}
0.49	0.688	-0.373	0.095	-3.922	8.77×10^{-5}
0.56	0.648	-0.434	0.109	-3.968	7.26×10^{-5}
0.63	0.610	-0.494	0.124	-3.999	6.35×10^{-5}
0.70	0.574	-0.555	0.138	-4.023	5.75×10^{-5}

The research team expected that any benefit resulting from posted advisory speeds would be reflected by the marginal effect of ASD. Table 5.4 shows this marginal effect, which is statistically significant for SFDs equal to or greater than 0.14. Quantitatively, this value reflects a decrease in crash frequency for values less than one (in this case this multiplicative effect ranges from 0.574 up to 0.931). Table 5.4 shows that the effect attributable to ASD is stronger at larger values of SFD (smaller multiplicative effect at higher values of SFD). This is notably different than the trend one would expect if the ASD reflects the indirect influence of the horizontal curve radius.

Although Table 5.4 presents the marginal effect of ASD as a direct impact on crash frequency, indicating that as the SFD incrementally increases the marginal effect of ASD decreases, the research team favored the model interpretation based on the hierarchy of the three influencing categories (Geometric Design, Operations, and Signage) as depicted in Figure 5.35. Based on this interpretation, the decrease in the number of crashes results from a change in driver behavior in the vicinity of horizontal curves as the driver perceives bigger differences between the advisory speed and the speed limit upstream of the curve. For this ASD analysis, the research team assumed that the speed limit crudely represents the operations upstream of the horizontal curve. This assessment was based on the surveyed speed data: the 85th percentile operating speed upstream of the curves was roughly 5 mph above the speed limit with a standard deviation of 3.9 mph (see Table 4.2 in Section 4.2). A Quantile-Quantile (Q-Q) plot of the 16 surveyed sites and their associated 85th percentile speeds supports the assumption that these differences are normally distributed (see Figure 5.36) suggesting that they can be evaluated using common regression techniques.

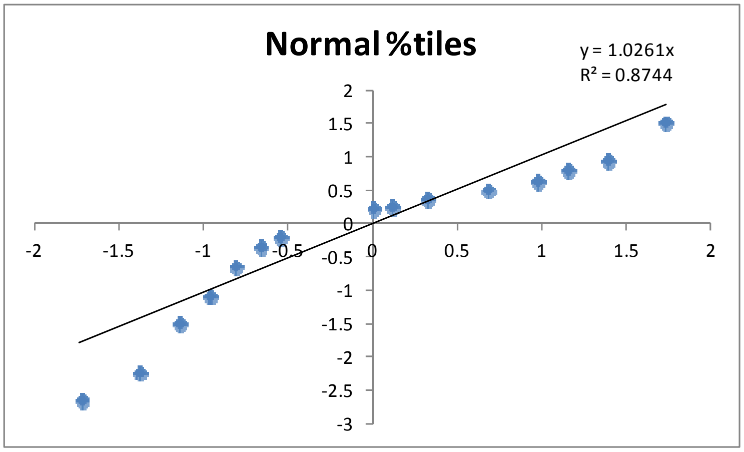


Figure 5.36: Q-Q plot for the Difference between Operating Speed and Speed Limit

As previously indicated, the research team anticipates that the marginal effect of the ASD does not conceal the influence of the horizontal radius. Upon inspection, it is clear that the marginal effect acts inversely to the radius influence when estimating crash frequency. Another way to state this is that as the horizontal curve radii increases, other factors tend to predict fewer crashes. Conversely, in the case of this marginal effect, it is precisely the region with smaller radii (represented by large SFD values) that exhibit a more relevant decrease in the number of expected crashes.

The trend shown in Table 5.4 provides convincing evidence of a positive safety benefit as a result of posted advisory speed signs, but the research team recognizes the need to compute the joint effect of SFD and ASD so as to better understand the safety implications beyond the marginal effect of the ASD.

Table 5.5 depicts the joint effect, developed using the model, and its associated statistical significance for typical ranges of SFD and ASD. In this table, the entire range of the values shown are statistically significant (p-values smaller than 0.1). Joint effects based on ASD values of 10 mph and many of the values for an ASD of 15 mph were not significant and so are not included in this table.

For ASD values of 5 mph, the expected crash frequency is higher than average and this value continues to rapidly increase with the increase of the SFD. Sites with ASDs of 5 mph are not required (and therefore unlikely) to have posted advisory speed signs (this results in a -0.831 Spearman correlation between the presence of advisory speed signs and ASDs of 5 mph). A unique characteristic of the advisory speed data is that Oregon does not require the posting of an advisory speed when the recommended value is only 5 mph less than the posted regulatory speed limit (when ASD = 5 mph). Any interpretations, therefore, within this 5 mph buffer must be considered cautiously as signage is not required until ASD approaches the 10 mph value.

The remaining values shown in Table 5.5 show a significantly smaller number of expected crashes (multiplicative effects smaller than one) at all levels of ASD for the entire range of SFDs. These ASD values are more likely to have posted advisory speed plaques. For the larger ASD values, the multiplicative effect trend is inverted so that higher SFD values are associated with substantially fewer expected crashes. This trend may indicate that the marginal effect of the ASD occurs when advisory speed plaques are present. For this study, the project team only evaluated operating speeds at locations with posted advisory speeds and so cannot directly extrapolate assumptions regarding speed behavior to locations where advisory speeds were not posted.

Table 5.5: Statistically Significant Joint Effect for Different Values of SFD and ASD

	ASD (mph)						
	5	**15**	**20**	**25**	**30**		**35**
	0.07	1.623					
	0.14	2.059					
	0.21	2.612			0.187	0.097	0.050
	0.28	3.313		0.185	0.071	0.027	0.010
	0.35	4.203		0.095	0.027	0.008	0.002
SFD	0.42	5.332		0.049	0.010	0.002	0.0004
	0.49	6.765		0.025	3.86x10-3	5.97x10-4	9.24x10-5
	0.56	8.582		0.013	1.47x10-3	1.68x10-4	1.92x10-5
	0.63	10.887		6.57x10-3	5.56x10-4	4.70x10-5	3.97x10-6
	0.70	13.811	0.054	3.37x10-3	2.11x10-4	1.32x10-5	8.23x10-7

One plausible explanation as to why the SFD and ASD joint effect occurs is that drivers assess an acceptable speed they are comfortable with driving above the posted advisory speed value (in other words, they judge to what extent not slowing down would produce "discomfort" resulting in high SFD values). When there is no advisory speed sign, however, drivers may experience difficulty estimating this difference resulting in a joint effect that predicts an increase in the number of crashes at these sites.

The research team developed a term called the advisory speed crash factor (ASCF) to represent the ASD:SFD joint effect. As previous suggested, this value appears to convincingly link the safety impact of drivers searching for a balance between the discomfort of driving a curve too fast and the inconvenience of slowing down. Since the ASCF is of special relevance for this research, the research team constructed a corresponding response-surface map. This graphic is shown in Figure 5.37. This figure can be useful in interpreting the values depicted in Table 5.5. The "flat" zone in Figure 5.37 represents a decreasing effect in the number of expected crashes so investing in an advisory speed sign for these locations would not be as cost effective as for other locations. As the cells in the figure increase vertically, the effect on the expected number of crashes also increases.

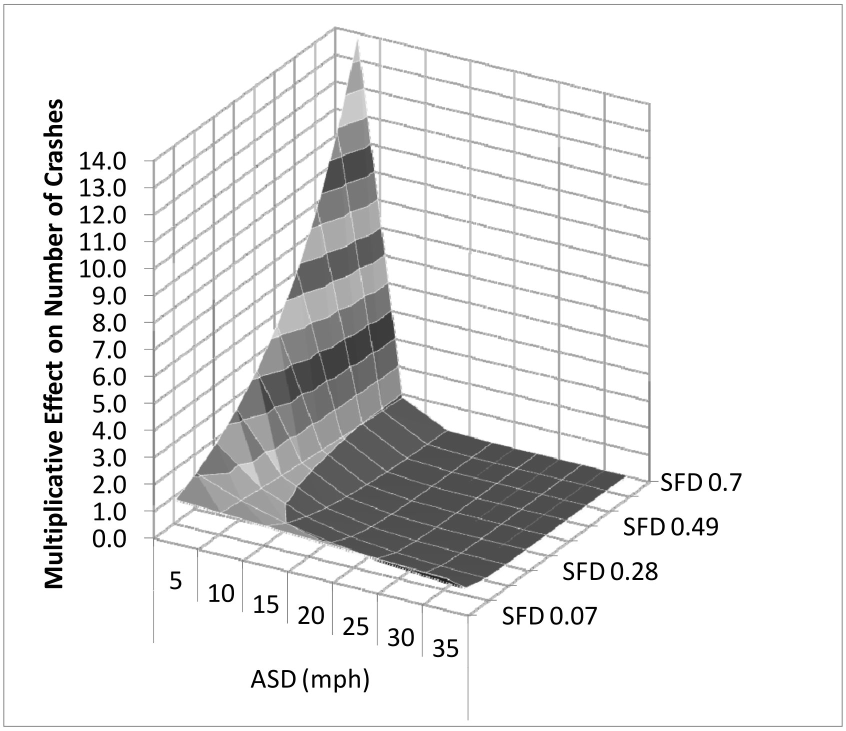


Figure 5.37: Response Surface Representation of the ASCF for Various ASD and SFD Thresholds

This figure provides useful information but its three-dimensional nature may pose a challenge for some users. As a result, Figure 5.38 provides detailed contour lines for the ASFC with a two-dimensional framework. For an example of how to use this figure, please refer to Appendix F.

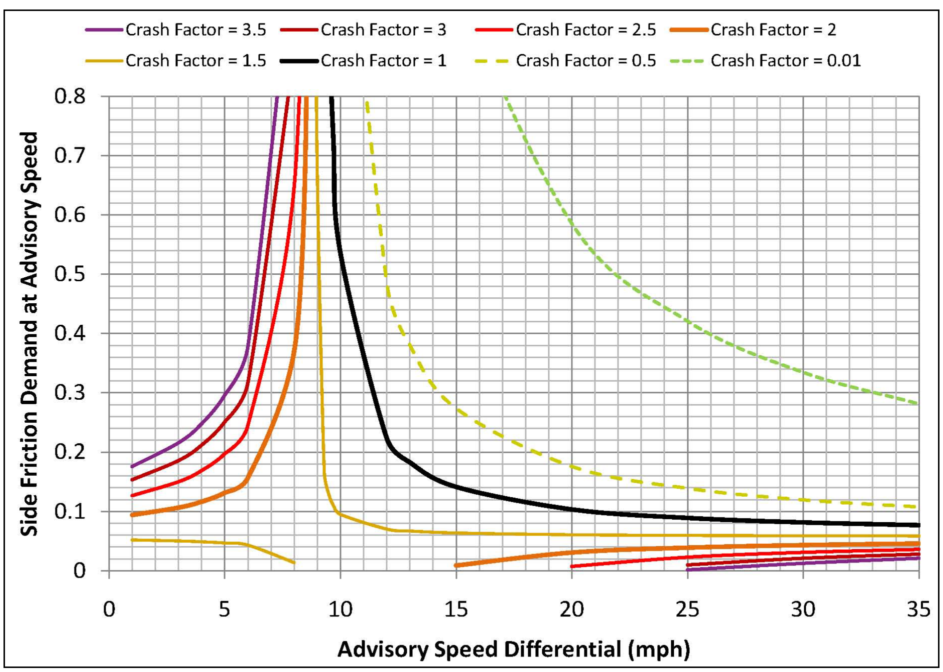


Figure 5.38: ASD:SFD Safety Relationship at Different ASCF Levels

5.5 SUMMARY

Chapter 5 summarized the relationship between observed speed and historic crash data. This assessment included high, low, and no crash locations. The descriptive statistics reviewed several physical and operational characteristics including radius, traffic volume (presented as AADT), shoulder width, superelevation, vertical grade, and side friction. For the 80 state-maintained corridors from the *statewide random sample*, the assessment also addressed the crash location noting that some of the crashes located on the corridor but not within the boundaries of the study curves included intersection-related crashes that should be removed from consideration when evaluating crashes common to a horizontal curve. The project team also developed a statistical model to link the number of crashes to physical characteristics and noted that the advisory speed contributes in a significant manner to predicting crashes at these locations. Ultimately the research team observed that crashes decrease at locations where drivers are able to perceive larger differences in the upstream regulatory speed limit and the posted advisory speed. This analysis also highlighted that as the horizontal curve radii increases, other factors tend to predict fewer crashes. Finally, Chapter 5 included a joint effect relationship between the ASD and the SFD that addressed how the advisory speed can be directly linked to predicted crashes as shown in Figure 5.38.

6.0 EFFECT OF ADOPTING THE *2009 MUTCD* THRESHOLDS

The *2009 MUTCD* suggests that ball-bank readings of 16 degrees or more should correspond to advisory speeds less than or equal to 20 mph. Similarly the new recommendations suggest advisory speeds of 25 to 30 mph for a 14 degree reading and values greater than 35 mph for a 12 degree reading. The *MUTCD* also allows for other options (an accelerometer that provides a direct determination of side friction factors and a design speed equation) for determining advisory speed. Prior to adopting the *2009 MUTCD*, Oregon used alternative ball-bank posting thresholds. The Oregon policy called for posting a less than or equal to 30 mph advisory speed sign for a 13 degree reading, a 35 to 55 mph speed for a 10 degree reading, and a greater than or equal to 60 mph advisory speed for a 7 degree ball-bank reading. See Table 1.1 on page 3 for side-by-side comparisons.

It is important to assess if there are any safety implications that could occur as a result of transitioning to the *2009 MUTCD* thresholds. The previously developed statistical model helps clarify the effect of advisory speed signs and associated factors and how they relate to crash frequency. This information can be used to help evaluate the safety implications of possibly transitioning Oregon to the *2009 MUTCD* posting criteria. This section demonstrates the results from a preliminary examination of the 80 state-maintained corridors from the *statewide random sample* (where dependable crash information could be acquired) that would require sign modifications and then addresses the question of the potential safety implications based on the statistical model application.

Figure 6.1 depicts the percent of sites (210 curve directions of travel) in the overall *statewide random sample* that did not have advisory speed signs at the time of data collection (96 curves) and would ultimately require signs (9 curves) versus those that would not need signs if Oregon adopted the *2009 MUTCD* posting recommendations (87 curves). Approximately 91 percent of these sites would continue to not require an advisory speed sign while the remaining 9 percent of the sites would require the installation of a new advisory speed sign and speed plaque.

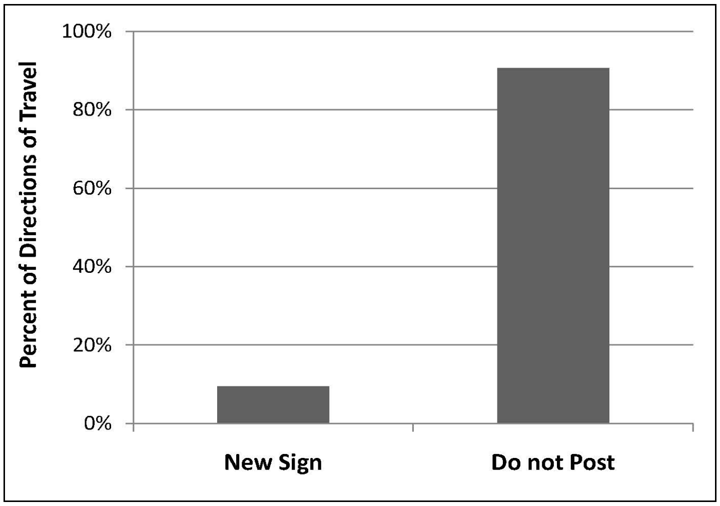


Figure 6.1: Percent of Curve Directions of Travel Without Existing Advisory Speed Posting Affected if *2009 MUTCD* Thresholds are Adopted

Figure 6.2 shows the percent of curve directions of travel that currently have posted advisory speeds (114 sites) and demonstrates how the advisory speeds would need to change as a result of the *2009 MUTCD* advisory speed thresholds. Approximately 29 percent of the locations would not require any changes and 28 percent of the sites would simply require sign removal. In addition, 33 percent of the sites would require a +5 mph adjustment, 6 percent of the sites would need a -5 mph adjustment, and 3.5 percent would need a +10 mph modification.

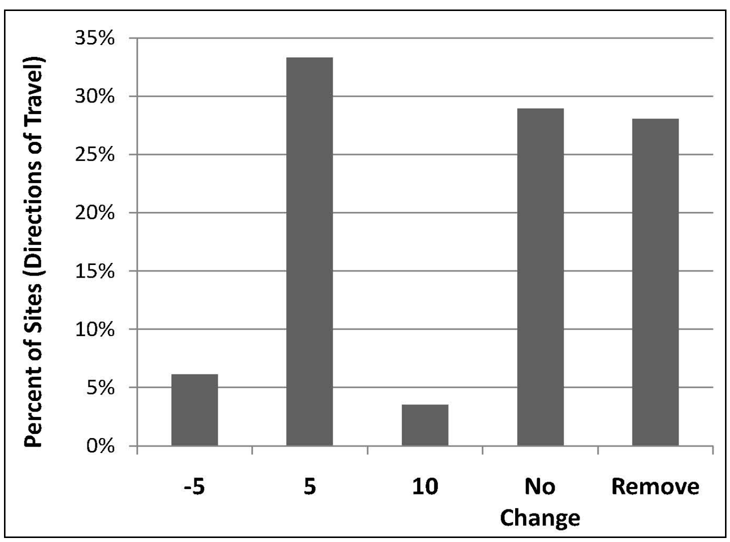


Figure 6.2: Percent of Curve Directions of Travel with Posted Advisory Speeds Affected if *2009 MUTCD* Thresholds are Adopted

Figure 6.3 shows the average crash density based on the expected *2009 MUTCD* advisory speed posting threshold modifications. This figure indicates that the safest speed categories would be those that would be unchanged or that would require removal of the speed plaques (because these categories have the smallest average crash density values). The +5 mph and the -5 mph categories have similar expected crash density values; however, the group that would require a

+10 mph increase is associated with the largest average crash density. Fortunately Figure 6.2 demonstrated that the +10 mph is a small percentage of the total number of sites (actually this occurred at only four sites). These trends suggest that the adoption of the *MUTCD* thresholds should initially concentrate on the +10 mph sites and then address the +5 mph and -5 mph locations. Adopting the new *MUTCD* thresholds, however, may prove beneficial if the current signs are posted lower than drivers expect or need to adequately respond to the road geometric, operational, and signage conditions.

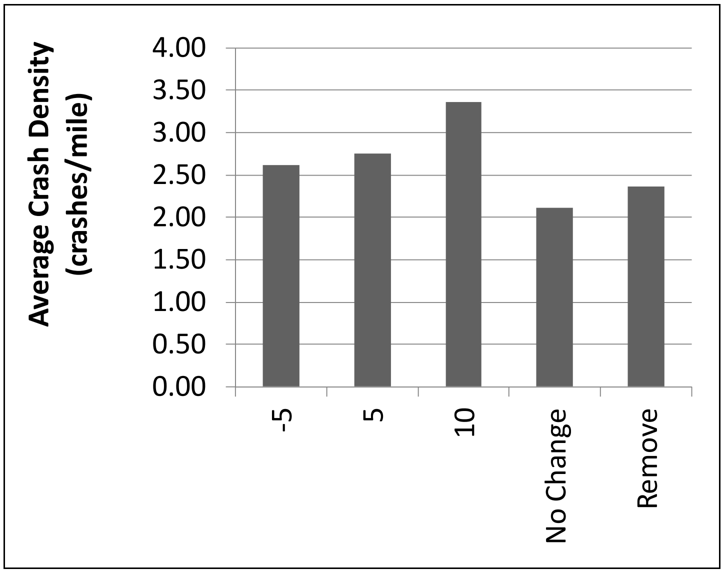


Figure 6.3: Average Crash Density by Speed for Expected *2009 MUTCD* Advisory Speeds Minus Existing Posted Advisory Speed

Based on the statistical model, if the +10 mph group was actually posted below appropriate advisory speed values, then the associated SFD would be smaller than expected for otherwise similar sites. Additionally, an "under-posted" curve would be characterized by a higher ASD than if it were properly posted. It is clear that the safety effect approaches the lower right corner of Figure 5.38 as the ASD value increases and the SFD decreases. This corner is, nonetheless, where the multiplicative effect shifts from values below 1.0 to higher values, indicating more expected crashes. Table 6.1 shows the ASD:SFD effect for current conditions at the sites that, according to the *2009 MUTCD* thresholds, would require a +10 mph increase in their advisory speeds.

Table 6.1: Total Advisory Speed Safety Effect for the Sites that Would Require +10 mph to their Current Advisory Speed

Site #	Advisory Speed	SFD	ASD	SFD:ASD Joint Effect	LowAdv Effect	Total Advisory Speed Effect
1	35	0.019	20	2.240	1.00	2.24
2	25	0.000	30	4.383	0.27	1.19
3	35	0.082	20	1.227	1.00	1.23
4	20	0.000	35	5.607	0.27	1.53
					Average	**1.55**

All of the ASD:SFD joint effects in the table are larger than one, indicating that current conditions of under-posting lead to an increase in the number of expected crashes based on the resulting ASCF. Since Sites #2 and #4 have posted advisory speeds of 25 and 20 mph respectively, the statistical model applies a factor of 0.27 to these locations (suggesting that the face value of these advisory speeds is not as relevant for the ASD:SFD effect). The final column in Table 6.1 shows the total effect of advisory speeds at these sites. All the effects are greater than one. According to the model, one would expect to encounter at least 19 percent more crashes than the average at Site #2, and up to 224 percent of the expected crash frequency (or an increase of 124 percent) at Site #1. The model results, therefore, suggest that the *MUTCD* criteria could be beneficial for the sites that would require a +10 mph change to their current advisory speed.

6.1 EFFECT OF INCREASING ADVISORY SPEEDS

The research team explored the effect of increasing the posted advisory speeds at the four sites where both the current Oregon and new *MUTCD* policies would require this change. The theoretical results of this change are shown in Table 6.2 and Table 6.3.

Table 6.2: Total Advisory Speed Effect After Increasing the Advisory Speed by 5 mph at Four Study Sites (According to the Current Oregon Policy)

Site #	Current Advisory Speed	ODOT Policy Advisory Speed	SFD	ASD	SFD:ASD Joint Effect	LowAdv Effect	Total Advisory Speed Effect
1	35	40	0.024	15	1.842	1.00	1.84
2	25	30	0.000	25	3.426	**1.00**	**3.43**
3	35	40	0.107	15	1.197	1.00	1.20
4	20	25	0.000	30	4.383	0.27	1.19
						Average	**1.91**

Table 6.3: Total Advisory Safety Effect After Increasing the Advisory Speed by 10 mph at Four Study Sites (According to the *2009 MUTCD* Criteria)

Site #	Current Advisory Speed	MUTCD Policy Advisory Speed	SFD	ASD	SFD:ASD Joint Effect	LowAdv Effect	Total Advisory Speed Effect
1	35	45	0.031	10	0.310	1.00	1.59
2	25	35	0.000	20	0.000	**1.00**	**2.68**
3	35	45	0.135	10	1.353	1.00	1.45
4	20	30	0.000	25	0.000	**1.00**	**3.43**
						Average	**2.29**

These computations assume that the driver's perception and his or her reaction to advisory speeds would not be altered after a period of time. Such an assumption, despite its convenience, is marginal, since the research team expects that more consistent posting would provide drivers with better and more reliable information to adjust their speeds. A good test for this would be, at a future date following such a change, to calibrate the statistical model to determine the long term effect and how this may alter drivers' perception of the alternative posting criteria.

As a general trend, the average influence on crash frequency deteriorates as the posted advisory speed increases. It is clear, however, this result is due to the two influencing variables previously identified (SFD and ASD) and their joint effect. Based on the statistical analysis, the ASD:SFD joint effect is associated with fewer crashes as the advisory speed increases. This is what would be expected upon examination of the response surface depicted in Figure 5.37. Conversely, increasing the advisory speed by 5 mph at Site #2 would minimize the impact that lower advisory speeds have on the model. That partial effect (LowAdv) changes from 0.27 as shown in Table 6.1 to a value of 1.00 as shown in Table 6.2. This change results in a total effect of advisory speeds and their influence on crash frequency from 1.19 to 3.49. Even though the other three sites consistently resulted in an overall expected reduction in crash frequency, the substantial increase at Site #2 caused the overall average to increase from 1.55 to 1.91. The same situation would occur when increasing all the advisory speeds by 10 mph to comply with the *2009 MUTCD*. For this case, Site #4 would suffer from removal of the lower posted advisory speed resulting in an overall average of 2.29.

Finally, it is worth to noting that Site #2 did not have crashes during the study period (years 2000-2005). There were a total of only six crashes in six years for all four sites and only one of these crashes involved injuries. All four sites had sharp horizontal curves to the left with superelevation slopes greater than 10 percent and curve lengths of 300 ft or less,

On average, therefore, it appears that increasing the posted speed limit at these under-posted locations would potentially result in an increase in overall crashes. Since these overall averages were substantially influenced by one or two sites and other sites appeared to potentially benefit from the changes, the use of the average outcome only provides a general perspective about the effect of increasing the advisory speed at these locations. It is clear that several of the sites would, in fact, marginally benefit from increased advisory speeds at these locations.

6.2 EFFECT OF DECREASING ADVISORY SPEEDS

The research team tested the performance of the statistical model for conditions where it is more likely to perform marginally (due to an over representation of the variables in the model at the locations). For example, mountainous roads with several horizontal and vertical curves located in close proximity would include extreme values for the various variables. Under these conditions, the model is expected to overestimate the ASD because speeds tend to be lower in mountainous regions and so the speed limit may not be an appropriate estimate of upstream operations. It is not common practice to post advisory speeds at every individual curve at locations with compound and reverse curvature. Instead, the advisory speed is generally posted upstream of the curves and the value is established for the most extreme curve condition in the series. The research team, however, used these curves to demonstrate the resulting computation, using the statistical model, to estimate the theoretical effect of introducing new advisory speeds.

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in close proximity would include extreme values for the various variables. Under these conditions, the model is expected to overestimate the ASD because speeds tend to be lower in mountainous regions and so the speed limit may not be an appropriate estimate of upstream operations. It is not common practice to post advisory speeds at every individual curve at locations with compound and reverse curvature. Instead, the advisory speed is generally posted upstream of the curves and the value is established for the most extreme curve condition in the series. The research team, however, used these curves to demonstrate the resulting computation, using the statistical model, to estimate the theoretical effect of introducing new advisory speeds.

Table 6.4 depicts a resulting baseline value equal to 5.10. This value reflects the expected overestimation based on the extreme variables as summarized above. The curve length and the radius are included in the table, as they were necessary components for computing the effect of posting new advisory speeds on crash frequency.

Table 6.4: Base Line Effect on Crashes for Would-Be Posted Sites under *2009 MUTCD* or Oregon Policy

Curve	Advisory Speed (mph)	SFD	ASD (mph)	SFD:ASD	CurveLength (ft)	Radius (ft)	Joint SFD:ASD effect	LowAdv Effect	AdvSpPresent	AdvSpPresent:Radius	AdvSpPresent:CurveLength	Total AdvSpPresent Effect	Total Base Line Effect
1	50	0.483	5	2.414	110	325	6.60	1.00	0.00	0.00	0.00	1.00	6.60
2	50	0.378	5	1.889	560	325	4.62	1.00	0.00	0.00	0.00	1.00	4.62
3	50	0.341	5	1.706	390	350	4.08	1.00	0.00	0.00	0.00	1.00	4.08
												Average	**5.10**

Table 6.5 shows the calculation of the total effect of posting all three curves at 30 mph as recommended by the Oregon Policy. The theoretical effect would be a reduced number of crashes at two out of three sites, and an increase in crashes at one of the sites. The result is an approximate 11 percent decrease in the expected number of crashes (calculated by dividing 5.10 (from Table 6.4) by 4.58 (from Table 6.5) and then subtracting 1.00).

Finally, Table 6.6 displays the theoretical effect of posting new advisory speeds according to the *MUTCD* thresholds. Two sites would benefit from this change and additional crashes would be expected at one site. The overall theoretical effect would be a reduction of 25 percent in the number of crashes ([5.10 / 4.07] – 1.00).

Table 6.5: Base Line Effect on Crashes for Would-Be Posted Sites under Current Oregon Policy

Curve	Advisory Speed (mph)	SFD	ASD (mph)	SFD:ASD	CurveLength (ft)	Radius (ft)	Joint SFD:ASD effect	LowAdv Effect	AdvSpPresent	AdvSpPresent:Radius	AdvSpPresent:CurveLength	Total AdvSpPresent Effect	Total Advisory Speed effect
1	30	0.174	25	4.345	110	325	0.31	1.00	1.00	325.00	110.00	18.42	5.68
2	30	0.136	25	3.400	560	325	0.52	1.00	1.00	325.00	560.00	5.83	3.04
3	30	0.123	25	3.071	390	350	0.63	1.00	1.00	350.00	390.00	8.05	**5.03**
												Average	**4.58**

Table 6.6: Base Line Effect for Would-Be Posted Sites under *2009 MUTCD*

Curve	Advisory Speed (mph)	SFD	ASD (mph)	SFD:ASD	CurveLength (ft)	Radius (ft)	Joint SFD:ASD effect	LowAdv Effect	AdvSpPresent	AdvSpPresent: Radius	AdvSpPresent: CurveLength	Total AdvSpPresent Effect	Total Advisory Speed effect
1	35	0.237	20	4.732	110	325	0.28	1.00	1.00	325.00	110.00	18.42	5.17
2	35	0.185	20	3.703	560	325	0.46	1.00	1.00	325.00	560.00	5.83	2.67
3	35	0.167	20	3.344	390	350	0.54	1.00	1.00	350.00	390.00	8.05	**4.38**
												Average	**4.07**

Though a few exceptions are observed, in general the trends suggest an improvement if posted advisory speeds were modified to comply with the current Oregon Policy. Similarly, the general trends suggest a more substantial improvement by modifying the posting procedures to conform to the thresholds recommended in the *2009 MUTCD*.

This chapter summarized the effect of adopting the *2009 MUTCD* posting recommendations and reviewed the expected safety effect of modifying current advisory speeds to conform to these new thresholds. For a select set of four curve locations, these new thresholds would actually require changes in posted advisor speeds by up to +10 mph. All four locations had short, relatively sharp horizontal curves to the left with superelevation slopes greater than 10 percent.

In addition, it appears that increasing the advisory speeds at locations where speeds are posted below expected levels for both the current Oregon and *2009 MUTCD* recommended values would result in marginal safety benefits, while decreasing advisory speeds at over-posted locations would improve safety based on the Oregon Policy and further reduce crashes if adjusted to conform to the *MUTCD* recommendations. Chapter 7 reviews an alternative to the current Oregon Policy as well as the *2009 MUTCD* thresholds that is computational and directly linked to crash history so that number of crashes can be the direct focus of advisory speed assessments.

7.0 DEVELOPMENT OF A COMPUTATIONAL METHOD TO POST ADVISORY SPEEDS

The safety implications of changing advisory speed values are not entirely clear based on the preliminary comparison between the advisory speed posted values, the current Oregon Policy, and the recently updated *MUTCD* thresholds. At some locations, it appears that updating the signs to either of the posting thresholds would prove beneficial. Other sites, however, would be adversely affected by such a change. These varying trends suggest that the safest way to update the signs may be on the basis of an individual site evaluation. However, since individual posting studies are not economically feasible for large scale evaluations and do not facilitate consistent treatment of facilities when selecting appropriate advisory speeds, suggesting an additional assessment technique may be warranted.

The authors of the previous Oregon advisory speed project observed inconsistencies in the advisory speed posting procedures across the State of Oregon. The field data from that research indicated that using the ball-bank indicator (BB) produces data with unexplained variability, even when repeatedly driving a curve at the same speed, with the same vehicle and driver. Consistent with this finding, recent work by other researchers has also raised concerns about the accuracy of the ball-bank indicator method (*Bonneson et al. 2009*) as previously reviewed in Section 2.2.

As a result, the research team developed and evaluated an alternative posting method that has several advantages. It could enable ODOT to have a more consistent procedure for identifying the appropriate advisory speeds at various locations. Additionally, this computational method does not require a visit to the field to determine the advisory speed of a curve and is based on expected safety performance metrics. Common field studies require field measurements that have a direct effect on assessment cost and schedule. A computational approach, however, could streamline the current BB approach resulting in a more consistent and efficient advisory speed posting procedure. The developed method is based on the statistical analysis and model previously presented in Section 5.4.

7.1 HUMAN FACTOR INTERPRETATION OF ADVISORY SPEED AND SAFETY

Although the statistical model introduced in Section 5.4 links advisory speeds to safety performance using three different variables, only two of these variables are derived from the actual posted advisory speed value: the advisory speed differential (ASD) and the binary variable indicating advisory speeds of 20 or 25 mph. This second variable represents a discrete adjustment (decrease) in the number of crashes for sites with low advisory speeds. This variable is statistically significant and the basis for this is that drivers are more cautious when they are presented with very low advisory speeds as they interpret the road to have more severe geometry. This discrete variable, however, should not be interpreted as an independent effect because locations with conservative advisory speed posting practices could ultimately result in a modification to this driver behavior (a decrease in driver adherence to the signs).

The research team further examined the third key variable, the advisory speed crash factor (ASCF), as described in Section 5.4. The ASCF is a multiplicative factor that represents the expected number of crashes. Such a factor is a function of two advisory speed related variables: ASD and SFD. ASCF values smaller than 1.0 represent a decrease in the expected number of crashes, and values larger than 1.0 indicate an expected increase. This value is similar to the recently developed concept known as a crash modification factor (CMF).

Figure 5.38 shows a detailed contour view of this effect. The thick, black line represents an ASCF value of 1.0. The region to the left and below this dashed line presents ASCF values larger than 1.0. Conversely, the region to the right and above this line represents ASCF values smaller than one. From a human factors perspective, the X-axis represents what the drivers perceive as a request from the signage: "If you are traveling at the speed limit now, you should slow down your speed by this amount (the ASD value)." On the other hand, the Y-axis represents the expected consequence of following the request: the friction that the vehicle tires would experience if the driver adheres to the recommended speed reduction.

The ASCF value represents a long term risk factor that collectively considers the two previously described variables. For instance, if the ASD value is large (say, 30 mph) and the SFD that results from adhering to the advisory speed is very small (say 0.06) then the ASCF results in a value that is larger than 1.0 (approximately 2.0 from Figure 5.38). A likely explanation for this high ASCF value is that if an occasional driver slows from his or her free flow speed to the advisory speed at this location, he or she will not experience the discomfort associated with a high SFD. More familiar drivers, though, would recognize that they can drive the curve at a significantly faster speed than the posted advisory speed. Figure 5.38 indicates that the ASCF decreases as the advisory speed increases. This change also decreases the ASD and increases the SFD, resulting in an ASCF closer to the dashed line depicted in Figure 5.38. This theoretical example suggests that a procedure that uses the ASCF as a posting criterion would be sensitive to the posting of unnecessarily low advisory speeds.

A posting method based on the ASCF would also provide robust results that would help to avoid posting advisory speed values higher than necessary. If, for instance, a particular curve has a posted advisory speed that requires a small ASD, say 10 mph, but the curve is also characterized by geometry that would result in a large SFD, say 0.2, then the resulting ASCF value would be very large (approximately 2.0 from Figure 5.38). Alternatively, the ASCF could be reduced by decreasing the posted advisory speed and this would result in larger values of ASD and SFD, creating an ASCF value that is closer to the dashed line (indicating no increase or decrease in expected crashes).

It is important to note that for an ASD of 10 mph, there are no SFD values that result in an ASCF smaller than 1.0. A plausible human factors interpretation of this observation is that the unfamiliar driver does not consider a speed reduction of 10 mph as critical information and may not elect to adjust his or her speed in the curve. Ignoring this posted advisory speed should result in a larger number of crashes, but based on the linkage of road characteristics to crashes (using the ASCF criterion) we observe that the advisory speed signs do not result in any substantive safety benefit at these locations.

Another observation associated with the modeled ASCF response is that marginally, higher SFDs are affiliated with smaller ASCF values (for ASDs larger than 15 mph). This observation suggests that at locations where the driver experiences more discomfort when traversing at the posted advisory speed (higher SFDs), the advisory speeds appear to be more effective in influencing safety. For these locations it is possible that familiar drivers will more likely adhere to the posted advisory speeds since they would be aware that disregarding the posted advisory speeds would result in noticeable driving discomfort (smaller SFDs).

Based on these general human factor evaluations of the statistical model variables, it appears logical that a posting method that depends on this modeled ASCF holds promise and will help provide consistent posting thresholds that are explicitly based on expected safety performance.

7.2 COMPUTATIONAL METHOD BASED ON THE ASCF

The research team developed a computational method based on the ASCF as an alternative to the current ball-bank indicator method. This method is referred to in this report as the OSU Method. The underlying principle is that the advisory speed value should be such that the value of the ASCF is minimized. However simple this principle may be, the associated mathematical form is relatively complex. The ASCF is based on two variables (one continuous and one discrete) that in turn are themselves functions of the advisory speed, the speed limit, the horizontal radius, and the superelevation. As a result, the ASCF is ultimately a multivariate function.

The research team has developed a spreadsheet that ODOT staff can use to determine recommended advisory speed values that will minimize the ASCF. This analysis can be performed upon identification of the basic geometric characteristics and site speed limit. This spreadsheet uses the Excel optimizer functions to determine preferred advisory speed values based on the statistical model reviewed in Section 5.4. A user can input curve radius and superelevation values to determine the recommended safety-based advisory speed and associated SFD value.

Since the actual radius value may be approximate and based on as-built plans or aerial photography and the superelevation could be unknown without field evaluations, the spreadsheet provides supplemental information about the best performing advisory speed for different radii and cross-slopes that are plus and minus 10 percent of the estimated radius value. This sensitivity analysis can then help the user determine if a field visit is required. If the same advisory speed is recommended for all thresholds, for example, a field visit may be deemed unnecessary.

Although it would be desirable to obtain the geometric parameters directly from the field (horizontal radius and superelevation), in most cases the horizontal radius can be satisfactorily estimated by analyzing aerial images and the associated superelevation rate may be estimated using Table 5-3 of the *Oregon Highway Design Manual* (*ODOT 2003*)

The research team performed a proof of concept by evaluating the OSU Method for a subset of 20 of the study sites. These sites were selected at random simply as an assessment effort to determine how the OSU Method would generally compare to the Oregon Policy and the *2009 MUTCD* methods and were not intended to constitute a statistically significant sample. Table 7.1 shows a detailed comparison between the three methods and the current advisory speed posting status at each site. In only one case does a pair of advisory speeds, including the current posted value, differ by more than a value of 5 mph. At Site #13 there is currently a posted 35 mph advisory speed, but the *2009 MUTCD* thresholds would support the use of a 45 mph advisory speed sign. The Oregon Policy and OSU Method, however, both recommend 40 mph advisory speeds at this site.

Table 7.1: Comparison of Advisory Speed Values by Posting Method for 20 Example Sites

Site	Name	Speed Limit (mph)	Radius (ft)	Super-elevation	Current Status (mph)	Oregon Policy(mph)	*MUTCD* (mph)	OSU Method (mph)
1	LwrColumbRiv_39_WB	55	1160	4.5%	Not posted	Do not post	Do not post	45
2	WilsonRiver_22_EB_2	55	880	10.0%	45	Do not post	Do not post	45
3	GreenSprings_6_WB	55	900	8.5%	Not posted	45	Do not post	45
4	Willamette_49_EB	55	1425	7.0%	Not posted	Do not post	Do not post	Do not post
5	KingsValley_6_NB	55	475	5.0%	Not posted	40	45	35
6	Alsea_38_EB	55	715	8.5%	Not posted	45	Do not post	45
7	Santiam_55_EB_2	55	325	16.5%	35	30	35	40
8	Hillsboro-Silverton_0_SB	55	950	9.5%	Not posted	Do not post	Do not post	45
9	Pendleton-ColdSprings_11_SB	55	520	11.0%	35	40	40	40
10	Paulina_5_EB_2	55	640	9.0%	40	35	40	40
11	WdburnEstcda_31_SB_2	55	475	7.0%	45	45	Do not post	40
12	KlamathFalls-Lakeview_35 EB_1	55	1430	5.5%	Not posted	Do not post	Do not post	Do not post
13	KlamathFalls-Lakeview_43_WB	55	360	14.5%	35	40	45	40
14	Umpqua_38_EB_1	55	1005	7.0%	Not posted	45	Do not post	45
15	CenturyDrive_10_EB	55	1432	9.5%	Not posted	Do not post	Do not post	Do not post
16	WallowaLake_33_WB	55	355	9.5%	35	30	35	40
17	Frenchglen_34_NB	55	930	10.5%	Not posted	45	Do not post	45
18	Ukiah-Hilgard_8_EB	55	785	9.0%	45	45	Do not post	45
19	Sherman_45_WB	55	1910	6.5%	Not posted	Do not post	Do not post	Do not post
20	WilsonRiver_4_EB_1	55	1050	12.0%	Not posted	Do not post	Do not post	Do not post

Table 7.2 presents the descriptive statistics for the 20 individual sites presented in Table 7.1. This summary shows the average, minimum, maximum, and total number of sites with posted advisory speeds based on the following three candidate posting methods: the current Oregon Policy, the *2009 MUTCD* thresholds, and the ASCF method (referred to as the OSU Method). It is worth noting that, on average, the current posted values are less than any of the recommended methods (consistently requiring lower advisory speeds than the other methods). The OSU Method appears to be, on average, result in marginally higher advisory speed recommendations.

Table 7.2: Advisory Speed Summary Statistics by Posting Method for 20 Example Sites

	Posted Advisory Speed	Oregon Policy	2009 *MUTCD* Thresholds	OSU Method
Average (mph)	39.4	40.4	40.0	42.3
Min (mph)	35	30	35	35
Max (mph)	45	45	45	45
Number of posted sites	8	12	6	15

It is useful to compare the SFD values to their associated advisory speed values. Table 7.3 shows summary information about the SFD associated with the advisory speed for the three different methods. Based on the average SFD relationship, the lowest average SFD occurs for the Oregon Policy, while the largest average SFD is associated with the *MUTCD* method.

Table 7.3: Side Friction Demand at Advisory Speed by Posting Method

	Current	SFD Oregon	SFD *MUTCD*	SFD OSU Method
Average	0.093	0.079	0.107	0.083
Min	0.021	0.020	0.021	0.021
Max	0.301	0.205	0.214	0.281

7.3 PREDICTED SAFETY PERFORMANCE

The research team also compared the methods based on the crash record for the 20 sites selected for this assessment. Table 7.4 displays the sites, the advisory speeds, AADT, number of crashes, and crash rates per 10,000 AADT. The sites are listed in descending order based on their crash rates. The six top sites are locations with at least one crash that occurred during the study period of 2000 through 2005.

There is an interesting difference between the three methods displayed in Table 7.4. Three of the six top crash sites did not have posted advisory speed signs. Based on the Oregon Policy, two of these three sites should have an advisory speed sign. Only one of these three sites would require an advisory speed based on the *2009 MUTCD* thresholds. The Oregon policy would require advisory speed signs at two of the three sites, while the OSU Method is the only one that would require an advisory speed sign at all three of these locations.

Table 7.4: Predicted Safety Performance Comparison by Posting Method

Site	Name	AADT (vpd)	#Crashes	Rate (crashes/ 10kAADT)	Current Status (mph)	Oregon Policy (mph)	*MUTCD* (mph)	OSU Method (mph)
9	Pendleton-ColdSprings_11_SB	382	1	26.2	35	40	40	40
6	Alsea_38_EB	1160	2	17.2	**Not posted**	45	**Do not post**	45
5	KingsValley_6_NB	4360	4	9.2	**Not posted**	40	45	35
16	WallowaLake_33_WB	1800	1	5.6	35	30	35	40
13	KlamathFalls-Lakeview_43_WB	2360	1	4.2	35	40	45	40
8	Hillsboro-Silverton_0_SB	9570	1	1.0	**Not posted**	**Do not post**	**Do not post**	45
1	LwrColumbRiv_39_WB	8840	0	0.0	Not posted	Do not post	Do not post	45
2	WilsonRiver_22_EB_2	4360	0	0.0	45	Do not post	Do not post	45
3	GreenSprings_6_WB	1200	0	0.0	Not posted	45	Do not post	45
4	Willamette_49_EB	2940	0	0.0	Not posted	Do not post	Do not post	Do not post
7	Santiam_55_EB_2	1090	0	0.0	35	30	35	40
10	Paulina_5_EB_2	398	0	0.0	40	35	40	40
11	WdburnEstcda_31_SB_2	6020	0	0.0	45	45	Do not post	40
12	KlamathFalls-Lakeview_35_EB_1	2360	0	0.0	Not posted	Do not post	Do not post	Do not post
14	Umpqua_38_EB_1	3190	0	0.0	Not posted	45	Do not post	45
15	CenturyDrive_10_EB	2300	0	0.0	Not posted	Do not post	Do not post	Do not post
17	Frenchglen_34_NB	218	0	0.0	Not posted	45	Do not post	45
18	Ukiah-Hilgard_8_EB	290	0	0.0	45	45	Do not post	45
19	Sherman_45_WB	2160	0	0.0	Not posted	Do not post	Do not post	Do not post
20	WilsonRiver_4_EB_1	5100	0	0.0	Not posted	Do not post	Do not post	Do not post

Finally, Table 7.5 displays the percentage of the 20 sites shown in Table 7.4 that would have posted advisory speed signs based on the posting method and the number of crashes.

Table 7.5: Percentage of Site Advisory Speeds by Posting Method and Crash History

	Current	**Oregon**	***MUTCD***	**OSU Method**
At least 1 crash	50%	83%	67%	100%
No crashes	36%	50%	14%	64%

It appears that all the methods, including the existing posted conditions, tend to result in a higher percentage of signs at sites with a verifiable history of crashes. A "coverage improvement" would result from a consistent use of the Oregon Policy for sites with crashes and without a crash history. The *2009 MUTCD* thresholds would result in a slight increase in the number of advisory speed signs for sites with crashes, but a decrease in coverage at sites without crashes. Finally, the OSU Method would result in total coverage of sites with crashes, but also in a substantial increase of coverage at sites without crashes. Since this example is based on crash history for a six year period (2000 to 2005), it would be valuable in the future to assess additional crash data to determine if this trend extends to additional years. Additional use of signs could be an issue of concern and it is unknown if having extra advisory speed signs would be beneficial in all cases. Since the basis for the placement of signs is safety, rather than strictly operational issues, these additional signs would actually be placed at locations where crashes are more likely to occur so these extra signs are expected to ultimately prove beneficial.

7.4 POTENTIAL LIMITATIONS OF THE OSU METHOD

The research team recognizes the potential safety improvement that would result from the proposed computational method referred to as the OSU Method. Additionally, the use of the OSU Method would result in a more consistent posting practice, eliminating the variation associated with repeatedly driving a curve to determine its advisory speed and minimizing the known inconsistencies resulting from the ball-bank indicator sensitivities. Furthermore, the computational method is expected to reduce the initial cost of posting advisory speed signs by minimizing the number and length of field visits since the spreadsheet provided in this research helps to identify the locations where the precision of the superelevation and the radius estimates affect the resulting advisory speed. For the cases where no substantial variation is recognized, the advisory speed can be estimated without a field visit. It is important, however, to also identify potential limitations that could occur as a result of using the OSU Method.

The OSU Method was developed by using a sample of 105 randomly selected curve sites (210 curve directions of travel). Although it is expected that these sites are representative of the state roads and thus the statistical model is already based on conditions in the state of Oregon, it is possible that because of the limited sample size, some relevant factors playing a role in the identified ASCF could have been excluded.

As discussed in this report, the ASD represents the change in the operating speed resulting from a posted advisory speed. Because of this definition, in an ideal case, the ASD should be computed using the best value of road operations. In the case of this research, the best way to estimate the ASD was by using the speed limit as a rough estimate of the operating speed. The project team collected speed data at a subset of the sites, but this smaller sample size was not adequate for use as a key variable in this model. Although the operating speed and the speed limit are expectedly correlated, the research team still anticipates some important variation between these two values at the individual sites. For example in mountainous conditions, where the operating speed is knowingly lower than the speed limit, the OSU Method is likely to result in larger recommended advisory speeds. In similar cases where the traffic analyst determines that the speed limit is a poorer approximation to the operating speed, the ASD should be computed using a better estimate for the operating speed. Methods like the one proposed by Bonneson et al. (*2009*) to estimate operating speeds based on the average speed of trucks along a corridor (as reviewed in Section 2.2) should be considered for these cases.

The research team also recognizes that using the OSU Method would result in a higher number of curves that would require posted advisory speeds than any of the other methods evaluated in this research. One potential option is, at some future date, to perform a cost benefit analysis to determine the offset of the initial advisory speed sign installation versus the expected improvements resulting from a method that is based explicitly on safety performance.

The research team is confident that the proposed OSU Method results in consistent and safe advisory speed values. At this time, the research team is not aware of any other method in use that determines the advisory speed values based on safety performance.

8.0 CONCLUSIONS

This research determined that drivers in western Oregon, as a general rule, do not adhere to the posted advisory speeds. Although this behavior is expected to extend to central and eastern Oregon, this research did not include speed data from those regions. The lack of compliance to posted advisory speeds does not necessarily constitute evidence that these signs are totally ineffective.

From a crash data analysis, this research convincingly indicates that advisory speed plaques have an impact on safety for two-way, two-lane rural roads in the State of Oregon. Such an effect, however, is minimal compared to other factors influencing safety such as traffic volume, curve length, and horizontal curvature. Additionally, according to this research, the safety impact of advisory speed plaques may be counterproductive under certain conditions. The research team determined that advisory speed signs are not always critical at locations where the posted advisory speeds are substantially lower than the speed limit if the location is also characterized by a small associated SFD values. The result of this configuration may cause a driver to perceive that the posted speed is too low and, as a result, familiar drivers may tend to drive faster at these locations.

The research team developed a mathematical model for the advisory speed safety effect (this was referred to as the advisory speed crash factor or ASCF) by isolating the advisory-speed related variables within a comprehensive statistical model that simultaneously accounted for other factors known to affect safety (such as traffic volume, horizontal radius, and horizontal curve lengths). The research team developed a posting procedure (referred to as the OSU Method) based on the resulting ASCF. Using 20 example sites, the research team compared this posting procedure to the current Oregon Policy and the *2009 MUTCD* posting thresholds. The OSU Method yielded advisory speed values that did not differ by more than 5 mph from either of the compared methods, including the current posted values.

When comparing the three methods, the *2009 MUTCD* method ranked as the method that would post advisory speeds associated with higher SFDs (see Table 7.3), followed by the OSU Method. Based on the average SFD values, the Oregon Policy proved to be the most conservative of the three compared methods. The OSU Method, however, was the only method that suggested posting advisory speeds at all the sites with recent crash histories. The *2009 MUTCD* threshold was the only method that increased the proportion of signs at sites with crashes while reducing the proportion of signs at sites without crashes; however, it failed to provide advisory speed signs at two of the 20 example sites with crashes that are currently not posted with advisory speeds.

The research team recommends the substitution of the current BB indicator posting method with a computational method that would produce more consistent values. The method suggested by Bonneson et al. (2009), for example, is one such computational method. Based on the findings of this research, the project team recommends the use of the OSU Method as the best available candidate method for Oregon since it performed better than the other methods evaluated for this research effort. Additionally, the OSU Method is based on the safety performance that depends on road geometry and operations. The OSU Method also limits the likelihood of the unnecessary posting of advisory speeds that are either higher or lower than appropriate for the site conditions. The research team is not aware of any comparable safety performance method currently available for the posting of advisory speeds.

The principle underlying the OSU Method is the ASCF, which offers a plausible interpretation from the human factors standpoint: drivers seem to take advisory speeds seriously for extreme postings and tend to disregard advisory speeds at locations that appear safer due to their perception of the geometry (unfortunately resulting in additional crashes at these locations). In fact, drivers tend to overlook advisory speeds with values similar to the speed limit, regardless of the discomfort that they may experience when traversing the curve. The ASCF captures all of these trends in a numerical format. Consequently, the ASCF reflects an increasing safety benefit as the advisory speed decreases from the speed limit and as the advisory speed has a larger associated SFD. Although there is no mathematical limit for this trend towards larger SFDs, the research team capped the SFD for the OSU Method at a maximum value of 0.25. This value is subject to modification, as site specific conditions, such as pavement condition and associated surface friction, will change with time. This temporal affect also applies to the current BB method which can also require posting modifications as the pavement surface deteriorates (assuming pavement resurfacing is not an option at the site).

The research team recommends additional research to refine the ASCF and to potentially develop similar safety response surface models for safety treatments other than advisory speed signs. The research team expects that it is possible to derive similar models for other treatments by refining the statistical analysis developed for this research effort.

9.0 REFERENCES

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APPENDIX A:
ABBREVIATIONS USED IN REPORT

Table A.1: Abbreviation Summary

Acronym	Definition
AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AIC	Akaike Information Criterion
ANGL	Angle Crash
ASCF	Advisory Speed Crash Factor
ASD	Advisory Speed Differential
BB	Ball-Bank (Indicator)
CMF	Crash Modification Factor (or Function)
FAT	Fatality Crash
FIX	Fixed-object Crash
FT	Feet
HEAD	Head-on Crash
INJ	Injury Crash
MPH	Miles Per Hour
MUTCD	Manual on Uniform Traffic Control Devices
NB	Negative Binomial
ODOT	Oregon Department of Transportation
OSU	Oregon State University
OTREC	Oregon Transportation Research and Education Consortium
PDO	Property-damage-only Crash
Q-Q	Quantile-Quantile (Plot)
REAR	Rear-end Crash
ROR	Run-off-road Crash
SE	Superelevation
SFD	Side Friction Demand
SPR	State Planning and Research
SS	Sideswipe Crash (includes overtaking and meeting sideswipes)
SS-M	Sideswipe-meeting Crash
SS-O	Sideswipe-overtaking Crash
TCD	Traffic Control Devices
TTI	Texas Transportation Institute
TURN	Turning Crash
VPD	Vehicles per day

APPENDIX B:
FIELD DATA COLLECTION FORM

Distances along the road

Site scheme:

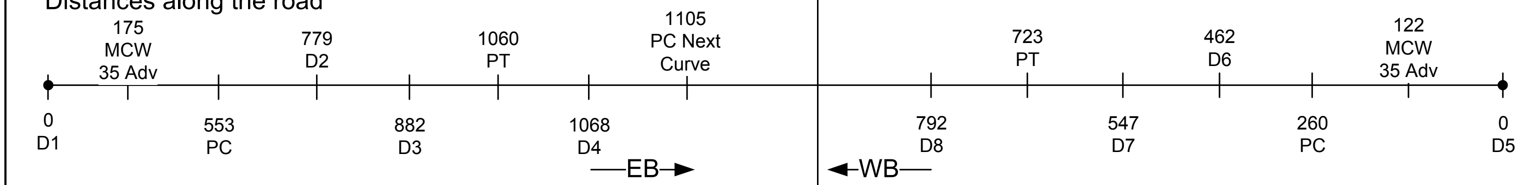
NOTES:

TITLE DATA COLLECTION FORM	DATE	COLLECTED BY
SITE NAME	TIME: START: FINISH:	

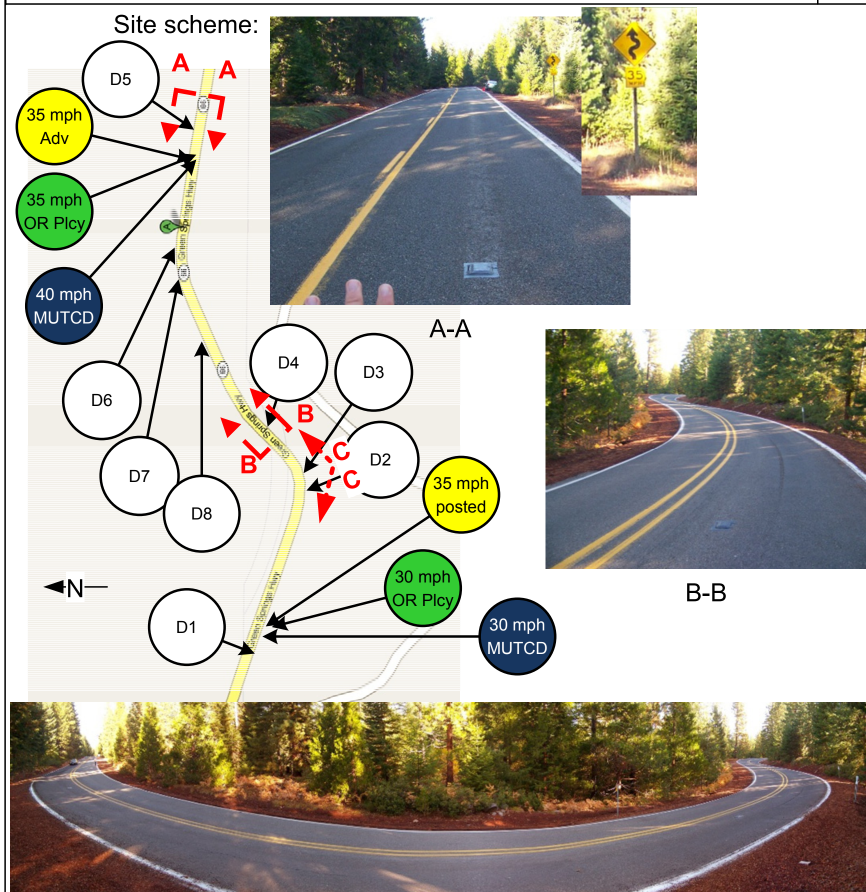
OSU Oregon State UNIVERSITY

APPENDIX C:
SITE DATA SUMMARIES

Distances along the road

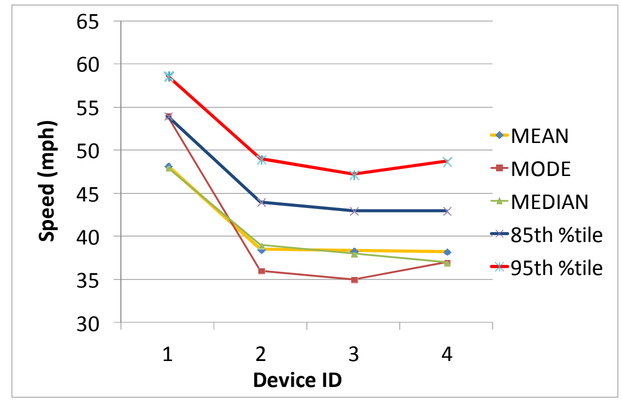


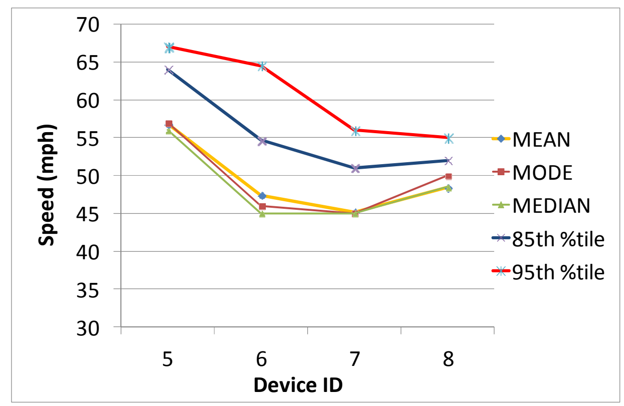
Site scheme:



C-C

NOTES: N45.26197 W122.33933 It was icy at the beginning of data collection





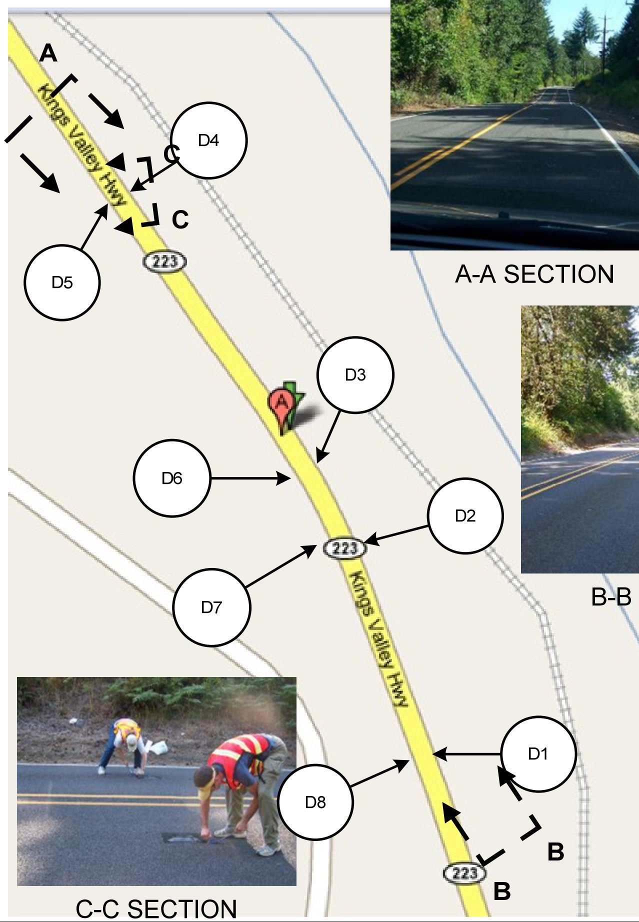
TITLE	DATE	COLLECTED BY	
DATA COLLECTION FORM	Oct-24	Yanfen Zhou, and Raul Avelar	OSU Oregon State University
SITE NAME	TIME:		
Green Springs OR 66 MP 30	START: 9:00	FINISH: 17:30	

Distances along the road

Distance	Location
0	D4, D5
422	Curve to Left (NA)
615	PC
634	Warning (45 Speed zone ahead)
709	D3, D6
809	D2, D7
879	PT
1018	curve to the right (NA)
1230	D1, D8

North

Site scheme:



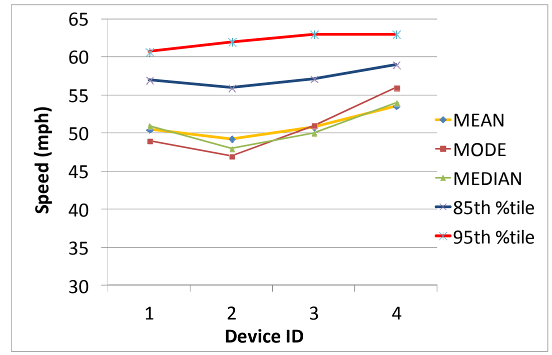
A-A SECTION

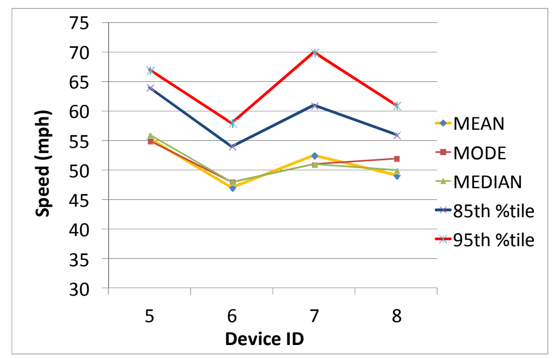
B-B SECTION

C-C SECTION

NOTES:

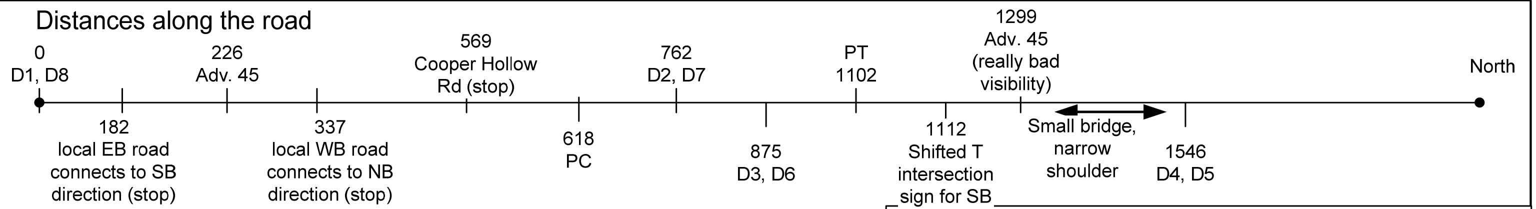
GPS reading: N44.71241, W123.43164
No advisory was available for this particular curve, but for the previous one south from this location



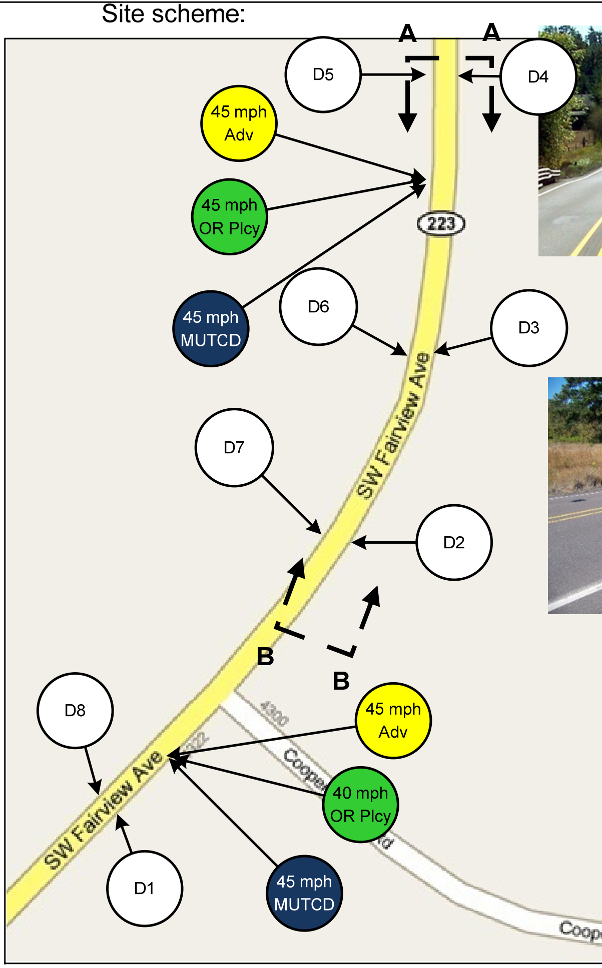


TITLE	DATE	COLLECTED BY	
DATA COLLECTION FORM	Sep 10	Raul and Neil	OSU Oregon State University
SITE NAME: Kings Valley 22	TIME: START: 7:30	FINISH: 17:30	

Distances along the road



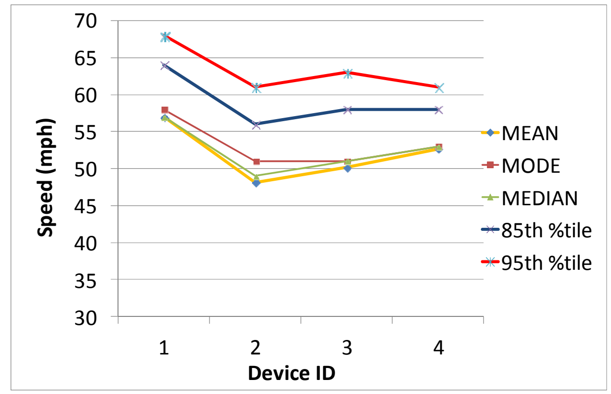
Site scheme:

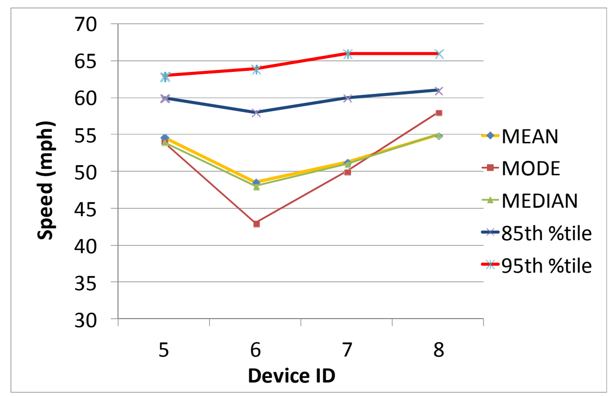


A-A SECTION

B-B SECTION

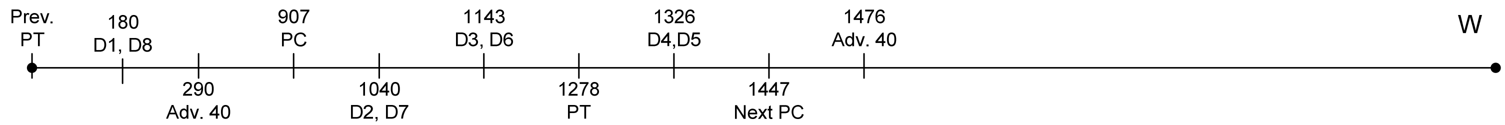
NOTES:
GPS reading: N44.87248, W123.33749



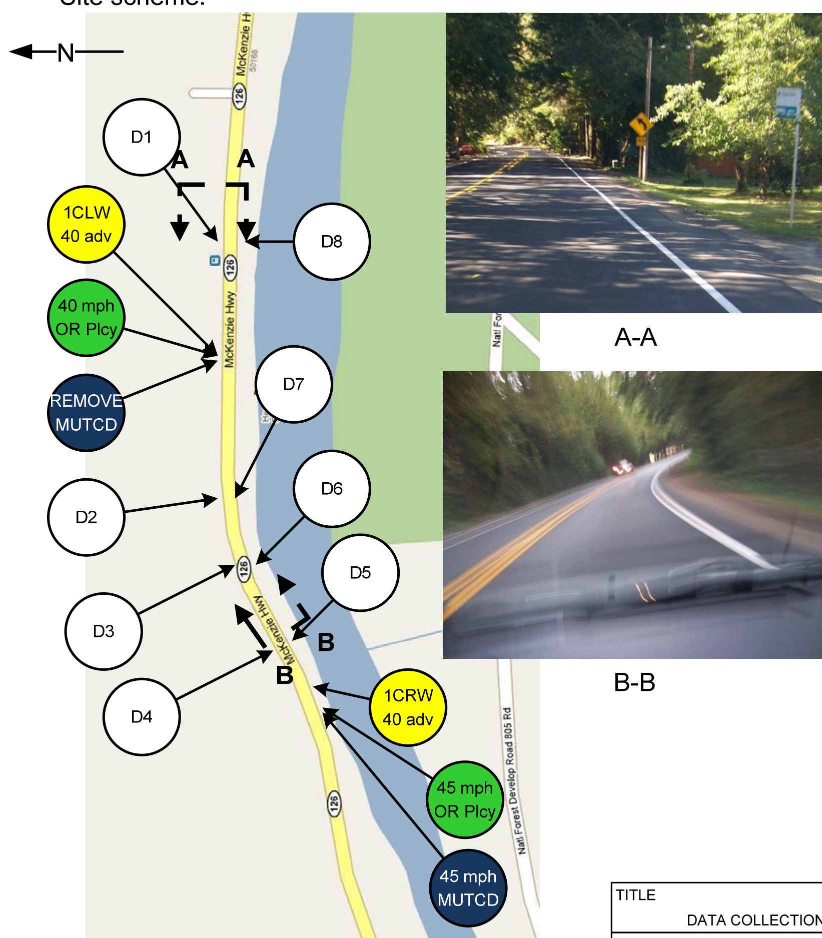


TITLE	DATE	COLLECTED BY	
DATA COLLECTION FORM	Sep 11	Raul and Neil	OSU Oregon State University
SITE NAME	TIME:		
Kings Valley 06	START: 7:30	FINISH: 13:30	

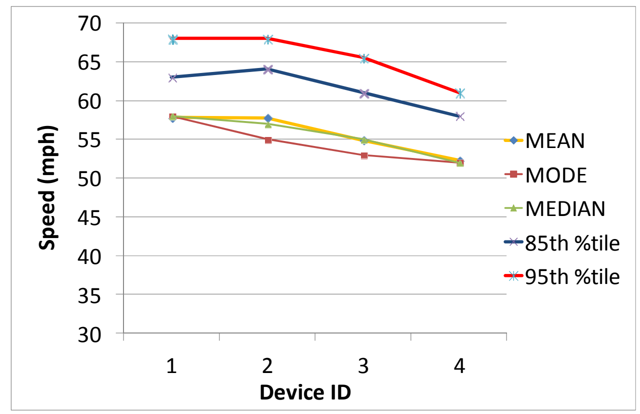
Distances along the road

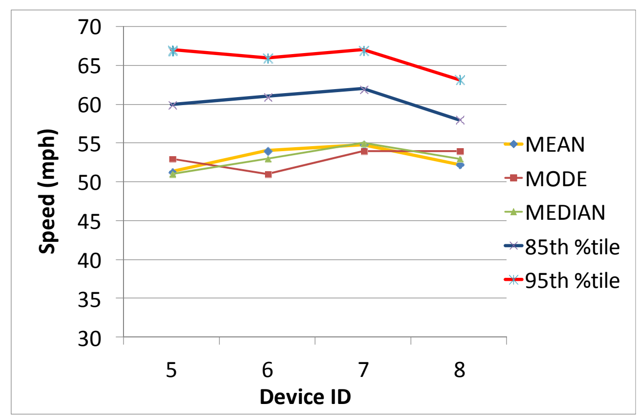


Site scheme:



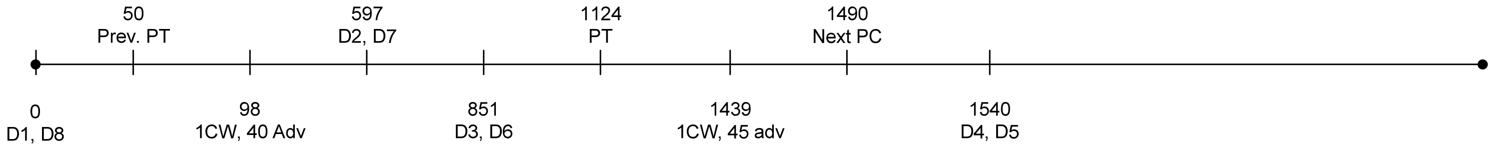
NOTES:



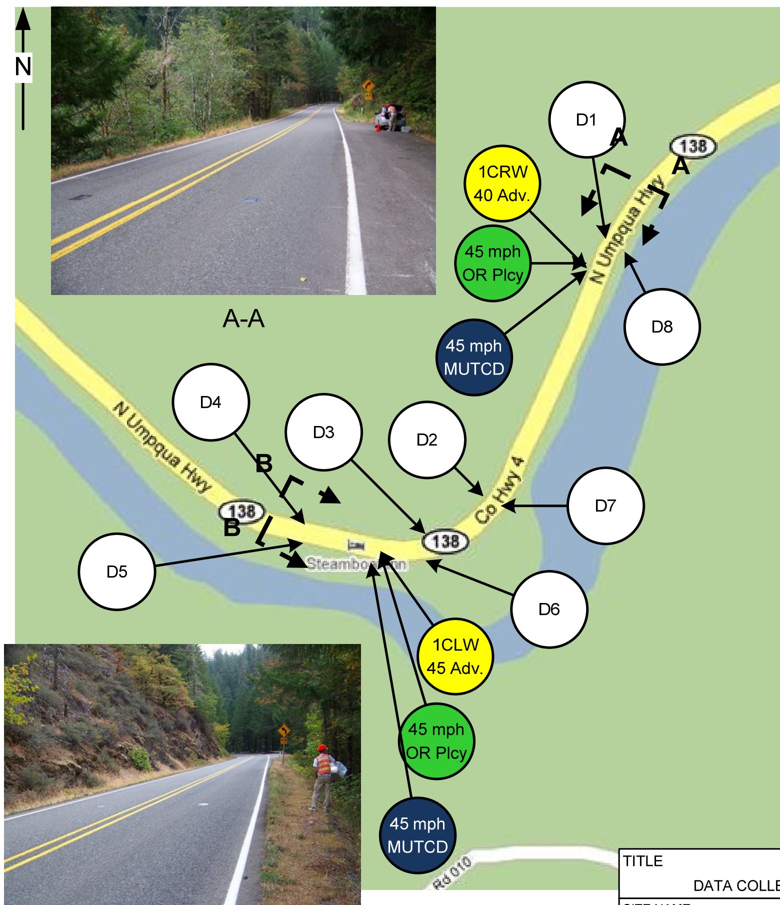


TITLE	DATE	COLLECTED BY	
DATA COLLECTION FORM	09/17/2009	Neil and Raul	OSU Oregon State University
SITE NAME: McKenzie 36	TIME: START: 13:00	FINISH: 18:00	

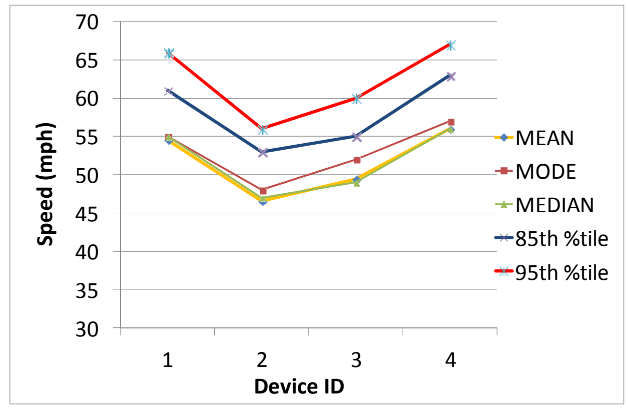
Distances along the road

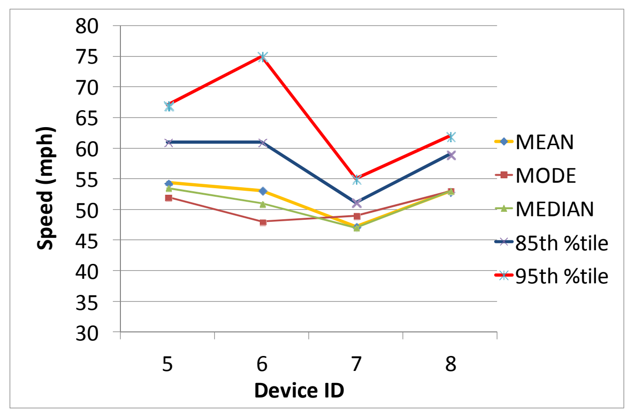


Site scheme:



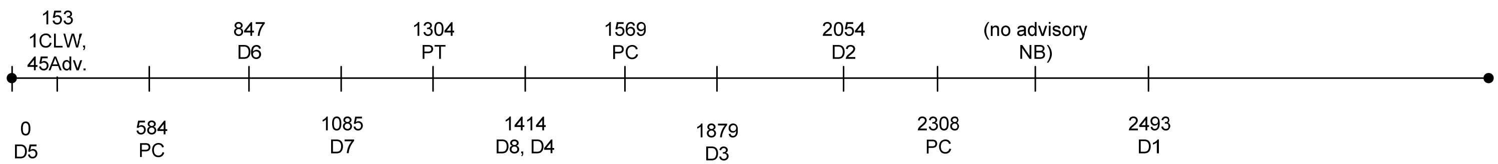
NOTES:



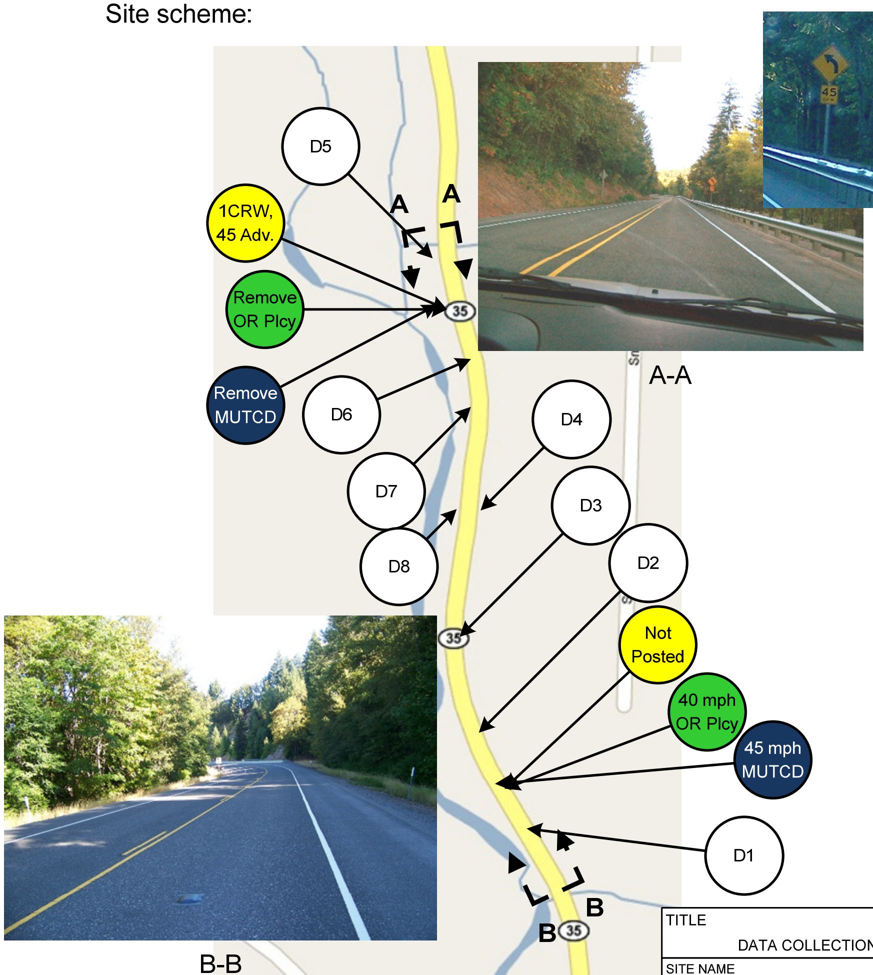


TITLE	DATE	COLLECTED BY	
DATA COLLECTION FORM	9/19/2009	Raul and Neil	OSU Oregon State University
SITE NAME	TIME:		
North Umqua 37	START: 09:30	FINISH: 18:00	

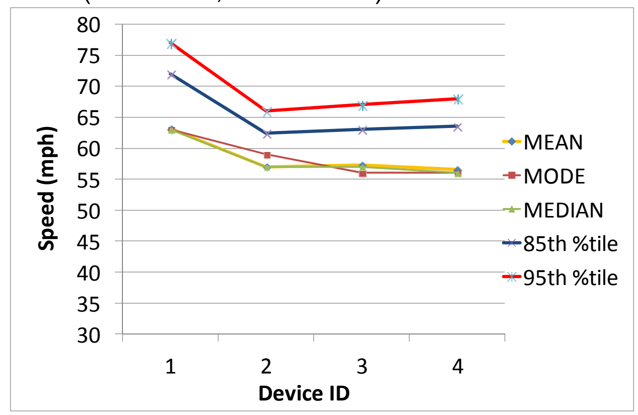
Distances along the road

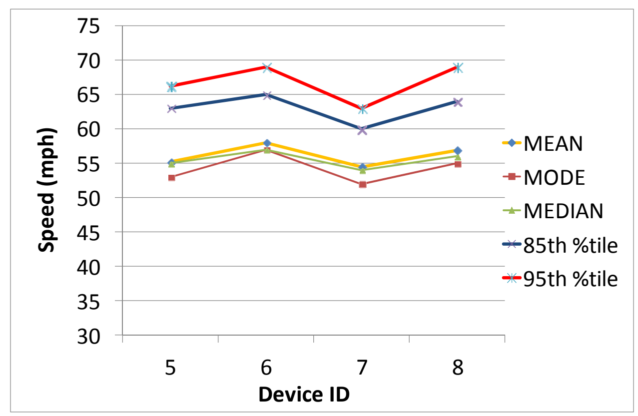


Site scheme:



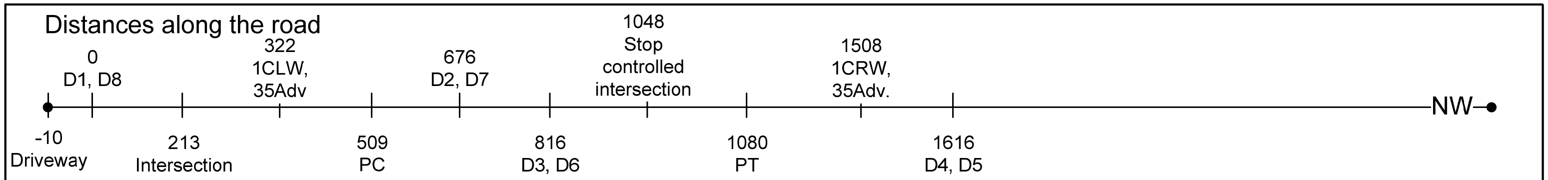
NOTES: (N45.50459, W121.56342)

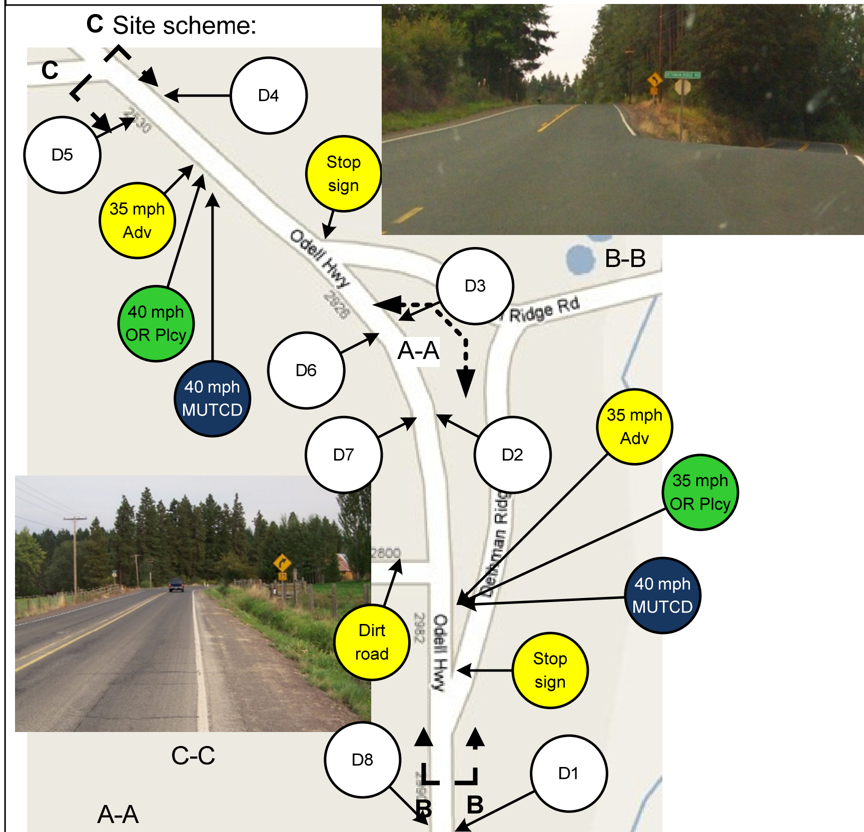




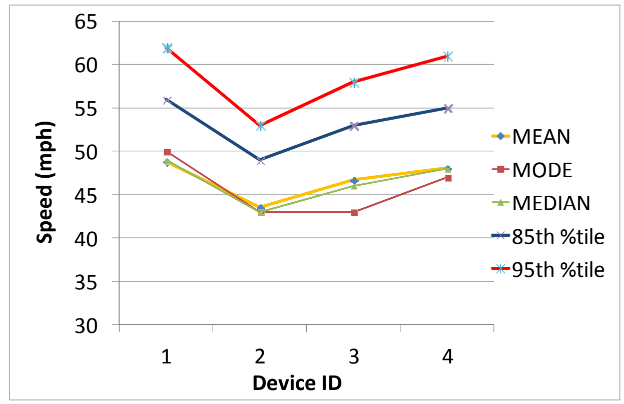
TITLE	DATE	COLLECTED BY
DATA COLLECTION FORM	09/22/2009	Neil and Raul
SITE NAME	TIME:	
Mt Hood 80-83	START: 10:00	FINISH: 17:30

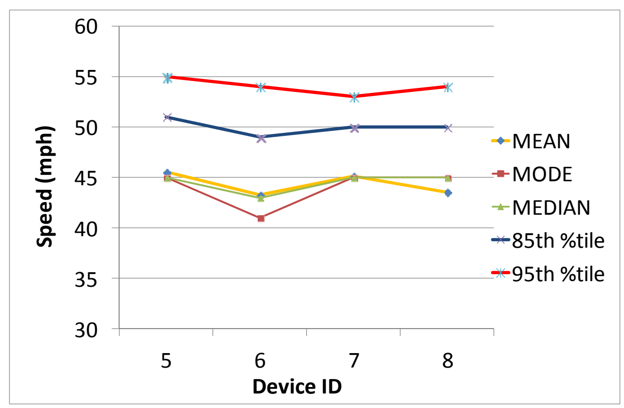
OSU Oregon State University





NOTES:



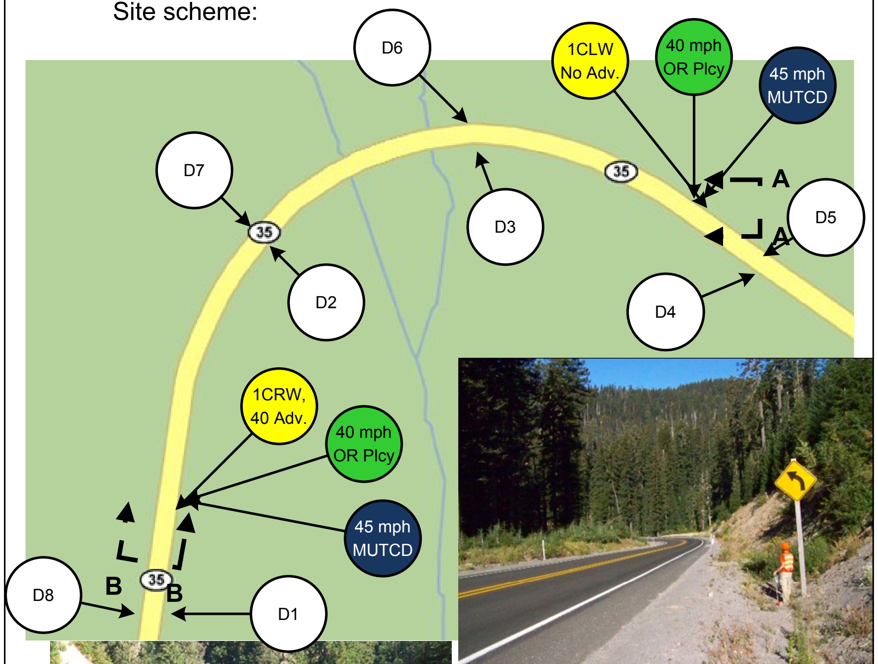


TITLE	DATE	COLLECTED BY	
DATA COLLECTION FORM	09/23/2009	Neil and Raul	OSU Oregon State University
SITE NAME Odel 0	TIME: START: 08:00	FINISH: 16:45	

Distances along the road

0	Bump W
246	D4, D5
395	1CLW No Adv.
524	PT
952	D3, D6
1388	D2, D7
1990	PC
2106	1CRW 45Adv (bent between 4 and 5)
2270	D1, D8
	SSW

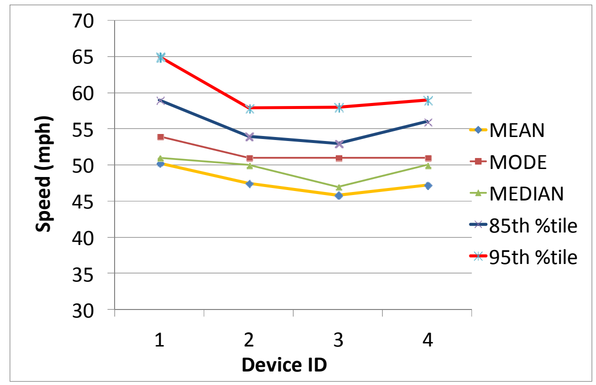
Site scheme:

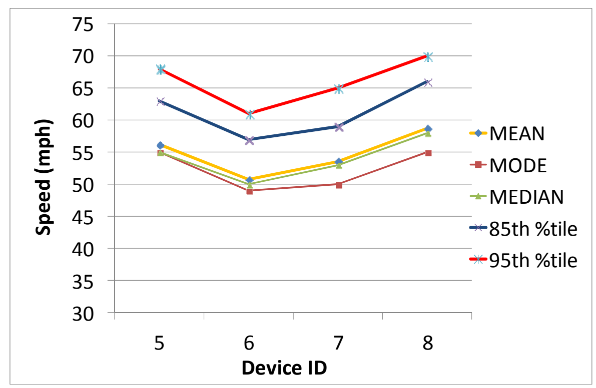


A-A

B-B

NOTES: N45.31517, W121.66026. Upgrade from 1 to 4, preceded by a long tangent. In the other direction there is a mid-length curve to the left prior to reaching D5





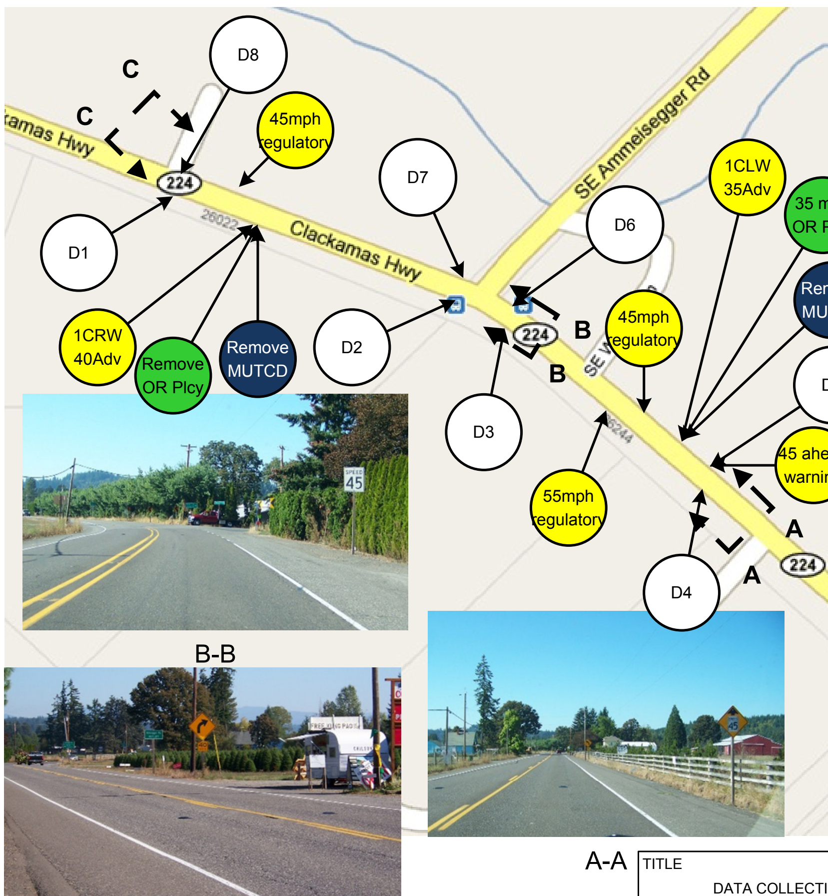
TITLE	DATE	COLLECTED BY
DATA COLLECTION FORM	09/24/2009	Neil and Raul
SITE NAME: MtHood 62	TIME: START: 10:00 FINISH: 17:45	

OSU Oregon State University

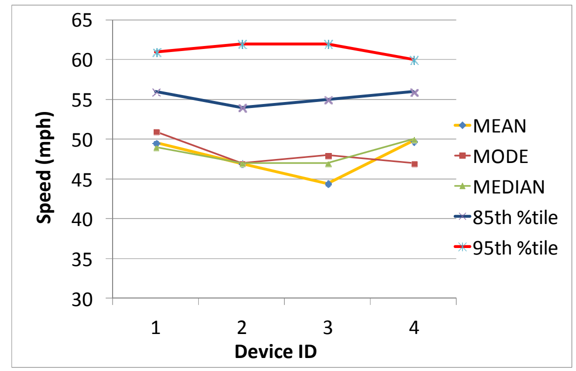
Distances along the road

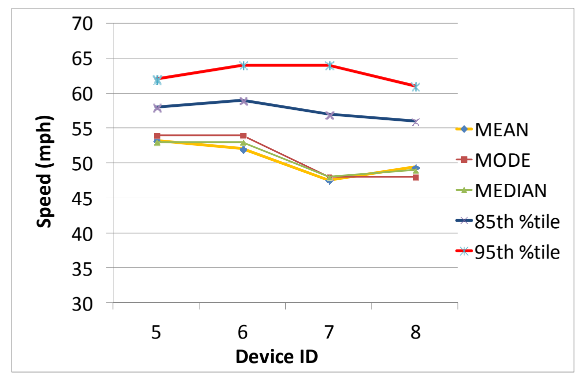
- 0 — D5, D4, 45mph ahead Warning sign
- 242 — 1CLW 35Adv
- 617 — PC
- 629 — 45 mph regulatory
- 647 — 55 mph regulatory (for EB)
- 684 — D6, D3
- 716 — Center of stop intersect. (from NE)
- 811 — D7,D2
- 923 — PT
- 1191 — 1CRW 40Adv.
- 1310 — 45mph Regulatory (for WB again)
- 1325 — D8, D1
- WNW

Site scheme:



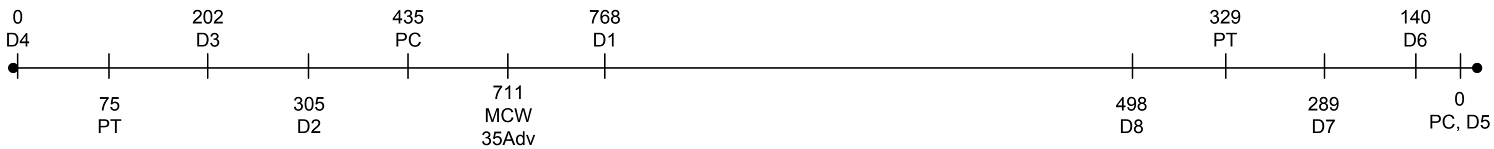
NOTES: N45.38652, W122.39828. There are two bus stops in the intersection, one in the NE corner and one just opposite of the N leg. There are chevron reflective signs for the WB traffic.



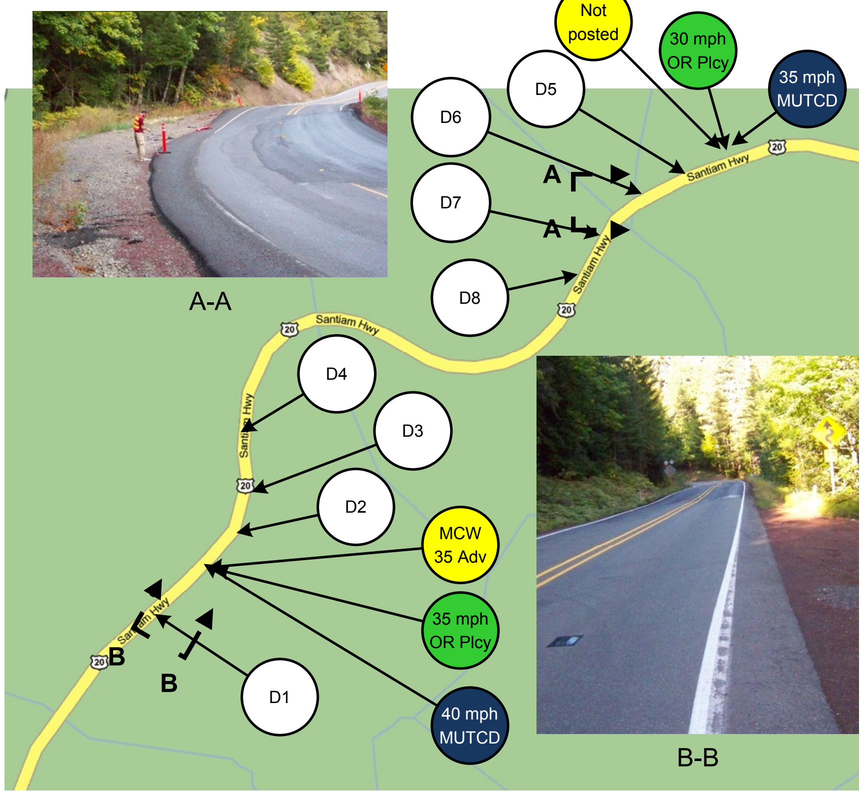


TITLE: DATA COLLECTION FORM	DATE: 09/25/2009	COLLECTED BY: Neil and Raul	OSU Oregon State UNIVERSITY
SITE NAME: Clackamas 13	TIME: START: 06:30	FINISH: 14:30	

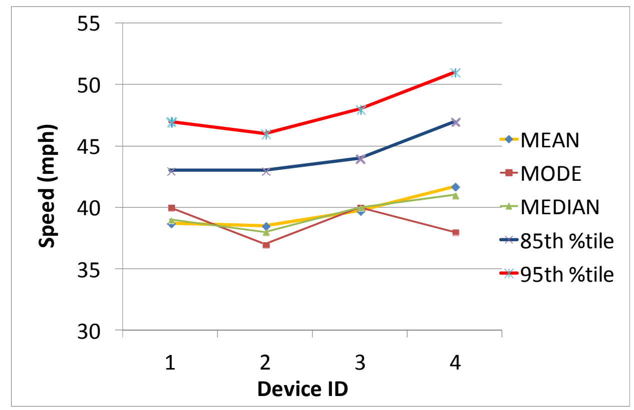
Distances along the road

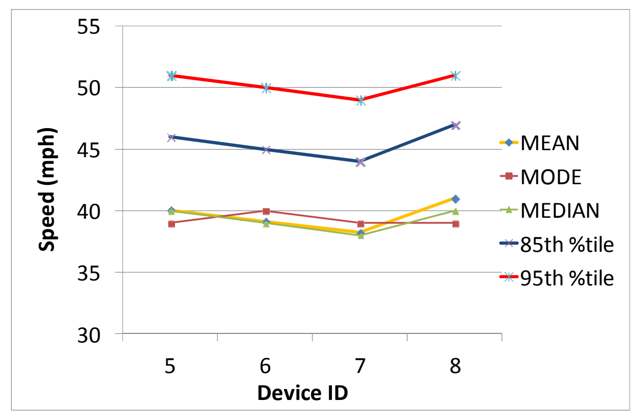


Site scheme:



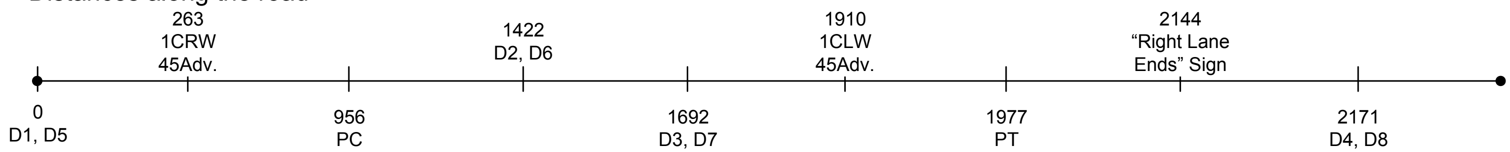
NOTES: N44.0253, W122.22977. Bumpy road before and after the compound of curves. Bad asphalt condition



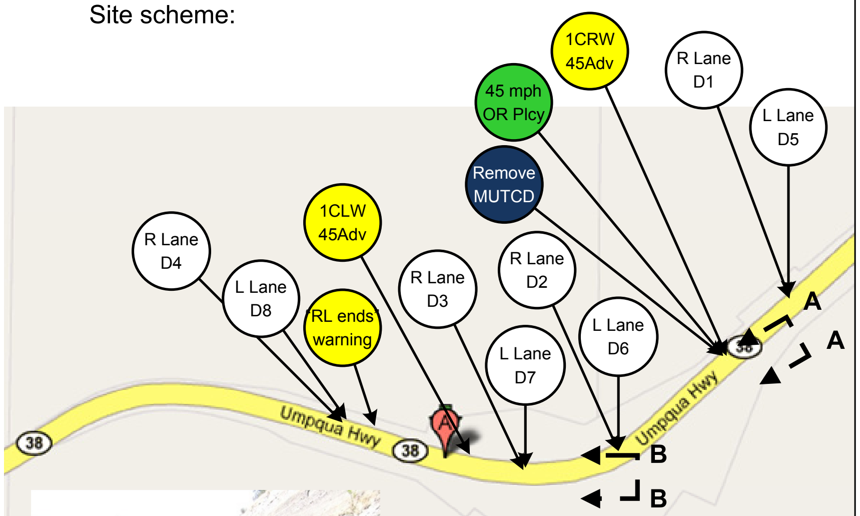


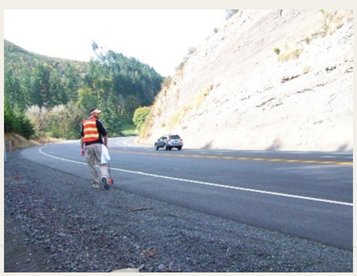
TITLE	DATE	COLLECTED BY	
DATA COLLECTION FORM	Oct-9	Raul and Neil	OSU Oregon State University
SITE NAME	TIME:		
Santiam_36	START: 7:40	FINISH: 16:30	

Distances along the road

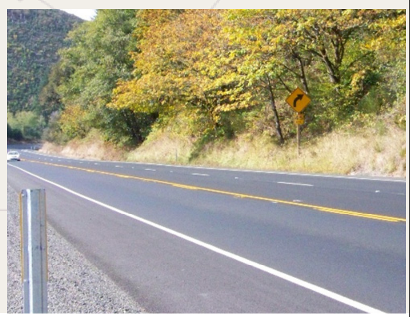


Site scheme:



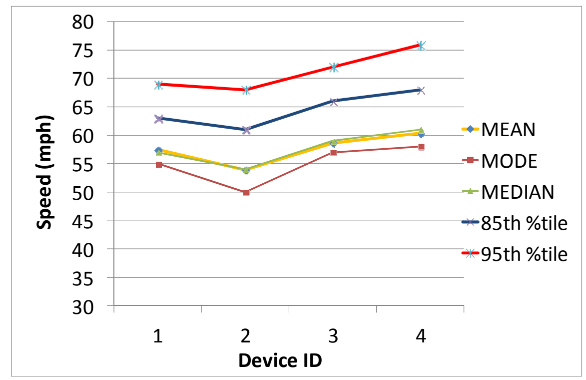


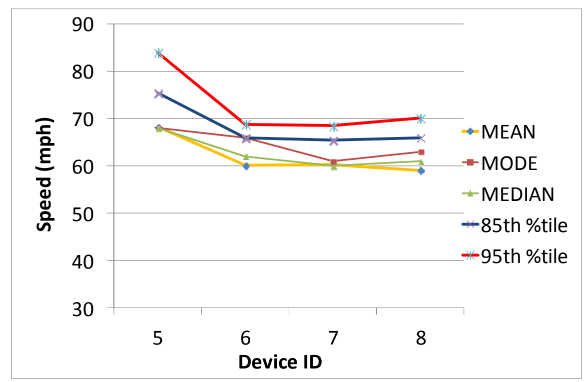
B-B



A-A

NOTES: N43.63830, W123.54892
It's a 3 lane section at D1, D5 but a 4 line section at D4,D8. It doesn't have a sign in the other direction. The next curve poses a similar layout, but adding a regulatory 45 mph sign as one enters the EB side, so this curve was chosen out of these two.





TITLE	DATE	COLLECTED BY
DATA COLLECTION FORM	Oct-10	RA and NK
SITE NAME	TIME:	
Umpqua_36	START: 11:00	FINISH: 16:00

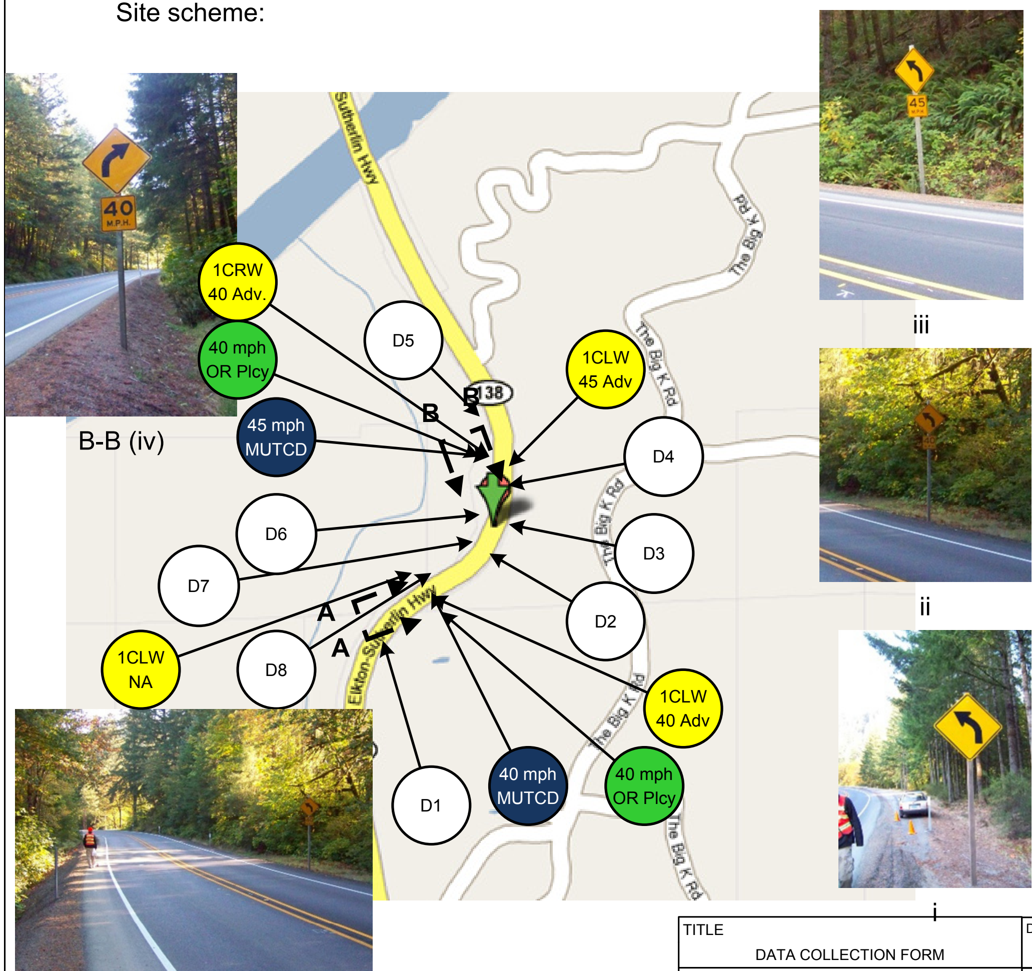
OSU Oregon State University

Distances along the road

0	1CLW NA next curve (i)
20	D1
173	PT prev curve
220	D8
224	1CLW 40 Adv (ii)
374	PC
628	D2, D7
777	D3, D6
983	PT
1022	D4
1107	1CLW 45 Adv next curve (iii)
1222	1CRW 40 Adv (iv)
1289	PC next curve
1330	D5

—NB→

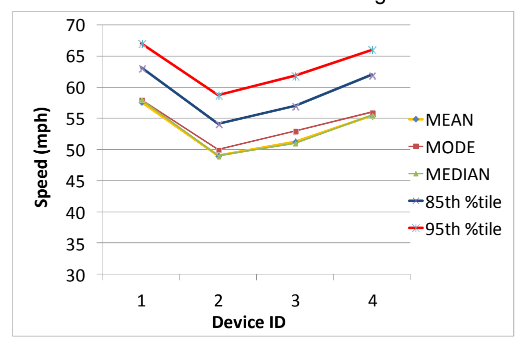
Site scheme:

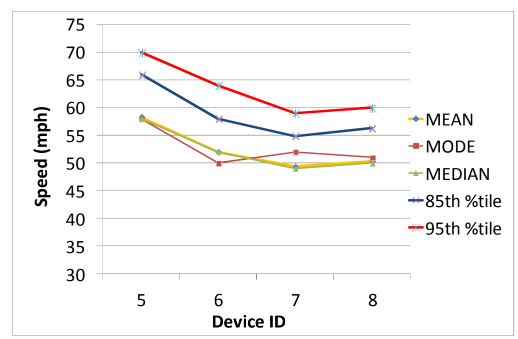


NOTES: GPS: at D4 N43.57919, W123.55384

Due to the position of the advisory sign, D1 was placed in the previous curve. This previous curve is downhill, and the grade levels at some point in the beginning of the studied curve

Just before data collection there was fog in the area.





TITLE	DATE	COLLECTED BY
DATA COLLECTION FORM	Oct-11	RA and NK
SITE NAME: Elkton_Sutherlin_4	TIME: START: 10:00 FINISH: 17:00	

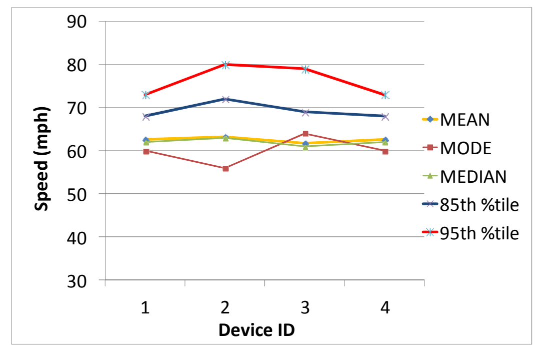
OSU Oregon State University

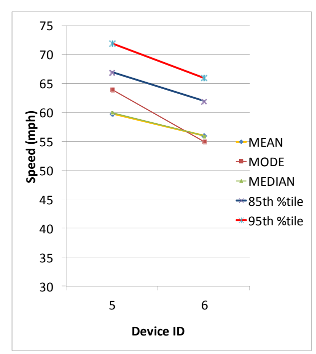
Distances along the road

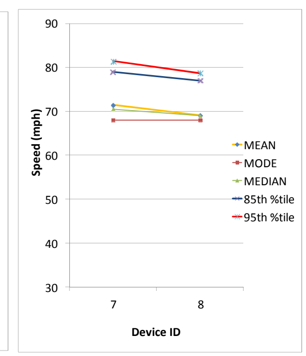
0	Old Hwy 42 (disconnected now)
183	D5, D7
499	D4
948	PT
1056	D3, D6, D8
1176	D2
1360	PC
1681	1CRW 45 Adv.
1900	D1

Site scheme:

NOTES: N42.97283, W123.75203
Site has advisory speed only at one direction of travel, and the other has a passing lane. In order to capture all traffic, the two exiting devices in the direction with two lanes (7 and 8) were placed next to the entering ones. In this way we get all four consecutive points in the posted side, but just the entering ones in the other (with two lanes).







TITLE	DATE	COLLECTED BY
DATA COLLECTION FORM	10/16/2009	Meng, Yanfen and Raul
SITE NAME: CoosBay-Roseburg 48	TIME: START: 11:30	FINISH: 17:30

OSU Oregon State University

Distances along the road

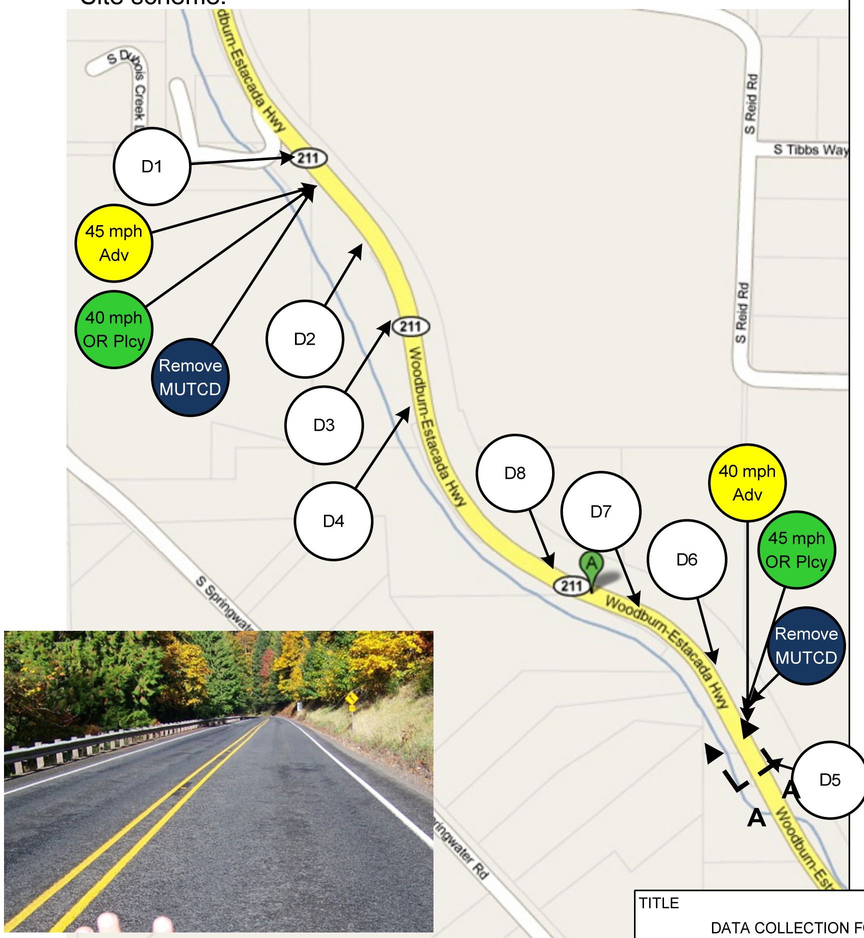
NB →

0 PC Next Curve	103 D4	330 PT	597 D3	727 D2	984 PC	1077 2CRLW 45 Adv.	1263 D1	1371 PT Prev. Curve

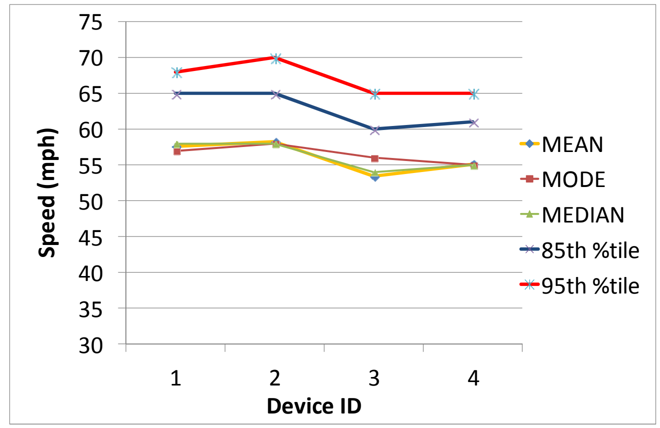
← NB

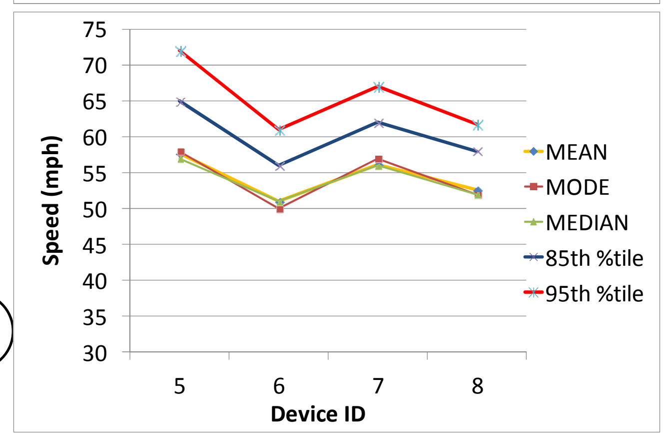
1513 Next PC	1285 D8	1090 PT	1036 D7	934 D6	618 PC	396 2CLRW 40 Adv.	225 D5	0 PT Prev Curve

Site scheme:



Notes:

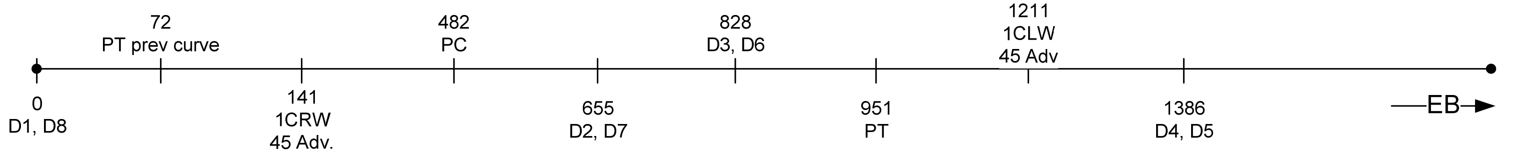




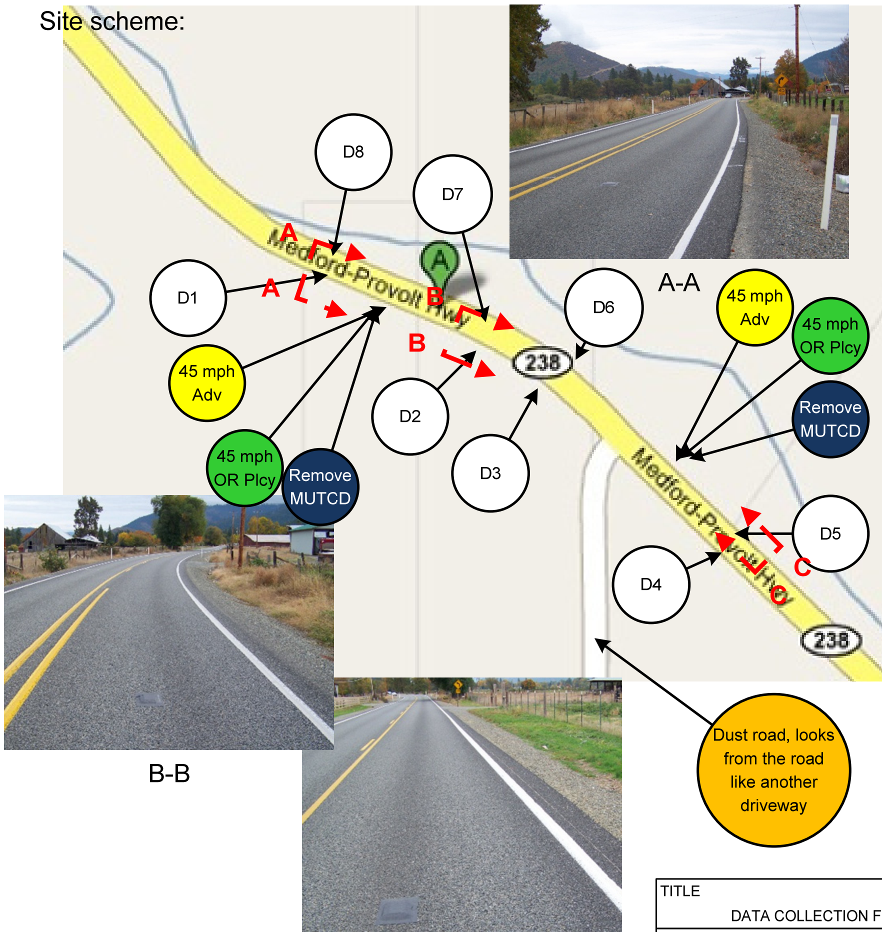
TITLE	DATE	COLLECTED BY
DATA COLLECTION FORM	Oct-22	Neil Kopper, Andrew Bernath, and Raul Avelar
SITE NAME: Woodburn-Stacada OR 211 MP 31	TIME: START: 10:45	FINISH: 17:15

OSU Oregon State University

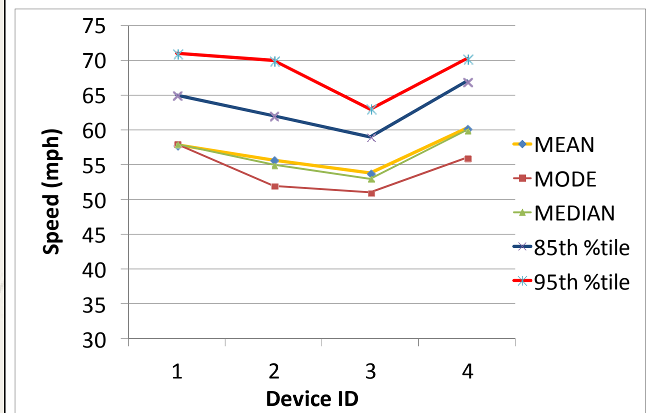
Distances along the road

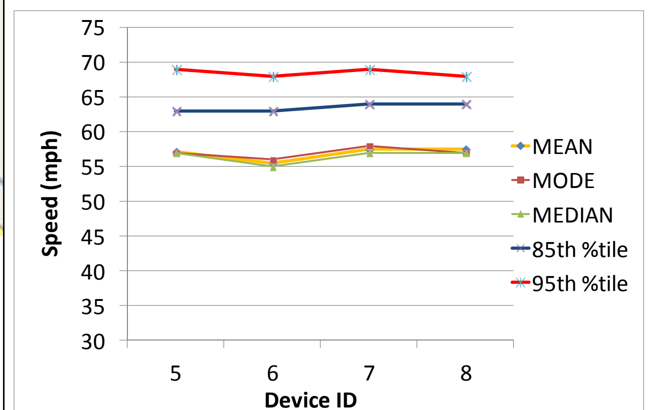


Site scheme:

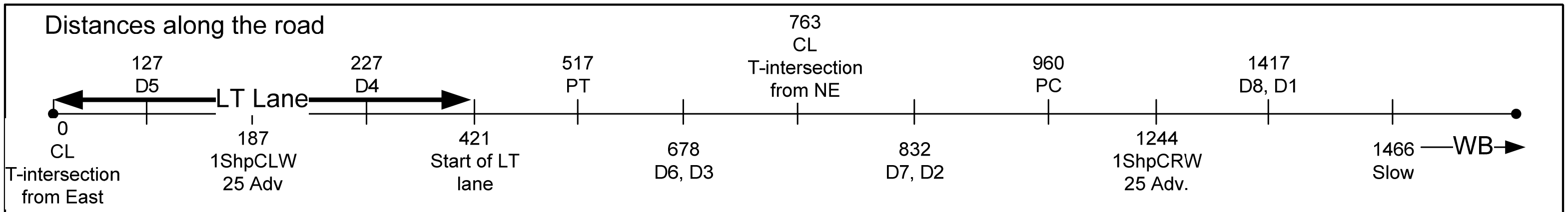


Notes: N42.26532, W123.20699

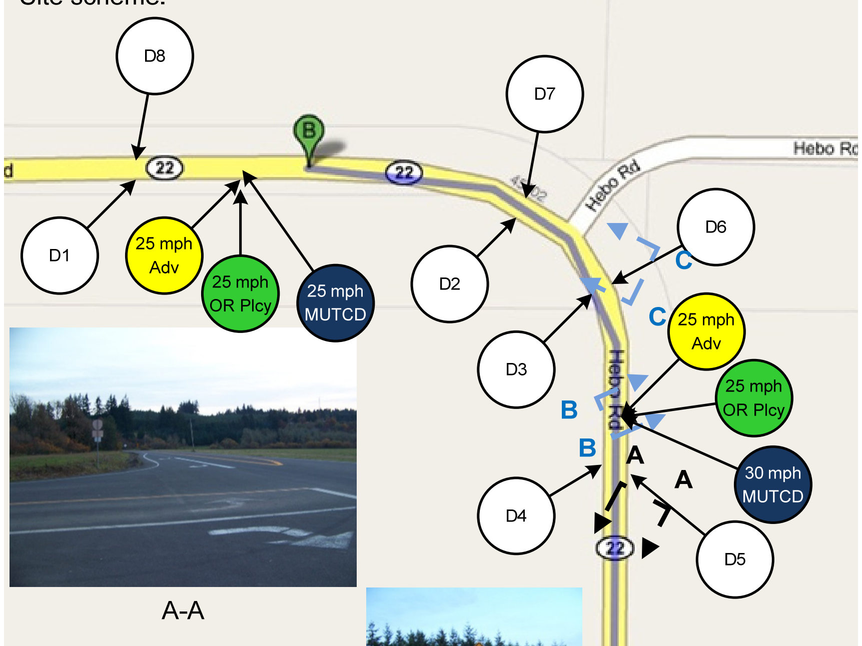




TITLE DATA COLLECTION FORM	DATE Oct-24	COLLECTED BY Yanfen Zhou, and Raul Avelar	OSU Oregon State University
SITE NAME Jacksonville OR 238 MP 15.4	TIME: START: 12:30	FINISH: 17:45	



Site scheme:

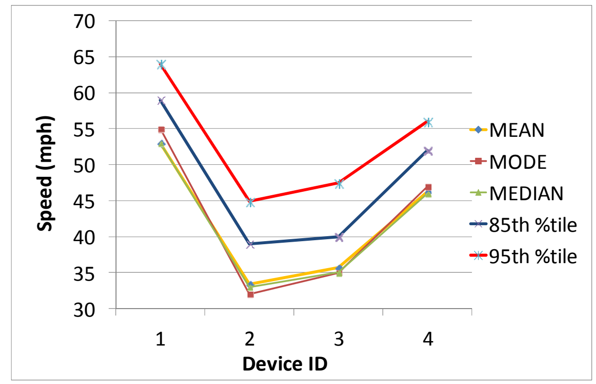


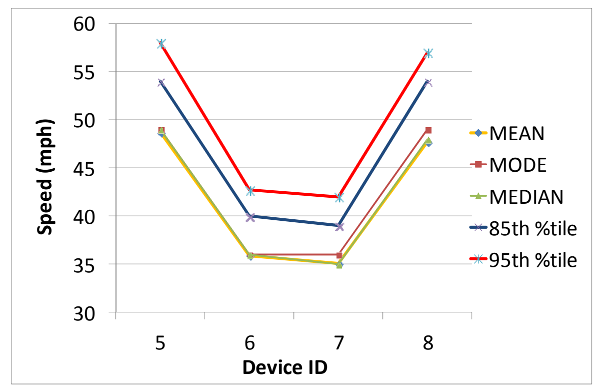
A-A

B-B

C-C

NOTES: N45.07491, W123.57619
Traveling EB, as the intersection appears in the center of the curve, the center double yellow separates almost into one center lane, after exiting the curve, a left turning lane appears.





TITLE: DATA COLLECTION FORM	DATE: 11/04/2009	COLLECTED BY: Neil Kopper, Ioana Cosma & Raul Avelar	OSU Oregon State University
SITE NAME: Three Rivers 22	TIME: START: 08:45 FINISH: 16:00		

APPENDIX D:
COMPUTER SIMULATION BASED RESULTS

Table D.1: Region 1 Simulation Results

REGION 1 SIMULATION RESULTS

	Mean	Variance	Confidence interval for Mean	Best estimate for Parameter	Bias	Adj. Confidence interval for Total number of posted curves	Correlation Matrix	*X1*	*X2*	*X3*
X1= Sample size	62.65	103.56	[38 , 90]	65	2.35	[36 , 88]	X1	1		
X2 = # of posted curves in sample	11.58	2.08	[8 , 15]	12	0.42	[8 , 15]	X2	0.0578066	1	
X3 = Number of posted curves in the region	30.81	39.09	[19 , 52]	30	-0.81	[20 , 53]	X3	-0.770215	0.5533	1

Table D.2: Region 2 Simulation Results

REGION 2 SIMULATION RESULTS

	Mean	Variance	Confidence interval for Total number of posted curves	Best estimate for Parameter	Bias	Adj. Confidence interval for Total number of posted curves	Correlation Matrix	*X1*	*X2*	*X3*
X1= Sample size	24.79	18.03	[16 , 37]	26	1.21	[15 , 36]	X1	1		
X2 = # of posted curves in sample	8.14	3.29	[4 , 13]	9	0.86	[4 , 13]	X2	0.0631913	1	
X3 = Number of posted curves in the region	240.43	4337.39	[95 , 441]	247	6.57	[89 , 435]	X3	-0.555667	0.7732	1

Table D.3: Region 3 Simulation Results

REGION 3 SIMULATION RESULTS	Mean	Variance	Confidence interval for Total number of posted curves	Best estimate for Parameter	Bias	Adj. Confidence interval for Total number of posted curves	Correlation Matrix	*X1*	*X2*	*X3*
X1= Sample size	25.01	14.53	[17 , 36]	26	0.99	[17 , 36]	X1	1		
X2 = # of posted curves in sample	7.29	3.35	[3 , 12]	8	0.71	[3 , 12]	X2	0.0634602	1	
X3 = Number of posted curves in the region	105.17	909.36	[38 , 188]	109	3.83	[35 , 185]	X3	-0.458001	0.8417	1

APPENDIX E:
STATISTICAL MODELS

The output summaries associated with the statistical models developed for the advisory speed analysis are shown in detail in the following sections. In some instances, an individual variable may have a marginal probability value but has been retained in the model. For these cases, the variable has been retained because it has a strong interaction component that is statistically significant.

E.1 REGRESSION MODEL EXPLICITLY ACCOUNTING FOR THE SUBGROUP OF CURVES WITH 25 MPH ADVISORY SPEEDS

```
Call:
glm(formula = Curve.Related ~ AADT + SLminusAdvSp + Excl.Primary.Adv_Speed.Y.N.total +
    Curve_Length + SFD + Radius + HigherAADT + LowAdv3 + Adv25total +
    SLminusAdvSp:SFD + Excl.Primary.Adv_Speed.Y.N.total:Radius +
    Excl.Primary.Adv_Speed.Y.N.total:Curve_Length + AADT:HigherAADT,
    family = poisson(link = "log"), data = CrashData3)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.3670  -0.8903  -0.4577   0.3673   2.4884

Coefficients:
                                               Estimate Std. Error z value Pr(>|z|)
(Intercept)                                  -3.648e+00  6.854e-01  -5.323 1.02e-07 ***
AADT                                          4.923e-04  6.394e-05   7.700 1.36e-14 ***
SLminusAdvSp                                  5.045e-02  2.508e-02   2.012 0.044257 *
Excl.Primary.Adv_Speed.Y.N.total              4.505e+00  7.459e-01   6.039 1.55e-09 ***
Curve_Length                                  8.700e-04  3.174e-04   2.741 0.006130 **
SFD                                           7.631e+00  2.338e+00   3.263 0.001102 **
Radius                                        4.601e-04  3.169e-04   1.452 0.146532
HigherAADT                                    1.820e+00  6.900e-01   2.637 0.008358 **
LowAdv3                                      -1.022e+00  5.116e-01  -1.998 0.045684 *
Adv25total                                   -1.618e+01  1.106e+03  -0.015 0.988334
SLminusAdvSp:SFD                             -8.394e-01  2.079e-01  -4.037 5.41e-05 ***
Excl.Primary.Adv_Speed.Y.N.total:Radius      -4.181e-03  1.051e-03  -3.979 6.93e-05 ***
Excl.Primary.Adv_Speed.Y.N.total:Curve_Length -2.647e-03  7.045e-04  -3.757 0.000172 ***
AADT:HigherAADT                              -4.282e-04  9.250e-05  -4.629 3.68e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for poisson family taken to be 1)
```

```
    Null deviance: 417.19 on 209 degrees of freedom
Residual deviance: 199.49 on 196 degrees of freedom
AIC: 437.09

Number of Fisher Scoring iterations: 16
```

E.2 REGRESSION MODEL ACCOUNTING FOR THE SQUARE OF SPEED LIMIT MINUS ADVISORY SPEED

```
Call:
glm(formula = Curve.Related ~ AADT + SLminusAdvSp + Excl.Primary.Adv_Speed.Y.N.total +
    Curve_Length + SFD + Radius + HigherAADT + LowAdv3 + AdvSp2total +
    SLminusAdvSp:SFD + Excl.Primary.Adv_Speed.Y.N.total:Radius +
    Excl.Primary.Adv_Speed.Y.N.total:Curve_Length + AADT:HigherAADT,
    family = poisson(link = "log"), data = CrashData3)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.2606  -0.8916  -0.4814   0.4644   2.5079

Coefficients:
                                               Estimate Std. Error z value Pr(>|z|)
(Intercept)                                  -2.365e+00  1.141e+00  -2.073 0.038177 *
AADT                                          5.031e-04  6.395e-05   7.868 3.62e-15 ***
SLminusAdvSp                                  2.941e-02  2.911e-02   1.011 0.312224
Excl.Primary.Adv_Speed.Y.N.total              4.143e+00  8.034e-01   5.157 2.51e-07 ***
Curve_Length                                  8.809e-04  3.140e-04   2.806 0.005022 **
SFD                                           8.248e+00  2.361e+00   3.493 0.000477 ***
Radius                                        5.351e-04  3.168e-04   1.689 0.091176 .
HigherAADT                                    2.208e+00  7.168e-01   3.080 0.002068 **
LowAdv3                                      -1.437e+00  5.030e-01  -2.857 0.004279 **
AdvSp2total                                  -5.387e-04  3.845e-04  -1.401 0.161252
SLminusAdvSp:SFD                             -8.934e-01  2.104e-01  -4.247 2.16e-05 ***
Excl.Primary.Adv_Speed.Y.N.total:Radius      -3.990e-03  1.072e-03  -3.721 0.000198 ***
Excl.Primary.Adv_Speed.Y.N.total:Curve_Length -2.448e-03  6.931e-04  -3.532 0.000412 ***
AADT:HigherAADT                              -4.830e-04  9.510e-05  -5.078 3.81e-07 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Dispersion parameter for poisson family taken to be 1)
    Null deviance: 417.19  on 209  degrees of freedom
Residual deviance: 203.07  on 196  degrees of freedom
AIC: 440.67
Number of Fisher Scoring iterations: 5
```

E.3 REGRESSION MODEL ACCOUNTING FOR POSTED AND NOT WARRANTED CURVES

```
Call:
glm(formula = Curve.Related ~ AADT + SLminusAdvSp + Excl.Primary.Adv_Speed.Y.N.total +
    Curve_Length + SFD + Radius + HigherAADT + LowAdv3 + PostedNotWarranted +
    SLminusAdvSp:SFD + Excl.Primary.Adv_Speed.Y.N.total:Radius +
    Excl.Primary.Adv_Speed.Y.N.total:Curve_Length + AADT:HigherAADT,
    family = poisson(link = "log"), data = CrashData3)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.4139  -0.8864  -0.4589   0.4279   2.4407

Coefficients:
                                               Estimate Std. Error z value Pr(>|z|)
(Intercept)                                  -3.653e+00  6.921e-01  -5.278 1.31e-07 ***
AADT                                          5.093e-04  6.391e-05   7.968 1.61e-15 ***
SLminusAdvSp                                  4.653e-02  2.627e-02   1.771 0.076592 .
Excl.Primary.Adv_Speed.Y.N.total              4.724e+00  7.620e-01   6.200 5.65e-10 ***
Curve_Length                                  8.478e-04  3.169e-04   2.675 0.007473 **
SFD                                           7.815e+00  2.395e+00   3.264 0.001100 **
Radius                                        4.357e-04  3.173e-04   1.373 0.169786
HigherAADT                                    2.101e+00  6.986e-01   3.008 0.002629 **
LowAdv3                                      -1.297e+00  5.057e-01  -2.565 0.010328 *
PostedNotWarranted                           -2.757e-01  4.257e-01  -0.648 0.517198
SLminusAdvSp:SFD                             -8.893e-01  2.146e-01  -4.144 3.42e-05 ***
Excl.Primary.Adv_Speed.Y.N.total:Radius      -4.426e-03  1.056e-03  -4.191 2.78e-05 ***
Excl.Primary.Adv_Speed.Y.N.total:Curve_Length -2.648e-03  7.119e-04  -3.720 0.000199 ***
AADT:HigherAADT                              -4.662e-04  9.279e-05  -5.025 5.04e-07 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 417.19  on 209  degrees of freedom
Residual deviance: 204.55  on 196  degrees of freedom
AIC: 442.15
Number of Fisher Scoring iterations: 6
```

E.4 REGRESSION MODEL ACCOUNTING FOR NOT POSTED AND WARRANTED CURVES

```
Call:
glm(formula = Curve.Related ~ AADT + SLminusAdvSp + Excl.Primary.Adv_Speed.Y.N.total +
    Curve_Length + SFD + Radius + HigherAADT + LowAdv3 + WarrantedNotPosted +
    SLminusAdvSp:SFD + Excl.Primary.Adv_Speed.Y.N.total:Radius +
    Excl.Primary.Adv_Speed.Y.N.total:Curve_Length + AADT:HigherAADT,
    family = poisson(link = "log"), data = CrashData3)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.3597  -0.8887  -0.4584   0.4048   2.4619

Coefficients:
                                               Estimate Std. Error z value Pr(>|z|)
(Intercept)                                  -3.676e+00  7.118e-01  -5.165 2.41e-07 ***
AADT                                          5.096e-04  6.545e-05   7.786 6.91e-15 ***
SLminusAdvSp                                  4.928e-02  2.610e-02   1.888 0.058972 .
Excl.Primary.Adv_Speed.Y.N.total              4.642e+00  7.909e-01   5.869 4.38e-09 ***
Curve_Length                                  8.482e-04  3.184e-04   2.664 0.007715 **
SFD                                           7.718e+00  2.497e+00   3.091 0.001995 **
Radius                                        4.424e-04  3.246e-04   1.363 0.172858
HigherAADT                                    2.006e+00  6.782e-01   2.958 0.003092 **
LowAdv3                                      -1.301e+00  5.036e-01  -2.583 0.009781 **
WarrantedNotPosted                           -3.110e-03  3.438e-01  -0.009 0.992782
SLminusAdvSp:SFD                             -8.627e-01  2.087e-01  -4.133 3.57e-05 ***
Excl.Primary.Adv_Speed.Y.N.total:Radius      -4.458e-03  1.063e-03  -4.195 2.73e-05 ***
Excl.Primary.Adv_Speed.Y.N.total:Curve_Length -2.556e-03  6.987e-04  -3.659 0.000253 ***
AADT:HigherAADT                              -4.577e-04  9.192e-05  -4.979 6.39e-07 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 417.19  on 209  degrees of freedom
Residual deviance: 204.99  on 196  degrees of freedom
AIC: 442.59
Number of Fisher Scoring iterations: 5
```

E.5. Basic Statistical Model for Crashes as Function of Operations, Geometry and Signage

```
Call:
glm(formula = Curve.Related ~ AADT + SLminusAdvSp + Excl.Primary.Adv_Speed.Y.N.total +
    Curve_Length + SFD + Radius + HigherAADT + LowAdv3 + SLminusAdvSp:SFD +
    Excl.Primary.Adv_Speed.Y.N.total:Radius + Excl.Primary.Adv_Speed.Y.N.total:Curve_Length +
    AADT:HigherAADT, family = poisson(link = "log"), data = CrashData3)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.3597  -0.8886  -0.4587   0.4046   2.4622

Coefficients:
                                                Estimate Std. Error z value Pr(>|z|)
(Intercept)                                   -3.678e+00  6.922e-01  -5.314 1.07e-07 ***
AADT                                           5.097e-04  6.399e-05   7.966 1.64e-15 ***
SLminusAdvSp                                   4.926e-02  2.594e-02   1.899 0.057597 .
Excl.Primary.Adv_Speed.Y.N.total               4.644e+00  7.447e-01   6.237 4.47e-10 ***
Curve_Length                                   8.485e-04  3.170e-04   2.677 0.007431 **
SFD                                            7.711e+00  2.381e+00   3.239 0.001198 **
Radius                                         4.430e-04  3.172e-04   1.396 0.162585
HigherAADT                                     2.007e+00  6.778e-01   2.960 0.003075 **
LowAdv3                                       -1.301e+00  5.035e-01  -2.584 0.009759 **
SLminusAdvSp:SFD                              -8.625e-01  2.077e-01  -4.152 3.30e-05 ***
Excl.Primary.Adv_Speed.Y.N.total:Radius       -4.459e-03  1.052e-03  -4.237 2.26e-05 ***
Excl.Primary.Adv_Speed.Y.N.total:Curve_Length -2.557e-03  6.965e-04  -3.671 0.000242 ***
AADT:HigherAADT                               -4.578e-04  9.134e-05  -5.011 5.41e-07 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 417.19  on 209  degrees of freedom
Residual deviance: 204.99  on 197  degrees of freedom
AIC: 440.59

Number of Fisher Scoring iterations: 5
```

APPENDIX F:
COMPUTATIONAL EXAMPLE TO DETERMINE ADVISORY SPEED

The research team prepared a computational example in order to provide the readers of this report with a sense of the data and calculations required to determine an advisory speed value using the OSU Method.

F.1 HAND CALCULATIONS FOR AN EXAMPLE SITE

This example shows the use of Figure 5.38 to compare ASCF values for advisory speed alternatives. Figure F.1 shows a satellite image for the example site. The speed limit is 55 mph at this location.

Source: http://maps.google.com/

Figure F.1: Example Curve Satellite Image

Since this image offers a scale, the radius may be quickly estimated after determining an approximate deflection angle and curve length. This measurement can be accomplished by printing and then measuring the radius from the printed image or by measuring the radius using an image editing software. In the example, the authors used an open source image editing package (GIMP 2.6) for the radius estimation. Figure F.2 shows the processed image and the corresponding estimates.

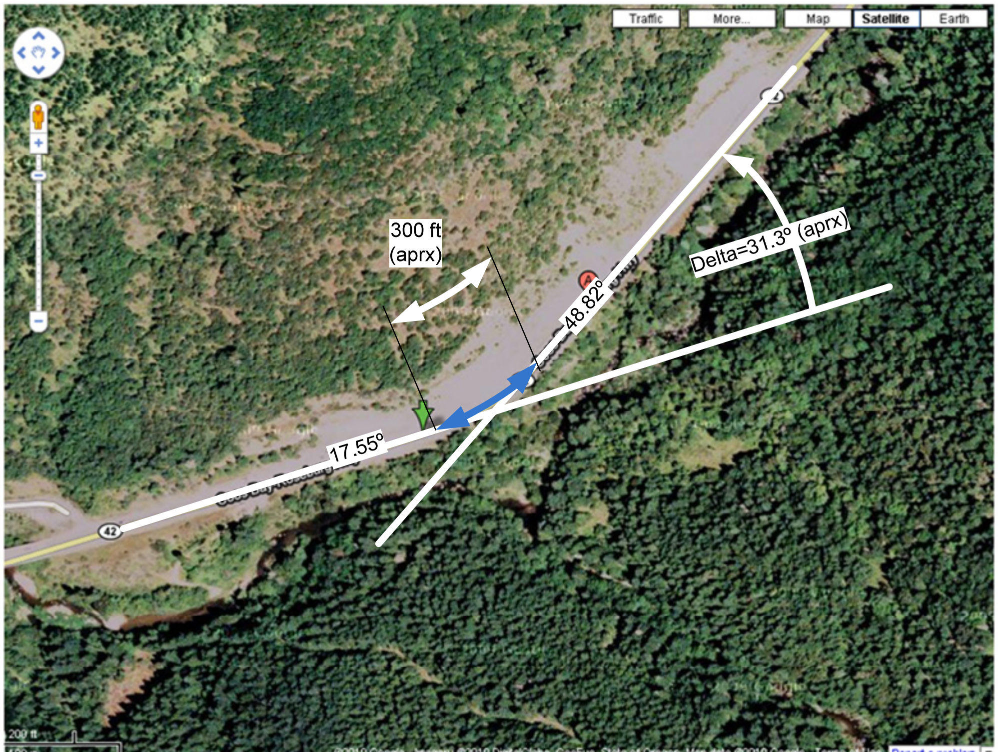


Figure F.2: Deflection Angle and Curve Length Estimation

The Horizontal Radius may be estimated using Equation F.1. In this particular case, Δ=31.3º, L=300 ft and then the radius is approximately 550 ft.

Equation F.1: Relationship Between Radius, Length, and Deflection Angle (F-1)

$$R = \frac{360 \times L}{2\pi\Delta}$$

The superelevation may be estimated from Table 5-3 of the Oregon Highway Design Manual (Oregon HDM, page 5-17). The design superelevation value should be 11 percent. However, because of the rough approximation that results from estimating the radius from an image, it is possible that the value may be overestimated or underestimated. Assuming that the true horizontal radius could be as small as 450 ft or as large as 650 ft, the corresponding superelevations could be 11.5 percent or 11 percent. The analyst should determine if the superelevation value obtained from the Oregon HDM is reliable. The analyst should do this based on his or her confidence in the available radius estimate (resulting from the deflection angle and curve length variables in this case). The analyst should perform the analysis in this example for any values of radius and superelevation that are likely for the study site. If considered necessary, the analyst may perform a quick field visit to measure the actual curve length and the superelevation.

To provide a sense of how accurate an estimate for the radius results from the image analysis, the research team also used a higher resolution image and performed a deeper image analysis considering the possibility that the curve might have spiral transitions. The radius estimate determined using a more in depth analysis was determined to be 570 ft, very similar to the previously estimated 550 ft. Figure F.3 displays the graphic analysis by which the research team obtained the new radius estimate. Because this new estimate is very similar to the first one, the research team considers that the simpler method described above should be sufficient for radius estimation.

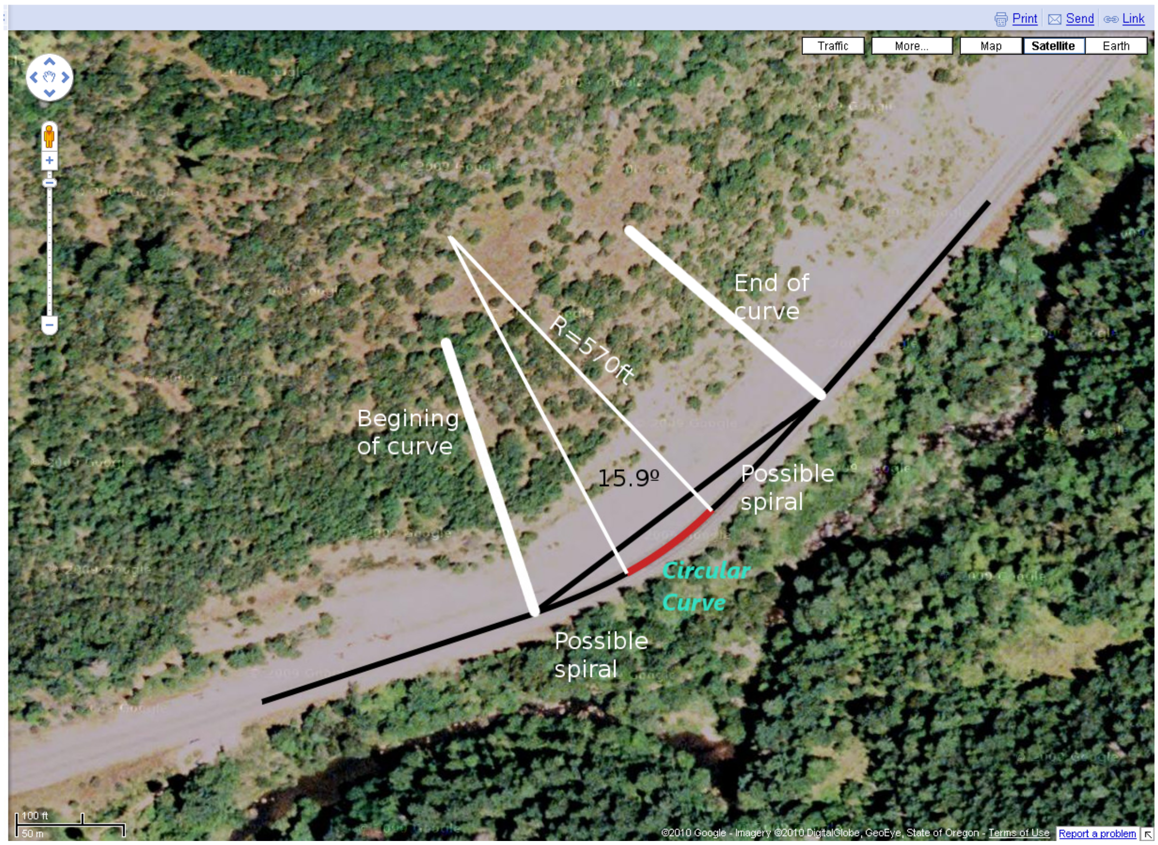


Figure F.3: Second Radius Estimate from a Further Image Analysis

Table F.1 depicts the calculated values required to obtain values for ASD and SFD (shown in the fifth and sixth columns respectively). The final column in the table is estimated directly from Figure F.4. This figure shows the location of the first three ASCF values in Table F.1. The recommended advisory speed is determined by choosing the advisory speed identified in Table F.1 based on the smallest calculated ASCF value. In this case, the recommended advisory speed is 40 mph (shown in bold type in the table).

Table F.1: Sample Calculations to Obtain the ASCF

Radius (ft)	Superelevation (%)	Speed limit (mph)	Advisory Speed (mph)	ASD (mph) = Speed Limit - Advisory Speed	SFD= (Advisory Speed)^2/ (15xRadius) - SE/100	Approximate ASCF (from Figure)
550	11	55	45	10	0.135	1.45
550	11	55	**40**	15	0.084	1.35
550	11	55	35	20	0.038	1.9
550	11	55	30	25	<0.0	3.5
550	11	55	25	30	<0.0	>3.5
550	11	55	20	35	<0.0	>>3.5

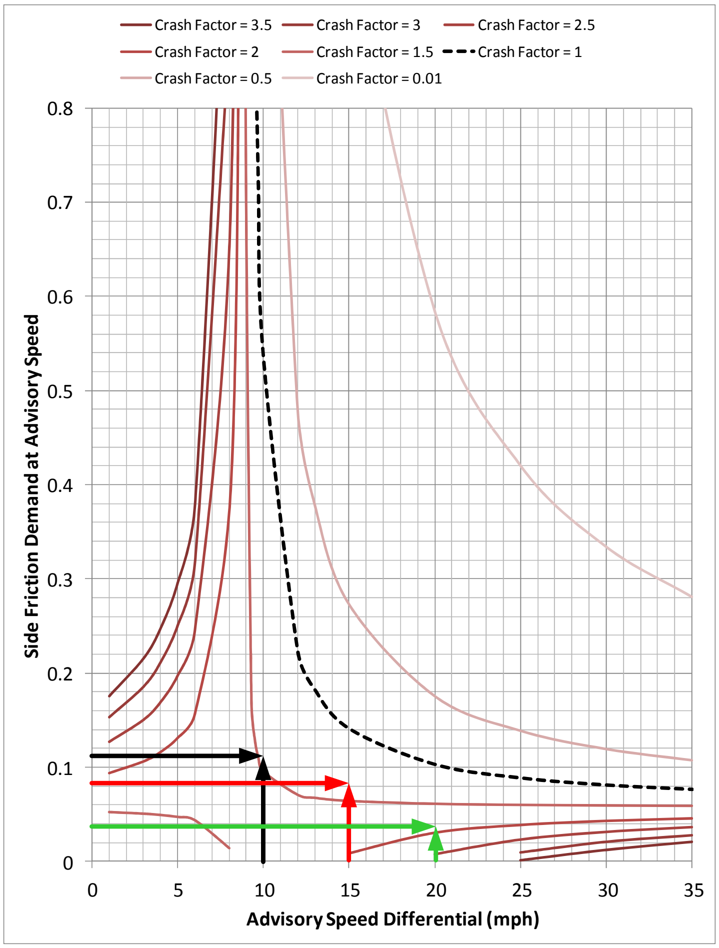


Figure F.4: Example Use of ASD:SFD Safety Relationship Contours

It is important to mention again that the calculations presented in Table F.1 should be repeated for a superelevation of 11.5 percent if the analyst believes that the value obtained from Table 5-3 of the Oregon HDM may differ from the actual site superelevation value.

Additionally, the analyst should notice that this method results in the same advisory speed independent of the direction of travel. Calculations could be modified if further information about different approach speeds at different directions of travel is available. For instance, if the 85th percentile speed is known, a slight correction of the speed limit might be made to the above calculation. The advisory speed resulting from such a modification is likely to remain unchanged or increase by a small amount (increases larger than 5 mph are extremely unlikely).

Table F.2 shows calculations similar to Table F.1 for a superelevation of 11.5 percent. These additional calculations are recommended, since the value obtained from Table 5-3 of the Oregon HDM may differ from the actual superelevation constructed at the site.

Table F.2: Sample Calculations to Obtain the ASCF for a Superelevation of 11.5 Percent

Radius (ft)	Superelevation (%)	Speed limit (mph)	Advisory Speed (mph)	ASD (mph) = Speed Limit - Advisory Speed	SFD= (Advisory Speed)^2/ (15xRadius) - SE/100	Approximate ASCF (from Figure)
550	11.5	55	45	10	0.130	1.5
550	11.5	55	40	15	0.079	1.4
550	11.5	55	35	20	0.033	2.0
550	11.5	55	30	25	<0.000	3.5
550	11.5	55	25	30	<0.000	>3.5
550	11.5	55	20	35	<0.000	>>3.5

Table F.2 shows that the recommended advisory speed is still 40 mph for a superelevation of 11.5 percent. At this point, it is feasible to identify the recommended advisory speed for this site without a required field visit. However, the research team recommends a more thorough sensitivity analysis, since these procedures do not included field data. Such an analysis and a computer tool to perform it in an easy and convenient manner are described in the next section.

F.2 ADVISORY SPEED ESTIMATION AND SENSITIVITY ANALYSIS BASED ON A SPREADSHEET

In order to provide ODOT with a tool to thoroughly and easily determine recommended advisory speeds, the research team prepared a spreadsheet that includes the computations shown in the previous section for various superelevation and radii values. The superelevations in the spreadsheet differ from each other by one percent. The spreadsheet computes three values above and three values below the available superelevation estimate. Additionally, the spreadsheet includes calculations for a radius that is 90 percent the value of the available estimate and for a radius that is 110 percent the value of the available estimate. The spreadsheet allows the analyst to modify these percentages as he or she may consider it necessary. Using these results, the analyst may easily determine whether or not a field visit would be necessary, given the confidence he or she has on the available radius and superelevation estimates.

Figure F.5 shows the spreadsheet interface and the resulting advisory speeds.

OSU METHOD TO DETERMINE ADVISORY SPEEDS IN OREGON

INPUT PARAMETERS

Speed Limit (mph)	Radius (ft)	Superelevation
55	550	11

Max SFD	0.25
Minimum Radius Factor	0.9
Maximum Radius Factor	1.1

		MATRIX OF RECOMMENDED ADVISORY SPEEDS		
		Radius		
Radius factor x		0.9	1.0	1.1
		495 ft	550 ft	605 ft
SE	8%	40 mph	40 mph	40 mph
	9%	40 mph	40 mph	40 mph
	10%	40 mph	40 mph	40 mph
	11%	40 mph	**40 mph**	45 mph
	12%	40 mph	40 mph	45 mph
	13%	40 mph	45 mph	45 mph
	14%	40 mph	45 mph	45 mph

		MATRIX OF SFD AT RECOMMENDED ADVISORY SPEED		
		Radius		
		495 ft	550 ft	605 ft
SE	8%	0.135	0.114	0.096
	9%	0.125	0.104	0.086
	10%	0.115	0.094	0.076
	11%	0.105	**0.084**	0.113
	12%	0.095	0.074	0.103
	13%	0.085	0.115	0.093
	14%	0.075	0.105	0.083

FigureF.5: Spreadsheet for Use of the OSU Method to Determine Advisory Speeds

The three input parameters required in the spreadsheet are speed limit (in mph), radius (in ft), and superelevation (in %).

The first matrix shows the recommended advisory speeds at different combinations of superelevations and radii. The second matrix displays the SFD values that would result from driving the curve at the advisory speeds shown in the first matrix.

The spreadsheet also includes three parameter cells that the analyst should avoid modifying unnecessarily. The Max SFD value bounds the recommended advisory speeds in the spreadsheet to values that result in SFDs smaller than or equal to the value in this cell. The research team considers that 0.25 is a safe parameter and thus recommends using this value. The cells that form the minimum and maximum radius factors allow the analyst to vary the smaller and larger radii for which estimates are presented in the spread sheet. By default, these values are set at plus and minus 10 percent of the value in the radius cell.

In the particular example of Section F.1, the advisory speed would be 40 mph for most combinations of radii and superelevations shown in Figure F.5. However, the advisory speed would be 45 mph only in case that the true superelevation is 13 percent or larger, or if the true radius is approximately 605 ft or larger. Considering a strict interpretation of this sensitivity analysis, a field visit would be recommended because the appropriate advisory speed may be 45 mph if the true radius is slightly larger than the one estimated from the satellite image. However, it appears unrealistic from the scale of the satellite image that the radius estimate might be smaller than the actual radius by such a large value (55 ft as shown in the first matrix of Figure F.5). The analyst, therefore, may safely determine that the advisory speed is 40 mph in this case.

F.3 SUMMARY OF ADVISORY SPEED ESTIMATION BY THE OSU METHOD

Section F.1 demonstrates the required calculations in order to determine advisory speed using the OSU Method. Section F.2 demonstrates the use of a spread sheet to perform such calculations for a range of possible superelevation and radius values, so as to present the analyst with a sensitivity analysis of the impact in the recommended advisory speed that would result from inaccurate radius or superelevation estimates.

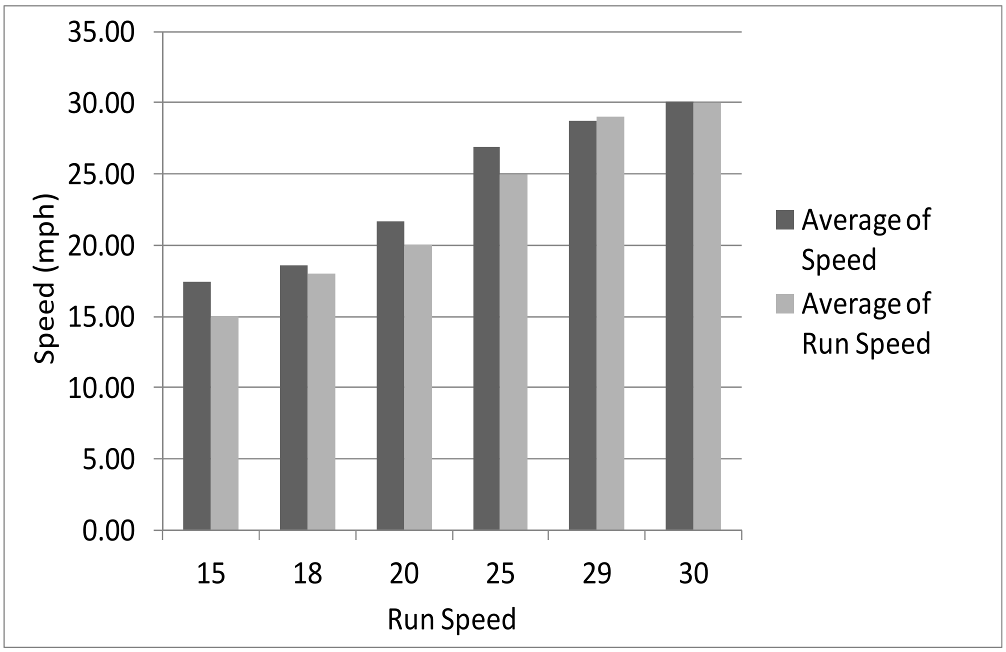
In practice, the tools the analyst needs to use the OSU Method are satellite images, Table 5-3 from the Oregon HDM, and the spreadsheet provided by this research (the spreadsheet is not strictly necessary, the ASCF values required by the OSU Method may be estimated from a copy of Figure 5.38 from this report). The advisory speed may be determined without a field visit if the analyst determines that the recommended advisory speed does not vary for a likely range of radius and superelevation values.

A test for 20 randomly selected sites from this research suggests that the use of the OSU Method yields advisory speeds that do not differ more than 5 mph from the currently posted advisory speeds. However, the advisory speeds determined by the OSU Method are based on the expected safety performance of the site, not on the notion of discomfort that is implied by using the ball-bank indicator method. Additionally, the ball-bank indicator approach results in reading variations that require repeated measurements in the field. The OSU Method only requires reliable speed limit, radius and superelevation estimates to produce recommended advisory speeds that are neither too slow nor too fast from the safety performance point of view.

APPENDIX G:
SPEED DEVICES CALIBRATION

The research team placed all eight speed devices in a row at a parking lot and drove a vehicle with cruise control at preset (approximate) speeds. Due to space constrains, it was not possible to drive faster than 30 mph, so the test speeds were 15, 18, 20, 25, 29 and 30 mph.

Figure G.1 shows a comparison between the run speeds and the speeds obtained from the devices. Although the match is acceptable, a trend is noticeable: the devices tend to give values larger than the actual speeds at the slower runs (from 15 mph through 25 mph). The manufacturer of the devices warns about accuracy issues at speeds lower than 17 mph, but the research team found that accuracy may be a concern at speeds up to 25 mph.



FigureG.1: Average Measures Speed and Run Speed

Figure G.2 shows the average error at different programmed speeds. In general, the performance improved at speeds greater than 25 mph, where average errors were less than 0.5 mph. Another relevant trend from this figure is that the programmed speed appears to alter the results (the devices require the user to program an expected average speed, and the user manual claims that this may affect the results). In this particular test, the programmed speed of 35 mph performed better than the programmed speed of 25 mph.

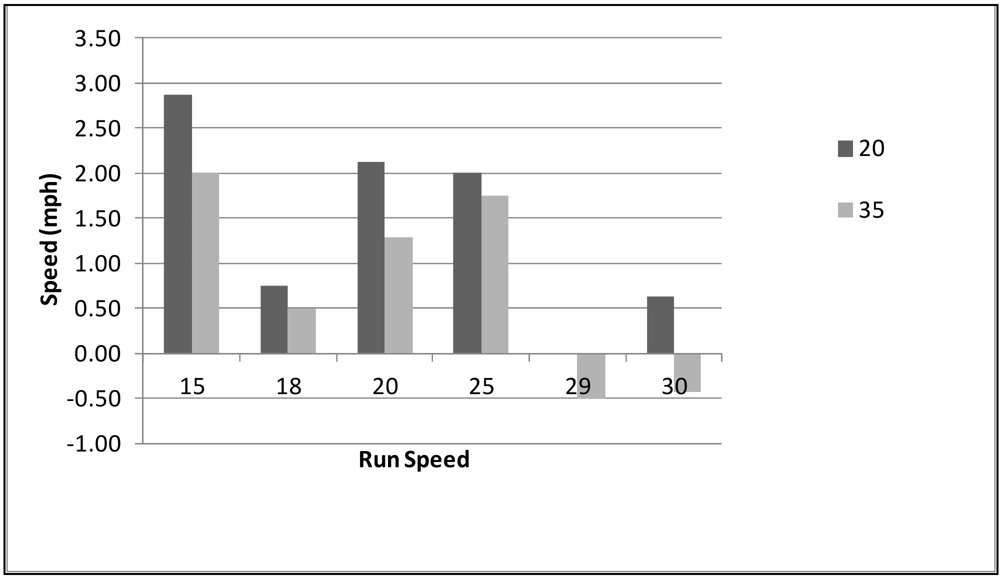


Figure G.2: Average Error by Programmed Speed and Run Speed

To estimate the standard error inherent to the device electronics, the research team performed an Ordinary Least Squares regression on the readings. The results are shown in Figure G.3. The estimate for the standard error is 1.13 mph, (based on 144 degrees of freedom). This number is very close to the 1.0 mph that the research team assumed in the sampling design. However, the research team recognizes that a large range of speeds were not included in the calibration tests, so the standard error may vary at such speeds.

Additionally, the research team found that some of the devices exhibit a behavior that was captured as statistically significant: devices 683, 181 and 688. These devices may be identified in Figure G.4 as the best performing and the two worse performing devices. Since the research team randomized the device placement during the field speed studies for this project, the effect of these devices is not expected to affect the computed statistics since such effect would appear as white noise variation in the overall sample.

The research team concludes, from this calibration test, that the devices are acceptably accurate for this research. Although the research team found accuracy deviations at different speeds, the differences resulting from such trends are not relevant when producing speed statistics, even for such a small range of speeds as evaluated in this test. The research team performed an ANOVA on the speed readings accounting for individual devices. The results indicate that there is no significant difference among the devices when comparing the average speed readings they produce (p-value of 0.8449 from an F-statistic of 0.4842 on 7 and 144 d.f.).

```
Call:
lm(formula = Speed ~ Run.Speed + Prog..Speed + Dev683 + BadDev
+
    Break.Lights + Run.Speed:Dev683 + Prog..Speed:BadDev, data
= Data,
    sorted = TRUE)

Residuals:
      Min        1Q    Median        3Q       Max
-2.720119 -0.847712  0.005589  0.697219  2.343293

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)         6.13809    0.59281  10.354  < 2e-16 ***
Run.Speed           0.83820    0.01872  44.785  < 2e-16 ***
Prog..Speed        -0.05082    0.01578  -3.221  0.00158 **
Dev683             -3.35869    1.17059  -2.869  0.00473 **
BadDev             -0.06586    0.82180  -0.080  0.93624
Break.Lights        0.57997    0.33956   1.708  0.08979 .
Run.Speed:Dev683    0.11911    0.05091   2.339  0.02069 *
Prog..Speed:BadDev  0.04268    0.02927   1.458  0.14705
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.128 on 144 degrees of freedom
Multiple R-squared: 0.9497,     Adjusted R-squared: 0.9472
F-statistic: 388.2 on 7 and 144 DF,  p-value: < 2.2e-16
```

Figure G.3: Computer Output for OLS Regression on Speeds

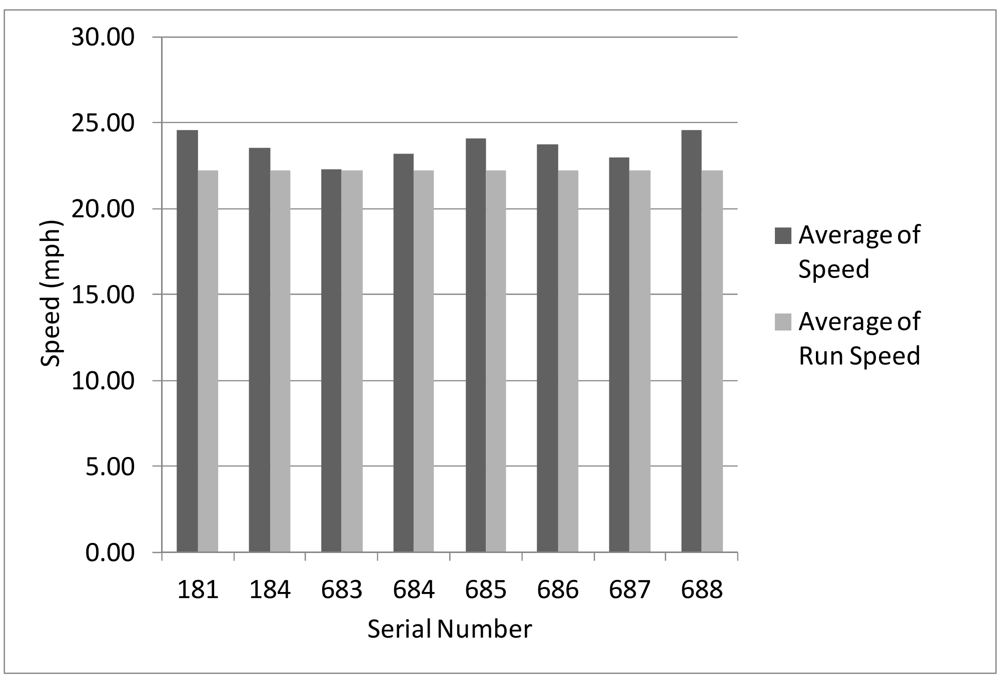


Figure G.4: Average Speed and Average Run Speed by Device Serial Number