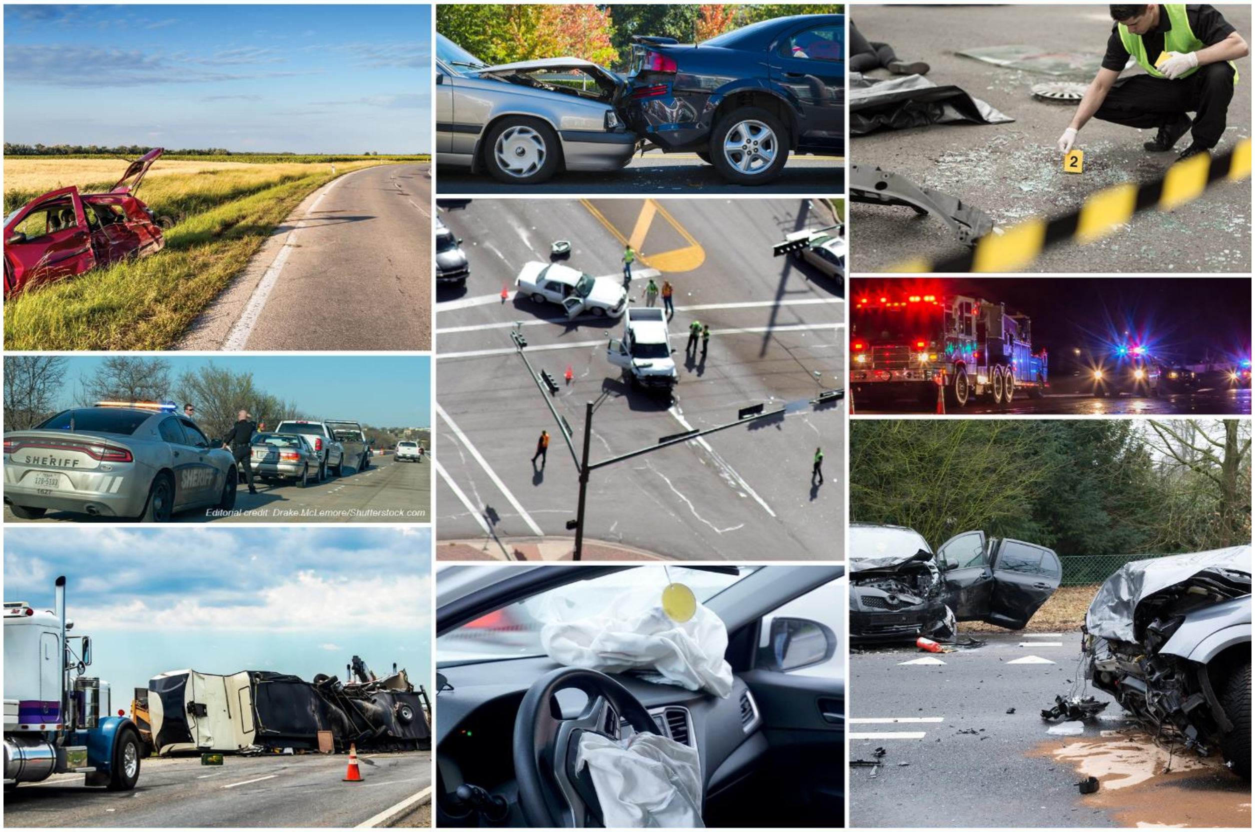
Data-Driven Safety Analysis:

A User Guide



Texas Department of Transportation

Texas A&M Transportation Institute

DATA-DRIVEN SAFETY ANALYSIS: A USER GUIDE

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Robert C. Wunderlich, P.E. #60467.

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Acronyms

AADT	average annual daily traffic
ADT	average daily traffic
B/C	benefit to cost
CMF	crash modification factor
CRIS	Crash Record Information System
HFST	high-friction surface treatment
KA	fatal and suspected serious injury crashes
KABC	fatal and all injury crashes
KABCO	all total crash severities
PDP	project development process
PFC	permeable friction course
SPF	safety performance function
SVROR	single-vehicle run-off-the-road crashes
TxDOT	Texas Department of Transportation
VMT	vehicle-miles traveled

Glossary

Benchmark—a crash level used for comparison purposes to determine if a segment or intersection crash level is greater than average. A benchmark is based on the predicted number of crashes for a given level of traffic volume.

Crash modification factor (CMF)—a measure of the safety impact of a particular roadway treatment or design element.

Expected crashes—the number of crashes expected to occur in a given period of time after adjusting for the random variation in crashes based on a statistical combination of predicted and observed crashes.

Exposure—a measure of travel. The typical unit of measurement used in crash analyses is vehicle-miles traveled (VMT).

Indexing—a graphing technique where the values of frequency of crashes over time are shown relative to the value of the initial time period.

Observed crashes—the number of actual crashes recorded for a given time period.

Predicted crashes—the number of crashes for a given period of time predicted by a safety performance function for any given traffic volume.

Risk—the likelihood of a crash, is expressed as crashes per VMT.

Risk factor—roadway characteristics associated with the likelihood of crash occurrence.

Safety performance function (SPF)—a statistically derived equation that estimates (or predicts) the number of crashes per year likely to occur on a roadway, or in an intersection, for a given traffic volume level.

Screening—identifying the level of potential safety improvement on roadway segments or intersections by comparing expected crashes to predicted crashes.

Systemic approach—identifying locations for safety improvements by assessing the likelihood that crashes of a particular type will occur based on the level of risk factors at that location.

Introduction

Purpose

The purpose of this guide is to demonstrate how to use data-driven safety analyses to improve safety on Texas Department of Transportation (TxDOT) roadways.

Sections

- **Describing** TxDOT district safety issues.
- **Screening** the network to identify locations with potential for safety improvement.
- **Prioritizing** targeted categories of safety improvements.
- **Integrating** safety into the project development process.

Green boxes with this icon denote information that relates to the specific safety tools included in the accompanying Safety Spreadsheet Toolkit.

Describing TxDOT District Safety Issues

Purpose

The first step in a data-driven approach to safety is to use descriptive statistics and graphics to understand the overall nature of crashes within a district. The purpose of this section is to understand the prevalent trends and types of crashes and how they relate to the state system of roads within the district.

Providing Context Is Important

It is important to give these descriptive statistics context, when possible, as a means of comparison. Examples include comparisons between road types, crash types and severities, first harmful events, and counties in the district. Furthermore, comparing these characteristics to the rest of Texas or selected other districts may be instructive.

Crashes = Exposure × Risk

Exposure is a measure of travel, and the typical unit of measurement used in crash analyses is vehicle-miles traveled (VMT). TxDOT maintains estimates of VMT for all counties and districts.

Risk is the likelihood of a crash and is expressed as crashes per VMT. Different types of crash severities, roads, vehicles, or drivers could have different crash risk rates.

Visualization through Graphing

Preparing graphs to display descriptive statistics can be a powerful tool to help understand the nature and trends in traffic crashes.

In This Section

This guide provides five example graphs that can help the district understand crash issues:

- Crash trend graphs.
- Indexed trend graphs.
- Crash trees.
- Proportional bar graphs.
- Comparison bar graphs.

Crash Trend Graphs

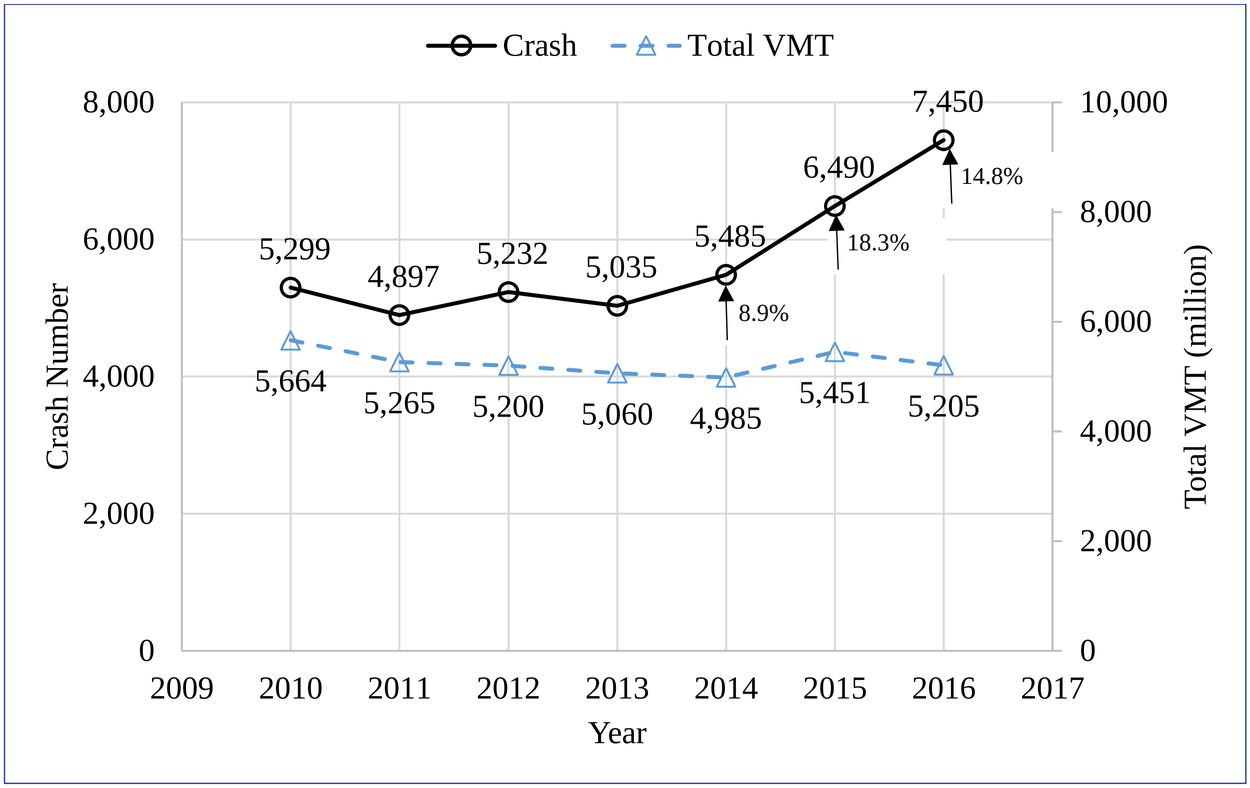


Figure 1. All Crashes on System Roadways Compared to Trends in VMT in the Beaumont District from 2010 to 2016.

What This Graph Indicates

After a period where crashes rose and fell slightly around 5,000 per year from 2010 through 2013, crashes began to rise each of the next three years. These crashes rose more dramatically than the associated growth in VMT. This indicates that risk increased in the district.

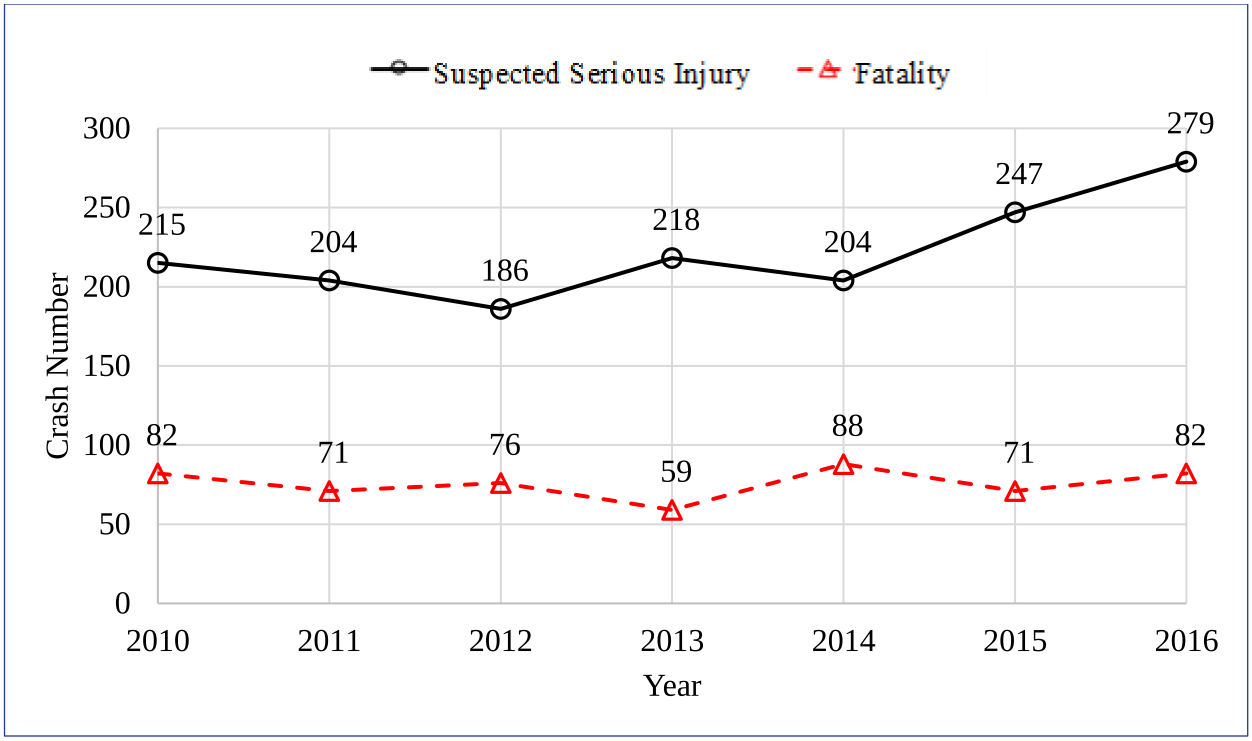


Figure 2. Trends in Fatal and Suspected Serious Injury Crashes in the Beaumont District from 2010 to 2016.

What This Graph Indicates

Fatalities were relatively stable during the entire period, but the trend of suspected serious injuries increased, similar to the trend in total crashes (given in Figure 1).

Indexed Trend Graphs

It can also be instructive to use *indexed* graphs to compare trends. In indexed graphs, values for the frequency of crashes over time are shown relative to the value in the initial year. Indexing eliminates the need for two different vertical axes as shown in Figure 1.

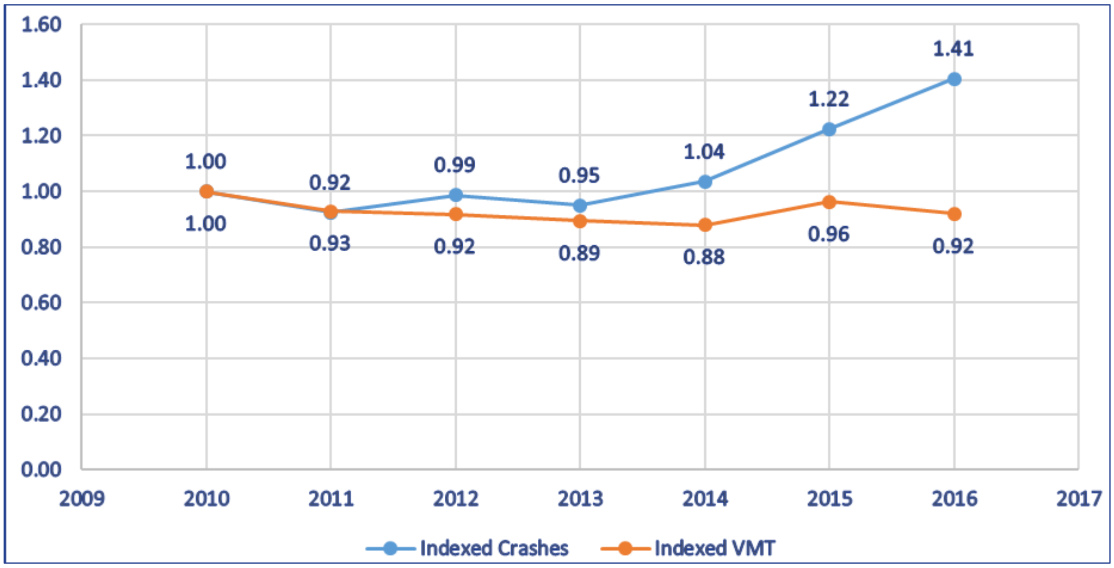


Figure 3. Indexed Version of Figure 4.

How This Graph Was Developed

Crash and VMT values are divided by the values in 2010. The base value for crashes is 5,299. Dividing each year's crashes by 5,299 produces an indexed value for each year.

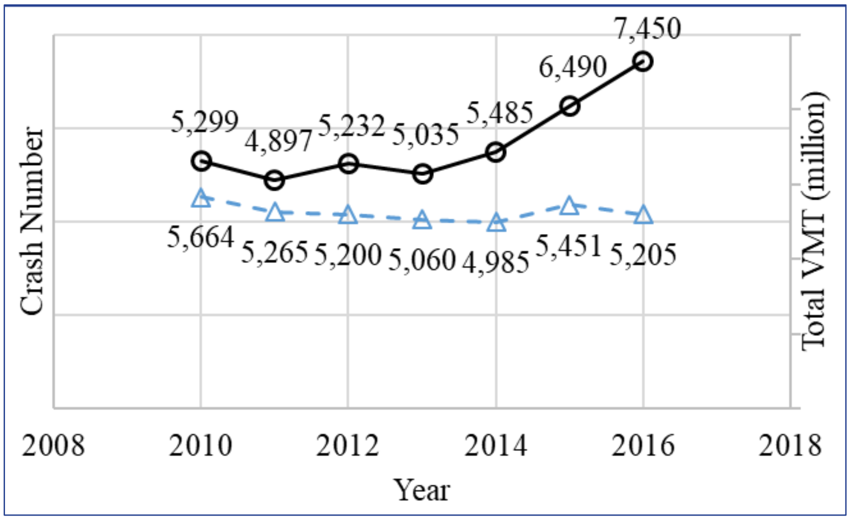


Figure 4. Base Graph for Figure 3 Indexed Graph.

Deriving Percent Change

Indexing also indicates the percentage change from the initial value. For example, crashes in 2016 increased by 41% (index value of 1.41) from their level in 2010, whereas VMT was 8% less (index value of 0.92) than 2012 as shown in Figure 3.

Why Indexed Graphs Are Useful

Indexed graphs may be particularly useful for comparisons between a district and the state because the raw number of crashes may differ by an order of magnitude and may be greater only because the amount of exposure, VMT, is greater and not necessarily the crash risk. Figure 5, Figure 6, and Figure 7 depict such comparisons.

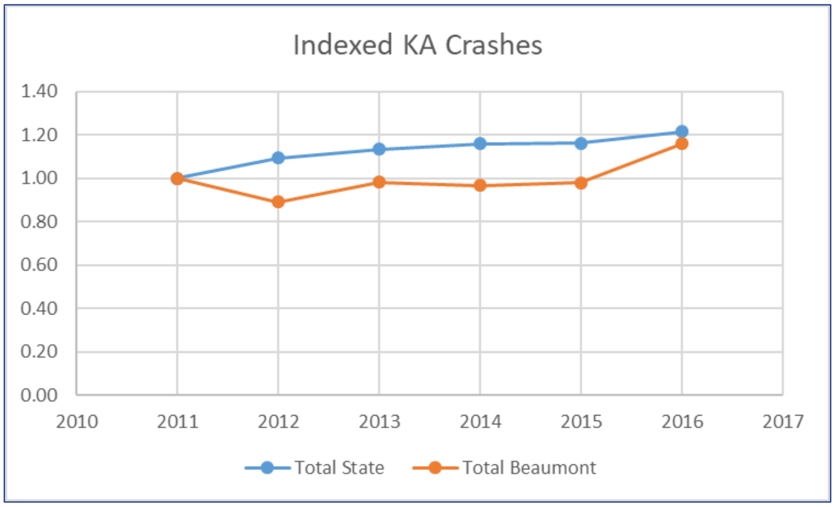


Figure 5. Indexed Fatal and Suspected Serious Injury Crashes.

What This Graph Indicates

Crashes in the Beaumont District were quite stable from 2010 to 2015 during the time that the state experienced increasing crashes. Then in 2015, crashes rose in Beaumont to nearly match the percentage increase of the state.

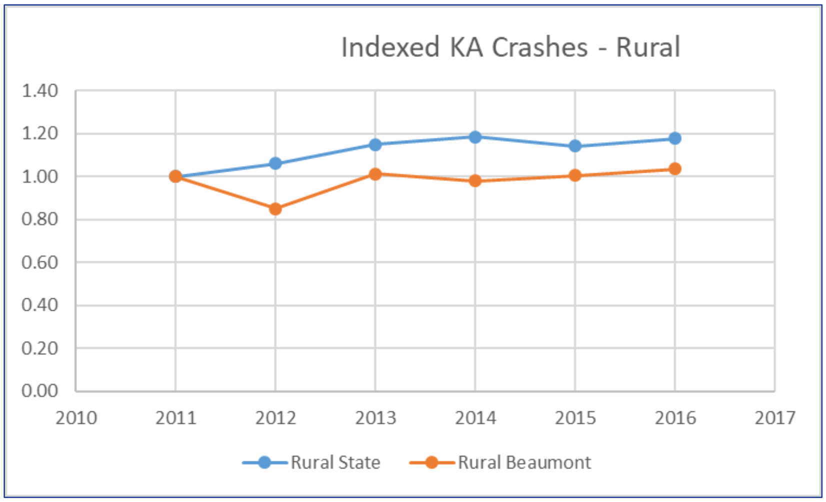


Figure 6. Indexed Fatal and Suspected Serious Injury Crashes in Rural Areas.

What This Graph Indicates

Rural crashes in the Beaumont District have changed very little since 2013, given that the index is very close to 1.00.

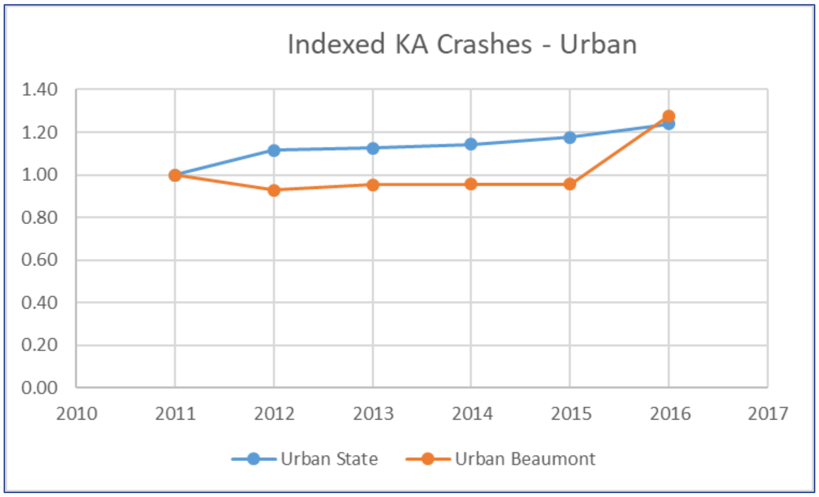


Figure 7. Indexed Fatal and Suspected Serious Injury Crashes in Urban Areas.

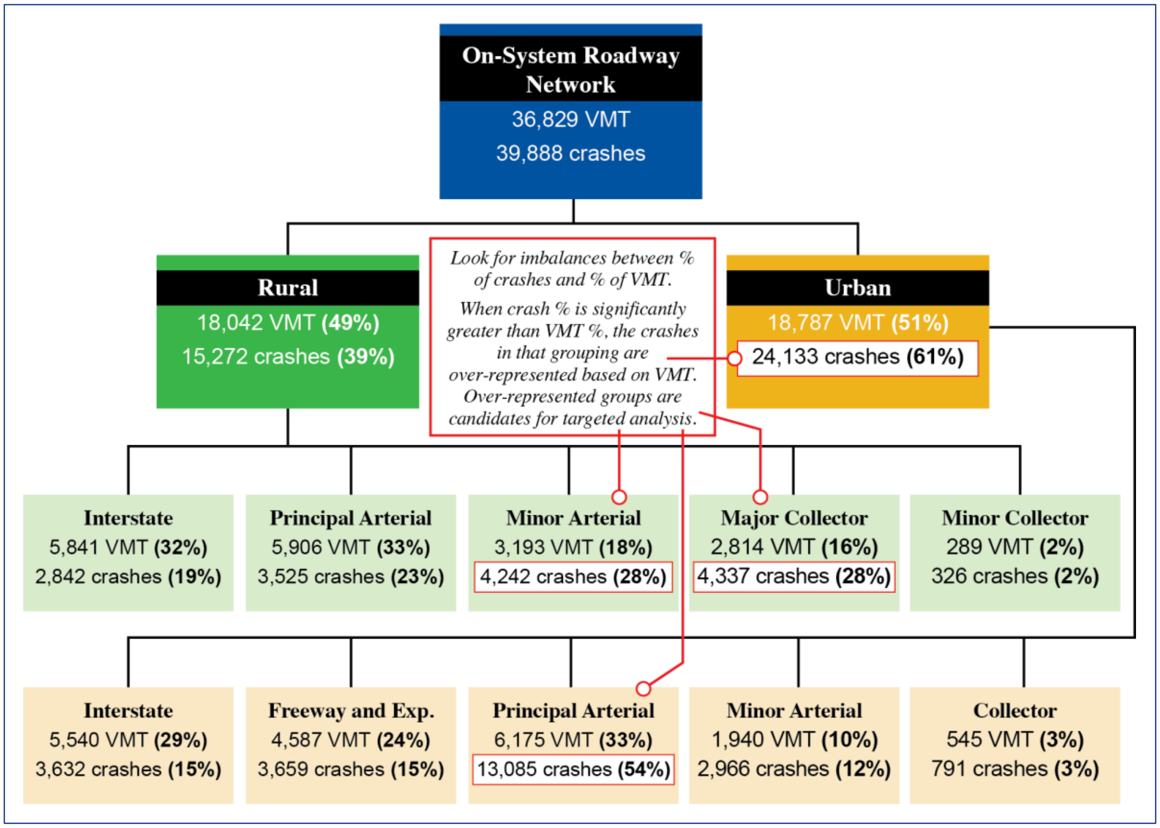
What This Graph Indicates

An increase in urban crashes is the reason the relative increase in crashes in the Beaumont District equaled the state increase by 2016.

Crash Trees

Crash trees offer a method to drill down into crash characteristics by roadway classification, functional type, area type (rural and urban), and crash types or characteristics. They can provide a big-picture view of crash issues and help the analyst identify focus areas.

Figure 8 divides the roadway network into rural and urban segments and then by highway functional classifications. The proportions of VMT and crashes are reported for each cell. This allows a comparison between them.



Notes: VMT = vehicle-miles of travel in a seven-year period (2010–2016), and the unit is in millions. There are 483 crashes with unknown rural or urban status.

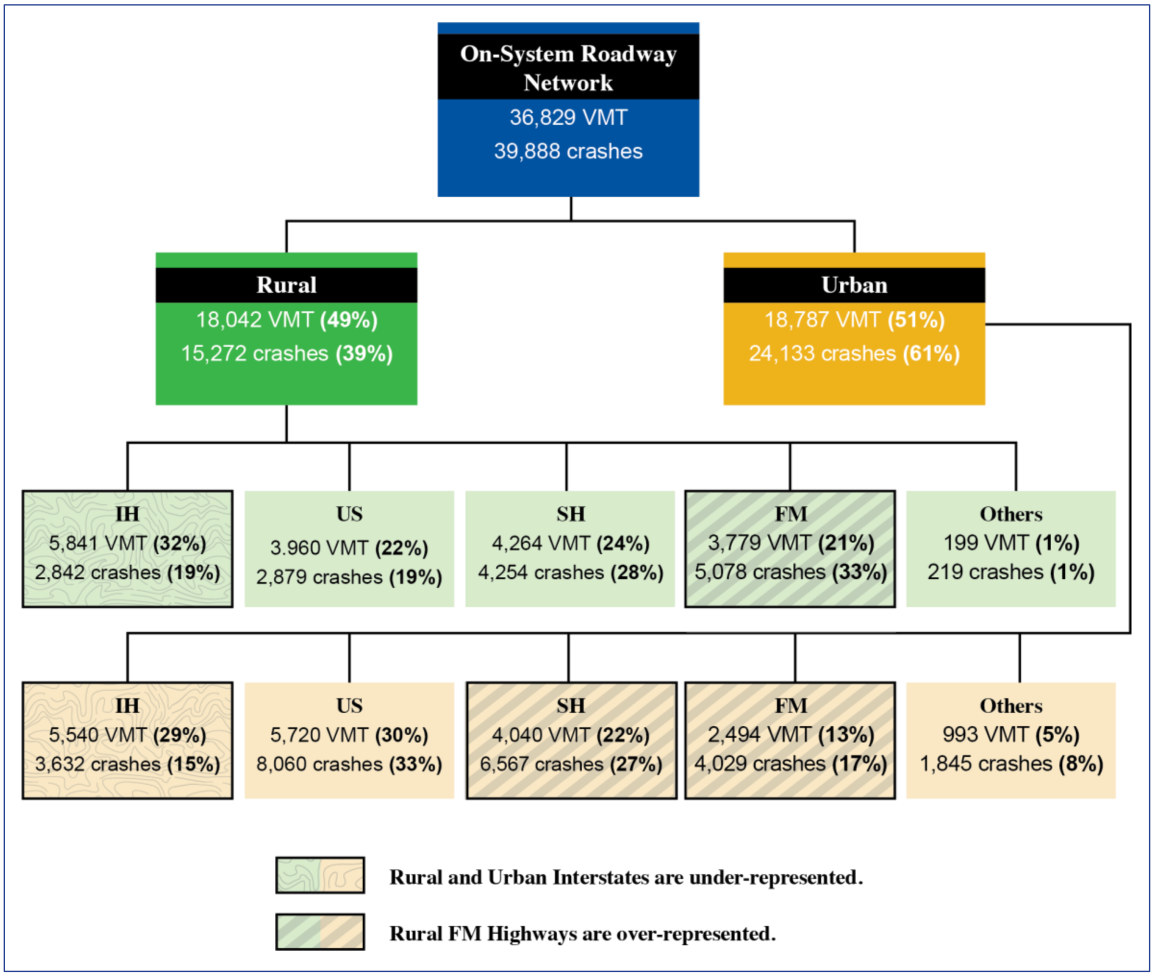
Figure 8. Crash Tree of VMT and Crashes Reported for Rural and Urban Segments, and Highway Functional Classifications.

What This Graph Indicates

These classifications are overrepresented in terms of crashes compared to VMT:

- Rural minor arterials and major collectors.
- Urban principal arterials.

Figure 9 is similar to Figure 8 except it organizes the rural and urban roadways by *highway designations*. The proportions of VMT and crashes are reported for each cell, which allows a comparison between them.



Notes: VMT = vehicle-miles of travel in a seven-year period (2010–2016), and the unit is in millions; IH = Interstate; US = US Highway; SH = State Highway; FM = Farm to Market. There are 483 crashes with unknown rural or urban status.

Figure 9. Crash Tree of VMT and Crashes Reported for Rural and Urban Segments, and Highway Designations.

What This Graph Indicates

These highway designations are underrepresented in terms of crashes compared to VMT:

- Rural and urban interstate highways.

These designations are overrepresented:

- Rural FM highways.
- Urban FM and state highways (but not to the same degree as rural FM highways).

Figure 10 looks at crashes differently than the first two crash trees (Figure 8 and Figure 9). Rather than comparing VMT to crashes by roadway segment classifications, here the user is interested in understanding how serious crashes are distributed by on- and off-system, rural and urban, intersection and non-intersection, and type of crash.

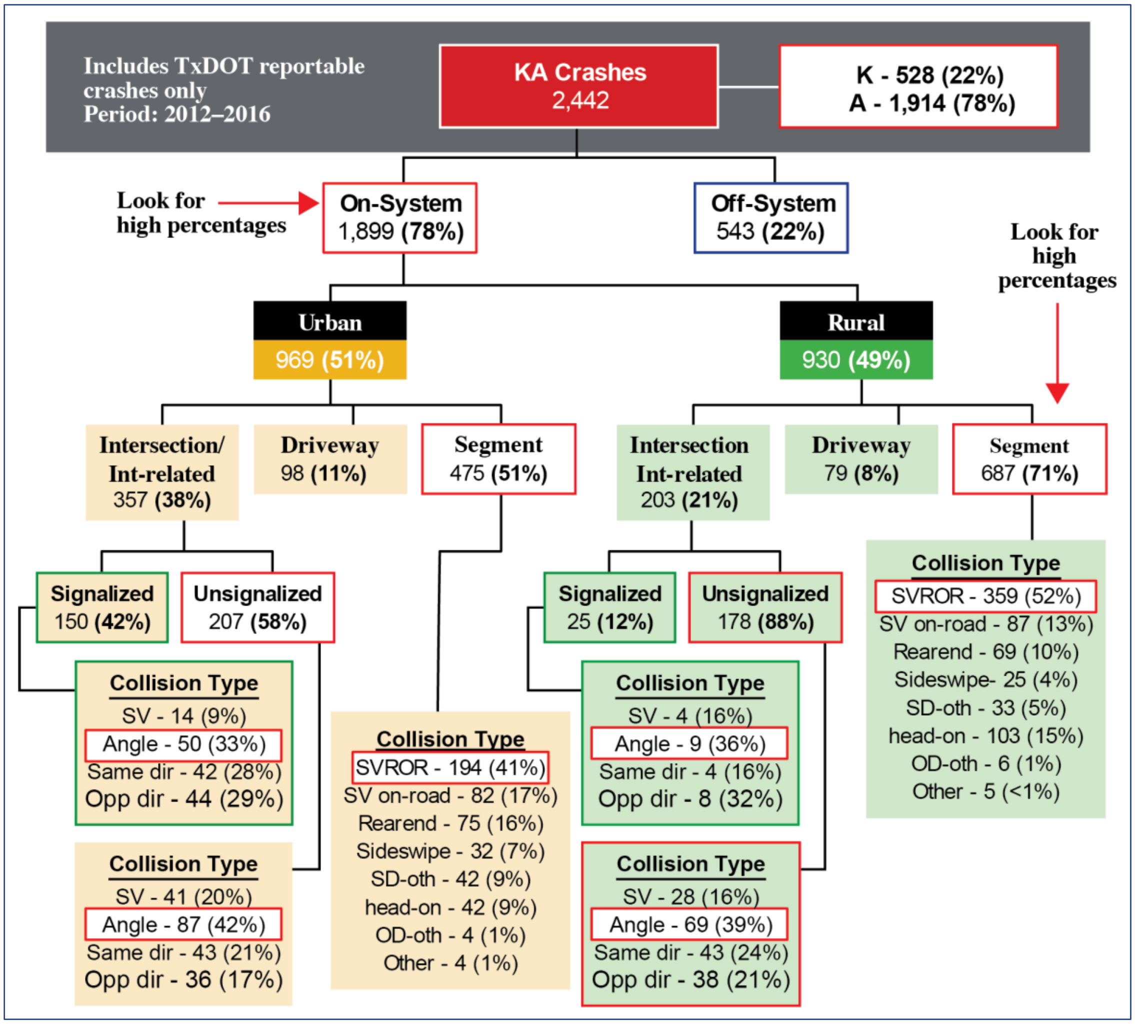


Figure 10. Crash Tree of VMT and Crashes Reported for On- and Off-System, Rural and Urban, Intersection and Non-intersection, and Type of Crash.

What This Graph Indicates

- Most (78%) of fatal and suspected serious injury crashes occur on state highways.
- On-system crashes are split almost evenly between urban and rural areas.
- Most rural crashes occur on segments.
- Single-vehicle run-off-the-road crashes (SVROR) make up significant proportions of rural and urban segment crashes.
- Angle crashes comprise the largest portion of intersections crashes.

Proportional Bar Graphs

The information in crash trees may also be displayed in a way that provides some sense of proportionality in a bar graph. In a proportional bar graph, the length of each bar is proportional to the value it depicts.

Figure 11 describes which system all-severity crashes occur on. The red bar is 70% of the overall bar length, and the blue segment is 30%.

Likewise, in Figure 12, the lengths of the bars describing the on-system urban and rural fatal and suspected serious injury (crashes are proportional to their respective values.

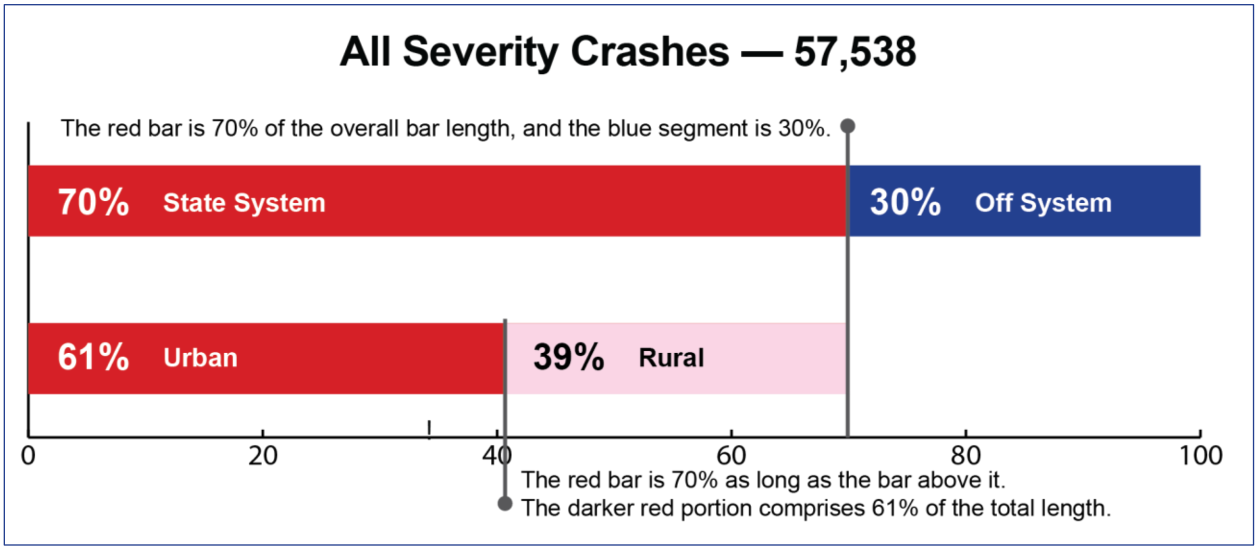


Figure 11. Proportional Bar Graph Showing the Systems Where Crashes Occur.

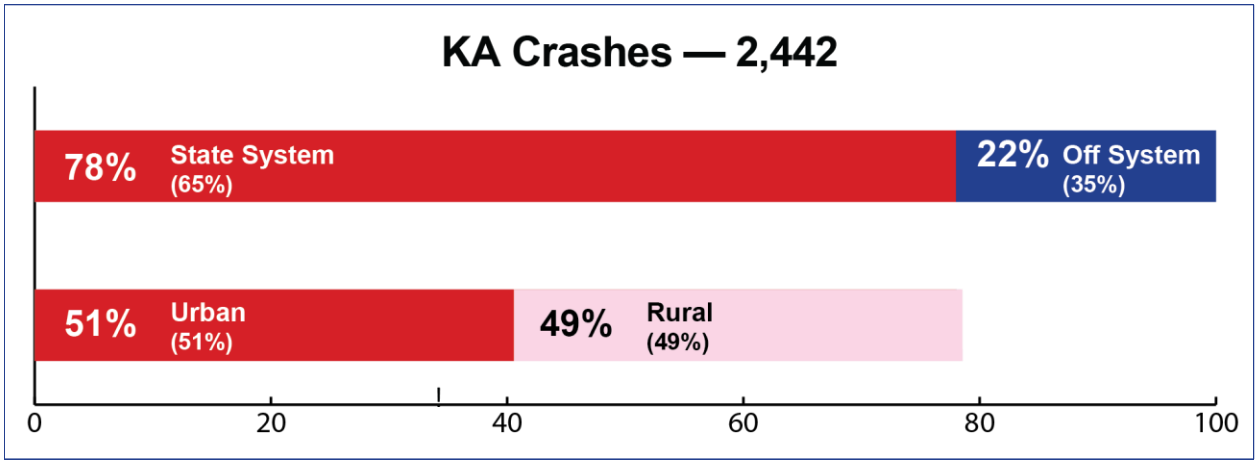


Figure 12. Proportional Bar Graph Showing the Systems Where Fatal and Suspected Serious Injury Crashes Occur.

Comparison Bar Graphs

Bar graphs comparing individual characteristics can help the analyst visualize relative differences and gain insight into crash characteristics.

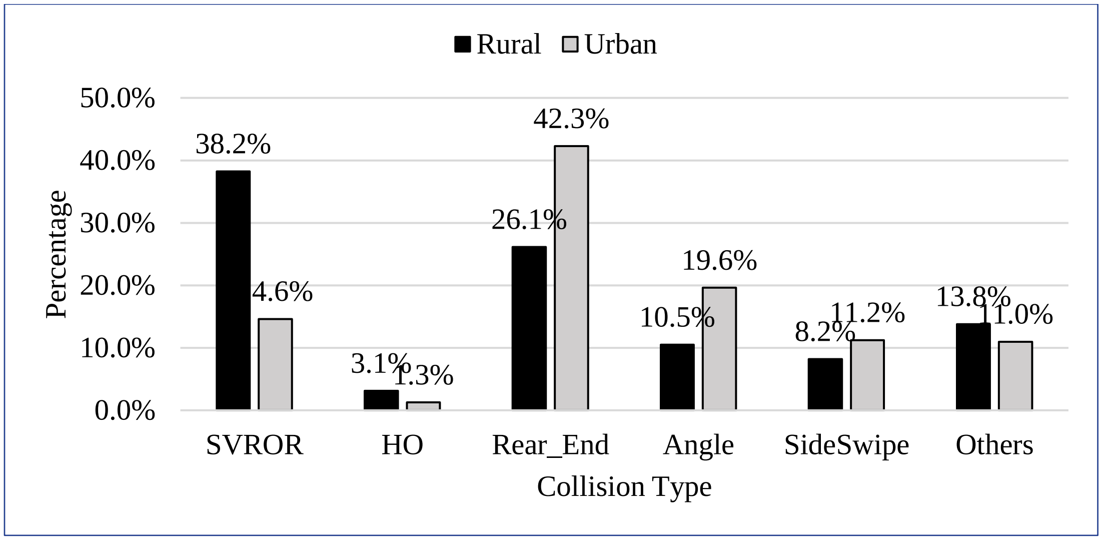


Figure 13. Collision Types on Rural and Urban Roadways.

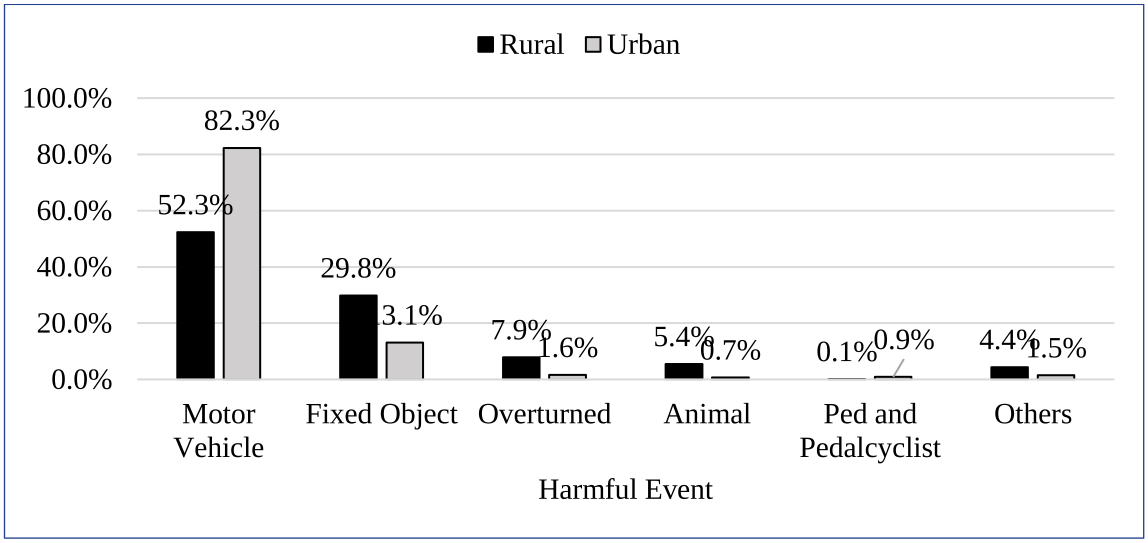


Figure 14. Harmful Events on Rural and Urban Roadways.

What These Graphs Indicate

SVROR crashes, also known as roadway departure crashes and rear-end collisions, are the most common types of collisions on rural roadways. Roadway and lane departure crashes also include head-on and opposite-direction sideswipe crashes.

Rear-end crashes make up a large portion of urban crashes, and angle and sideswipe crashes are also significant.

Most of the urban crashes involve one vehicle striking another, which is much less the case in rural areas.

Screening the Network to Identify Locations with Potential for Safety Improvement

Measuring Potential for Safety Improvement

The potential for improving safety is measured by comparing the safety performance (as measured by the number of crashes) for a roadway segment or intersection against the average safety performance of segments or intersections with similar characteristics.

Establishing Benchmarks

Benchmarks are defined by developing a statistically derived mathematical relationship between traffic volume and crashes for roadway segments and intersections with similar characteristics. These relationships are called safety performance functions (SPFs).

Observed, Expected, and Predicted Crashes

The SPFs, along with recorded crashes, allow establishing the observed, predicted, and expected crashes for a segment or an intersection:

- **Observed crashes:** the number of actual crashes recorded for a given period of time.
- **Predicted crashes:** the number of crashes for a given period of time predicted by the SPF for any given traffic volume.
- **Expected crashes:** the number of crashes expected to occur in a given period of time after adjusting for the random variation in the occurrence of crashes. This value is based on a statistical combination of predicted and observed crashes. Expected crashes are the measure of the safety of a segment or an intersection.

Quantifying Potential for Safety Improvement

The greater the number of expected crashes is than the level predicted by the benchmark, the higher the potential for safety improvement. Likewise, if the number of expected crashes is less than the predicted amount, then the potential for safety improvement is low.

Separating Intersections and Segment Crashes

Typically, the nature of crashes on roadway segments and intersections is quite different, so it is appropriate to screen each condition separately. Therefore, separate benchmarks should be established for intersections and segments.

Roadway Intersection and Segment Database

In order to develop separate benchmarks, it is necessary to first have an inventory of segments and intersections. This inventory does not currently exist for all TxDOT districts. This guide is based on the pilot project in the Beaumont District where such an inventory was created based on data from TxDOT.

Roadway data were obtained from the 2017 Roadway Inventory Annual Report. The procedure for establishing this inventory is a fairly complex task involving the use of geographic information system methods.

Screening Roadway Segments

Grouping Roadway Segments for Analysis

Roadway segments are grouped by several factors so that segments with similar characteristics are compared with one another. Roadway characteristics and traffic volume are the largest determinants of safety performance. Therefore, we want to compare similar roadways and also have a method for considering traffic volume.

Roadway Segment Groupings

Roadway segments can be classified into eight groups based on the following characteristics:

Rural:

- Two lane.
- Multilane undivided.
- Multilane divided.
- Interstate/freeway/expressway mainlanes.

Urban:

- Two lane.
- Multilane undivided.
- Multilane divided.
- Interstate/freeway/expressway mainlanes.

Note: Crashes on freeway and expressway frontage roads are currently assigned to the centerline of the mainlanes. Therefore, it is not possible to assign the crash to the correct frontage road and frontage road segments are not included.

Benchmarking Segment Safety Performance

Separate benchmarks exist for each of the eight groupings. These benchmarks, referred to as SPFs, are equations that relate the crashes per mile per year to the average annual daily traffic (AADT), based on a statistical modeling of several years of crash experience. This average number is referred to as the *predicted number of crashes per mile per year*. Multiplying this by the length of the segment gives the *predicted number of crashes per year*.

Segment Benchmarks by Crash Severity

For each roadway segment grouping, there is a benchmark curve for at least one of the following crash severity combinations:

- Total crashes (KABCO).
- Fatal and all injury crashes (KABC).
- Fatal and suspected serious injury crashes (KA).

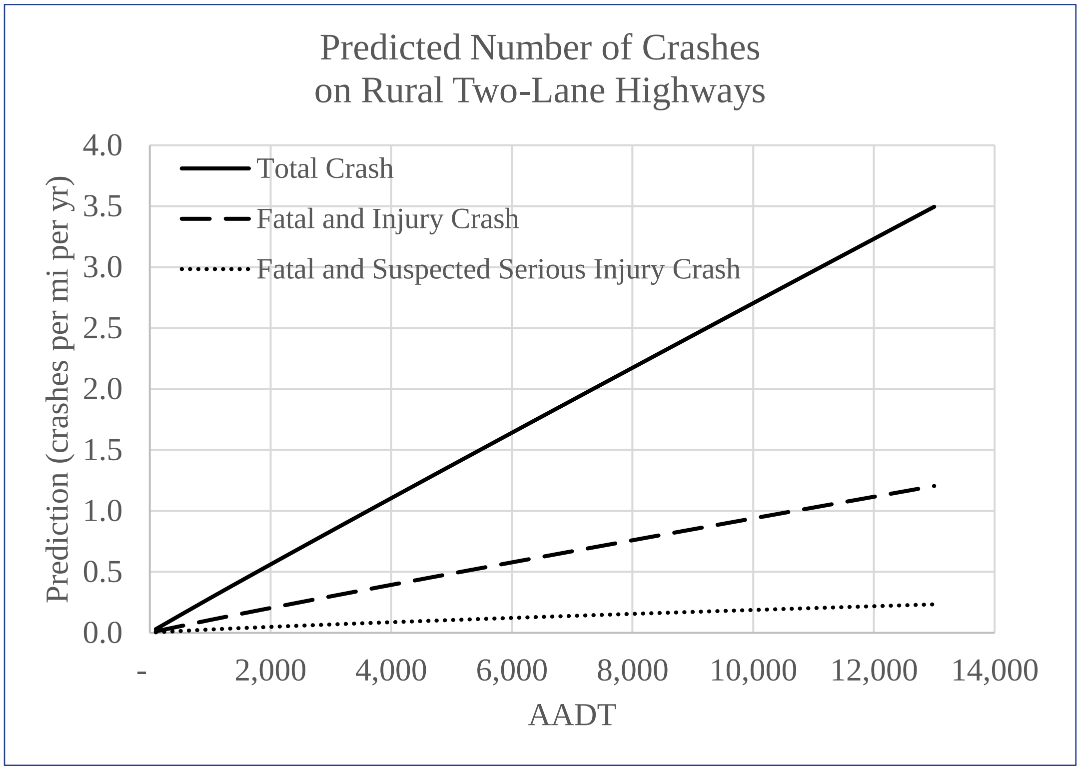


Figure 15. Benchmark Example: Rural Two-Lane Highways.

Crash Severity Classification (KABCO)

Crashes reported in the TxDOT Crash Record Information System (CRIS) are classified using the KABCO system. Crashes are classified by the single most serious injury suffered by any person involved in the crash.

The definitions for the five severity levels are:

- K: fatality.
- A: suspected serious injury.
- B: non-incapacitating injury.
- C: possible injury.
- O: property damage only (non-injury).

What Information Do You Need to Determine Potential for Safety Improvement for Segments?

Determining the potential for safety improvement on any particular roadway segment requires knowing the following information:

- Roadway cross section.
- Freeway or non-freeway.
- Rural or urban setting.
- AADT (or daily volume).
- Number of crashes by severity and years of data.
- Segment length.

Beaumont District Roadway Segment Benchmarks

Appendix A includes equations and graphs of these benchmarks for each of the eight roadway classifications so that the analyst can see how crashes per mile vary by AADT. An example is provided next for two-lane rural roadways.

The Safety Spreadsheet Toolkit includes worksheets for inputting information for any given segment and calculating the difference between the expected and predicted number of crashes to determine the potential for safety improvement. The worksheet also plots the observed, predicted, and expected number of crashes for the segment.

Note: Benchmarks are included for every roadway segment grouping. The spreadsheet tool indicates when caution should be used because the sample size is low.

Worksheet Example for Screening Roadway Segments

Let’s take a 2-mile-long rural two-lane roadway segment and determine the potential for safety improvement. The segment has an ADT of 8,000 vehicles per day and 14 observed crashes in two years.

User Input:

Variable	Selection/Value	Note
Facility Type	Rural Two-Lane	Roadway type
Crash Severity Level	Total	Crash severity
Segment Length (mi)	2.00	Length of the roadway segment (mi)
ADT on the roadway	8,000	Range:100-13,000 vehicles per day
Duration	2	Number of years
Observed	14	Observed number of crashes in 2 years

User Input Area

Choose from the drop-down menu in the blue cells.

Type values in the yellow cells.

Model Output:

Observed	3.50	Observed number of crashes per mi per year
Predicted	2.17	Predicted number of crashes per mi per year
Weight	0.33	Weight factor for predicted number of crashes
Expected	**3.07**	Expected number of crashes per mi per year
Potential for Safety Improvement (Crashes per mile per year)	0.89	Difference between expected and predicted number of crashes per mi per year
Ratio of Expected to Predicted Crashes	1.41	Ratio of expected to predicted number of crashes

Output Area

Observed: The number of crashes per mile per year for the selected crash severity level calculated from the length of the segment, number of years of crash data, and number of crashes of that severity during that period.

Predicted: the benchmark number of crashes per mile per year. The predicted number of crashes is based on a formula derived from fairly complex statistical methods. The toolkit calculator performs this computation.

Weight: the emphasis placed on predicted versus observed crashes to determine the expected number of crashes. In this case the weight is 0.33, so 33% of the expected estimate is based on predicted crashes, and 67% is based on observed crashes. The weight is based on a fairly complex statistical method. The higher the weight factor, the better the data fits the model. The toolkit calculator performs this computation automatically.

Expected: the number of crashes per mile per year expected over the number of years based on observed and predicted crashes. In this case, expected crashes = (0.33 × predicted crashes) + (0.67 × observed crashes) or (0.33 × 2.17) + (0.67 × 3.50) = 0.72 + 2.34 = 3.07 crashes per mile per year.

Potential for Safety Improvement (crashes): The difference between the number of expected and predicted crashes per mile per year. In other words, there would be 0.89 crashes per mile per year less if the segment's safety performance was equal to the benchmark for this type of facility, which equates to 1.78 per year for the 2 mile length (2 x 0.89) = 1.78.

Ratio of Expected to Predicted Crashes: This value, 1.41, provides an indication of the degree to which the expected number of crashes exceeds, or is less than, the benchmark.

The toolkit calculator performs these calculations for the analyst.

Identifying Segments for Safety Improvement

Combining the Potential for Safety Improvement and the Ratio of Expected to Predicted Crashes methods will provide the analyst with the information on the degree to which safety may be improved and the magnitude of that improvement.

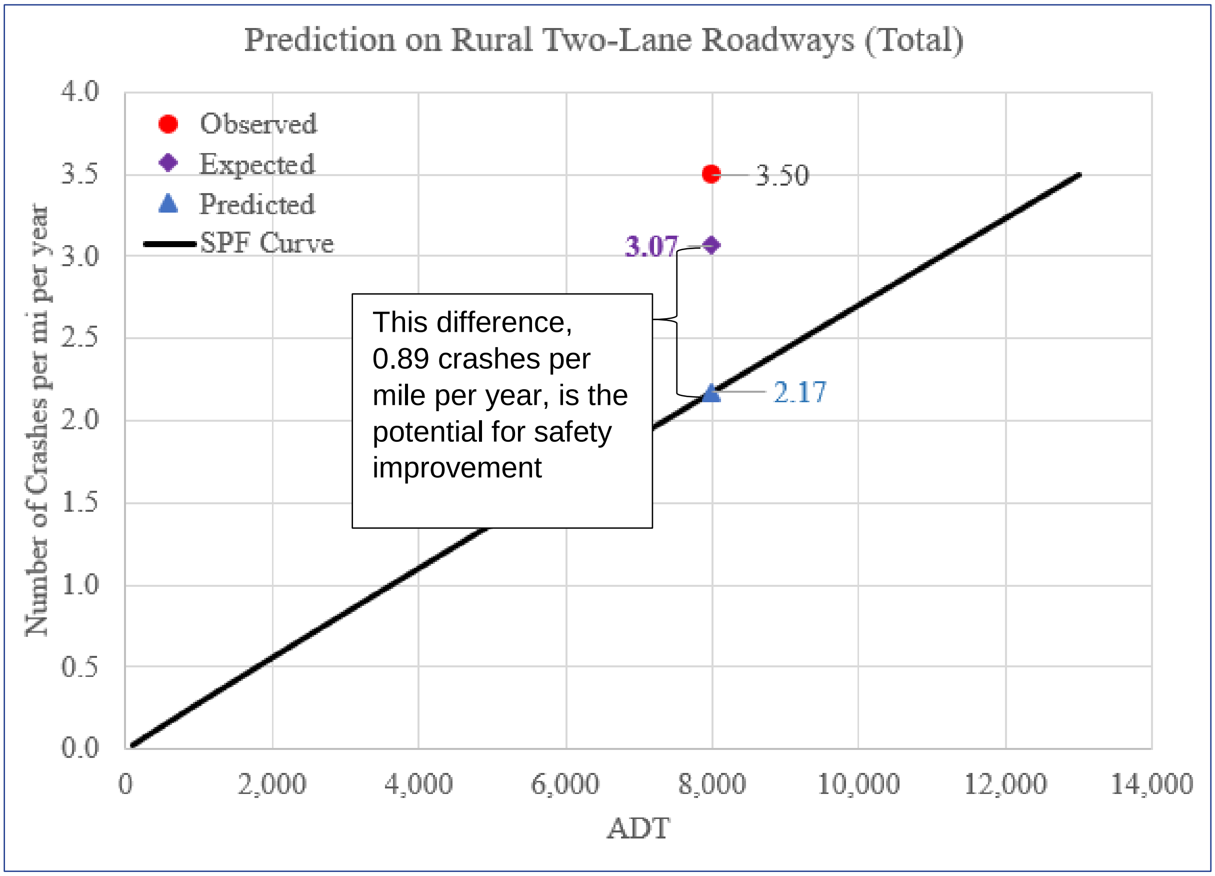


Figure 16. Plot of the Observed, Expected, and Predicted Crashes for the Two-Lane Roadway Example.

Screening Intersections

Intersections are grouped by several factors so that those with similar characteristics are compared with one another. The rural or urban setting, number of legs, traffic control, and traffic volume are the largest determinants of safety performance. Therefore, those characteristics are considered in the benchmarking process.

Intersection Groupings

Intersections were classified into six groups based on the characteristics in Table 1.

Table 1. Intersection Classifications.

Traffic Control	Number of Approaches
Unsignalized	3 leg rural
	4 leg rural
	3 leg urban
	4 leg urban
Signalized	3 leg
	4 leg

Note: Crashes on freeway and expressway frontage roads are currently assigned to the centerline of the mainlanes. Therefore, it is not possible to assign the crash to the correct frontage road intersection, so frontage road intersections are not included.

Note: Only isolated intersections are considered in the analyses. An isolated intersection is defined as an intersection where there are no other intersections within 250 feet of that intersection.

Benchmarking Safety Performance

Separate benchmarks exist for each of the six groupings. These benchmarks are referred to as SPFs, or equations that relate the average number of crashes per year to the AADTs of the two roadways, based on a statistical modeling of several years of crash experience. The average number of crashes per year is referred to as the *predicted crashes per year*.

For intersections, we want to consider the volumes on both the major and minor intersecting roadways. The higher volume is always considered the major roadway, and the lesser volume is the minor roadway.

Crash Severity Classification (KABCO)

Crashes reported in CRIS are classified using the KABCO system. Crashes are classified by the single most serious injury suffered by any person involved in the crash.

The definitions for the five severity levels are:

- K: fatal crash.
- A: suspected serious injury crash.
- B: non-incapacitating injury crash.
- C: possible injury crash.
- O: property damage only crash (non-injury).

Intersection Benchmarks by Crash Severity

For each intersection grouping, there is a benchmark for:

- Total crashes (KABCO).
- Fatal and all injury crashes (KABC).
- Fatal and suspected serious injury crashes (KA).

What Information Do You Need to Determine Potential for Safety Improvement for an Intersection?

Determining the potential for safety improvement at any particular intersection requires knowing the following information:

- Intersection control type.
- Rural or urban setting.
- AADT (or daily volume) on major and minor crossing roadways.
- Number of legs.
- Number of crashes by severity and years of data.

Appendix B includes the benchmark graphs so that the analyst can see how the predicted crashes per year vary by AADT. Because the benchmarks vary by both major and minor traffic volumes, several minor-road volume levels are shown on each graph for reference.

A worksheet in the Safety Spreadsheet Tool allows the user to input the information for any given information and calculate the difference between expected and predicted number of crashes to determine the potential for safety improvement. The results are also plotted on a graph in the “Worksheet Example for Screening Intersections” section.

Worksheet Example for Screening Roadway Segments

Let’s take a rural four-leg unsignalized intersection and determine the potential for safety improvement. The intersection has a major road ADT of 8,000 vehicles per day and a minor road ADT of 1,200 vehicles per day and 10 observed crashes over 2 years.

User Input:

User Input Area

Choose from the drop-down menu in the blue cells.

Type values in the yellow cells.

Variable	Selection/Value	Note
Intersection Type	Rural 4-Leg	Intersection type: area and number of legs
Crash Severity Level	Total	Crash severity: Total, FI, or KA
Minor Road ADT	1,200	Range: 100 - 1,800 vehicles per day
Major Road ADT	8,000	Range: 100 - 14,000 vehicles per day
Duration	2	Number of years
Observed	10	Observed number of crashes in 2 years

Model Output:

Observed	5.00	Observed number of crashes per year
Predicted	2.08	Predicted number of crashes per year
Weight	0.24	Weight factor for predicted number of crashes
Expected	**4.29**	Expected number of crashes per year
Potential for Safety Improvement (Crashes per year)	2.21	Difference between expected and predicted number of crashes per year
Ratio of Expected to Predicted Crashes	2.06	Ratio of expected to predicted number of crashes

Output Area

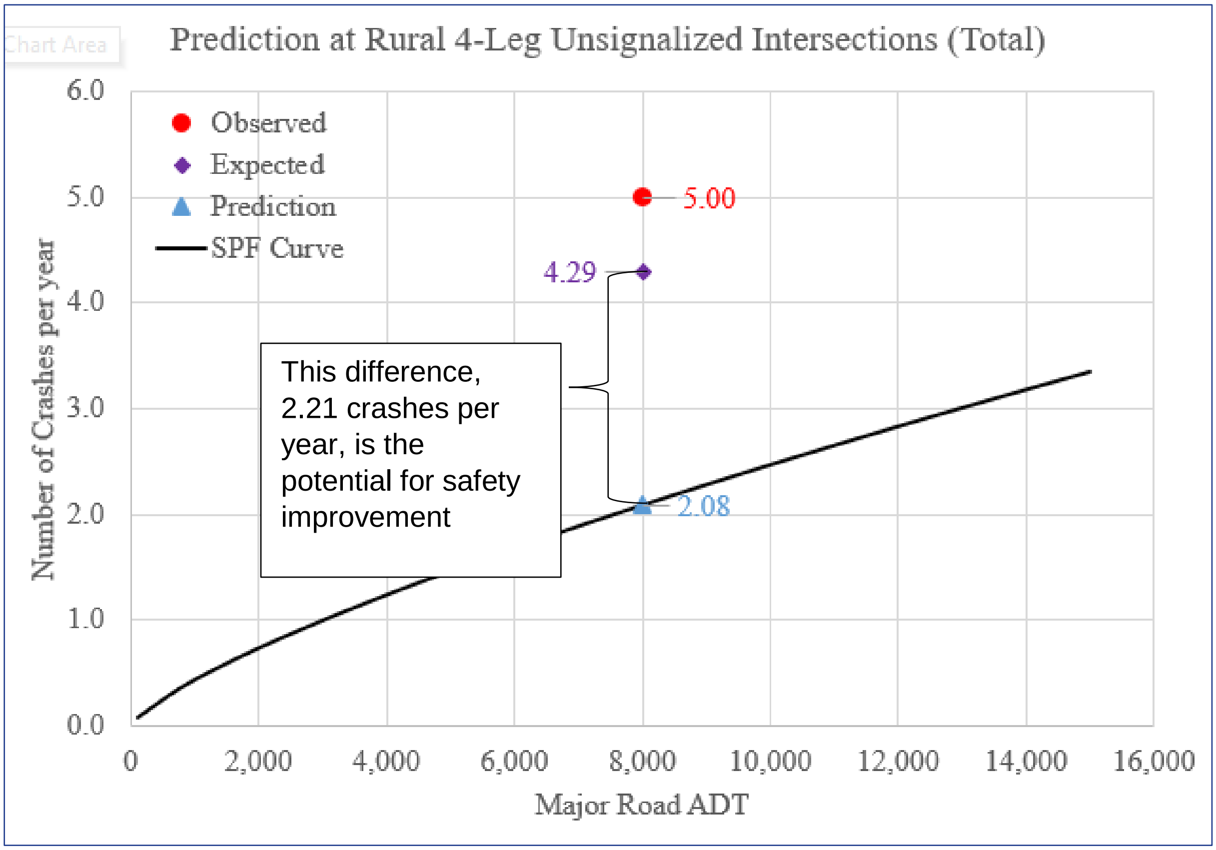
Predicted: the benchmark number of crashes per year. The predicted number of crashes is based on a formula derived from fairly complex statistical methods. The toolkit calculator performs this computation.

Weight: the emphasis placed on predicted versus observed crashes to determine the expected number of crashes per year. In this case, 24% of the expected estimate is based on predicted crashes, and 76% is based on observed crashes. The weight is based on a fairly complex statistical method. The toolkit calculator performs this computation.

Expected: the average number of crashes per year expected over time based on observed and predicted crashes. . In this case, expected crashes = (0.24 × predicted crashes) + (0.76 × observed crashes) or (0.24 × 2.08) + (0.76 × 5.00) = 0.50 + 3.80 = 4.30 crashes per year. (The model reports this value as 4.29. The difference is due to rounding in the example calculation.)

Potential for Safety Improvement (crashes): The difference between the number of expected and predicted crashes per year. In other words, there would be 2.21 fewer crashes per year if the countermeasure implementation improved the intersection's safety performance to the benchmark for this type of facility.

Ratio of Expected to Predicted Crashes: This value, 2.06, provides an indication of the degree to which the expected number of crashes exceeds, or is less than, the benchmark.



This difference, 2.21 crashes per year, is the potential for safety improvement

Figure 17. Plot of the Observed, Expected, and Predicted Crashes at Four-Leg Rural Unsignalized Intersections.

Prioritizing Targeted Categories of Safety Improvements

In This Section

This section of the user guide provides information on addressing:

- Narrow two-lane roadway crashes (widening and rumble strips).
- Systemic tools.

Systemic tools include:

- Systematically prioritizing locations to improve pedestrian safety.
- Systematically prioritizing locations to reduce wet-weather crashes on two-lane highway curves.
- Systematically prioritizing locations for median barrier installation on multilane highways.
- Systematically prioritizing locations to improve horizontal curve safety on two-lane highways.

In some cases, we know that certain crash types are common occurrences or concerns, and we are looking to prioritize locations where they are likely to occur, based on an understanding of the characteristics associated with specific crash types.

In the previous section on screening, we were seeking to identify roadway segments or intersections with high potential for safety improvement, regardless of the type of crash.

In this section, we have already decided to target certain crash types, and we want to determine how to prioritize locations for improvement.

Narrow Two-Lane Roadway Crashes

Some districts place an emphasis on widening narrow roadways. Research indicates that roadways less than 24 feet wide have higher crash rates than those 24 feet and wider. Rumble strips are an essential element in the reduction in crashes.[1]

Narrow Roadway Widening Benefit-to-Cost Calculator

The Safety Spreadsheet Toolkit includes a narrow roadway benefit-to-cost (B/C) calculator tool that allows the user to estimate the B/C ratio for widening narrow (less than 24 feet wide) two-lane roadways to 26 or 28 feet with rumble strips or profile markings. The tool is based on a comprehensive review of crashes on two-lane highways less than 24 feet versus those 24 feet and wider. The spreadsheet calculations are based on widening with rumble strips. A separate calculator has been included that calculates the B/C ratio for the addition of rumble strips alone.

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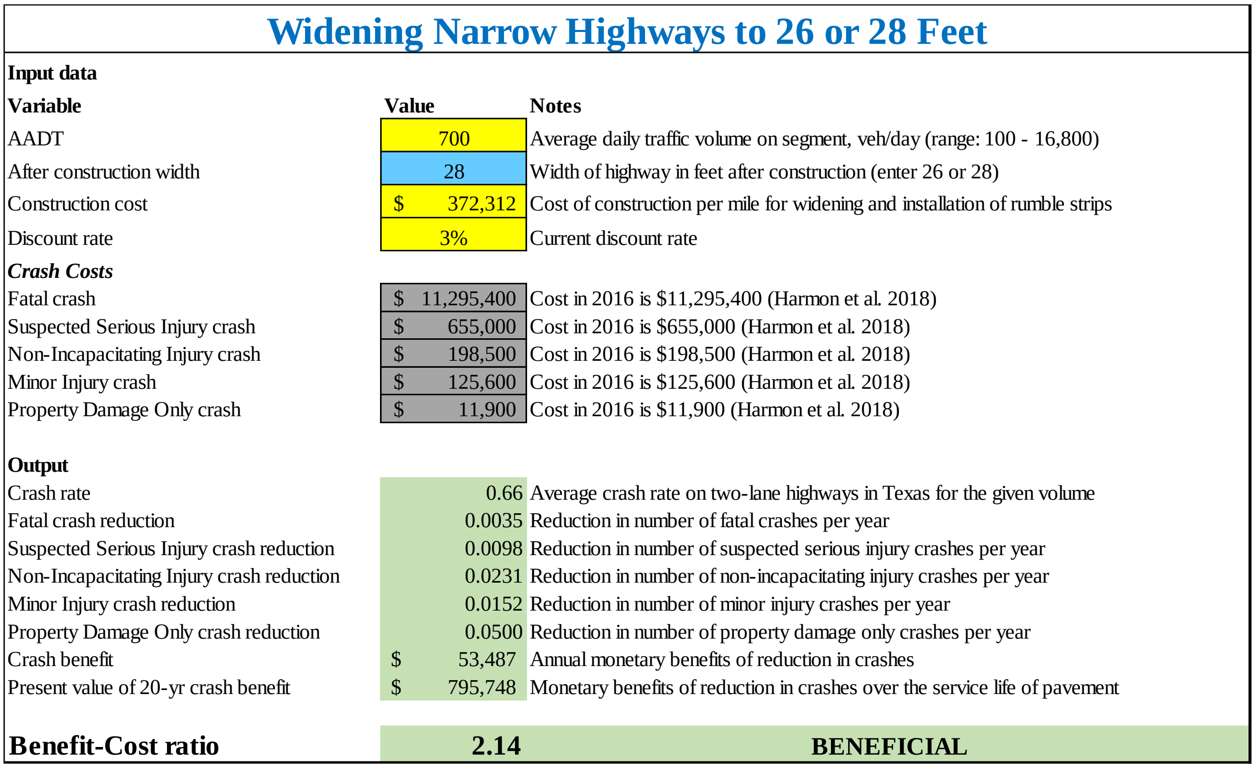
[1] Wunderlich, R., Dixon, K., Wu, L., Geedipally, S., Dadashova, B., and E. Shipp. *Making Every Day Count: Applying Data-Driven Safety Analyses in a TxDOT District*. Publication FHWA/TX-19/5-9052-01-R1, Texas A&M Transportation Institute, College Station, 2019.

Cells in yellow are filled out by the analyst. The default cost per mile is $373,000 and can be modified by the analyst.

The analyst may change the cost of crashes but should have a valid, documented reason to do so.

The cells in green are calculated by the spreadsheet tool.



Widening Narrow Highways to 26 or 28 Feet

Input data

Variable	**Value**	**Notes**
AADT	700	Average daily traffic volume on segment, veh/day (range: 100 - 16,800)
After construction width	28	Width of highway in feet after construction (enter 26 or 28)
Construction cost	$ 372,312	Cost of construction per mile for widening and installation of rumble strips
Discount rate	3%	Current discount rate
Crash Costs		
Fatal crash	$ 11,295,400	Cost in 2016 is $11,295,400 (Harmon et al. 2018)
Suspected Serious Injury crash	$ 655,000	Cost in 2016 is $655,000 (Harmon et al. 2018)
Non-Incapacitating Injury crash	$ 198,500	Cost in 2016 is $198,500 (Harmon et al. 2018)
Minor Injury crash	$ 125,600	Cost in 2016 is $125,600 (Harmon et al. 2018)
Property Damage Only crash	$ 11,900	Cost in 2016 is $11,900 (Harmon et al. 2018)
Output		
Crash rate	0.66	Average crash rate on two-lane highways in Texas for the given volume
Fatal crash reduction	0.0035	Reduction in number of fatal crashes per year
Suspected Serious Injury crash reduction	0.0098	Reduction in number of suspected serious injury crashes per year
Non-Incapacitating Injury crash reduction	0.0231	Reduction in number of non-incapacitating injury crashes per year
Minor Injury crash reduction	0.0152	Reduction in number of minor injury crashes per year
Property Damage Only crash reduction	0.0500	Reduction in number of property damage only crashes per year
Crash benefit	$ 53,487	Annual monetary benefits of reduction in crashes
Present value of 20-yr crash benefit	$ 795,748	Monetary benefits of reduction in crashes over the service life of pavement
Benefit-Cost ratio	**2.14**	**BENEFICIAL**

Figure 18. Narrow Roadway Widening Benefit-to-Cost Calculator.

Generally speaking, the higher the ADT, the higher the B/C ratio, so a systematic approach might prioritize improvements starting with the highest-volume roadways.

Where a maintenance or resurfacing project is already planned, the user could input only the additional cost of widening to determine the B/C ratio because the other costs will be expended regardless.

Systemic Tools

Addressing Unconcentrated Crashes

Because crashes are fairly rare events (crash rates are typically expressed in terms of per million vehicle-miles) and are not always concentrated in particular locations where they can be addressed by locational screening, there is another method to prioritize safety improvements. This method, referred to as the *systemic approach*, focuses on identifying locations where crashes of a specific type are likely to occur because they have the characteristics associated with crashes.

Linking Roadway Characteristics with Crashes

Typically, a particular crash type, such as wet-weather curve crashes, are selected for association with roadway characteristics. Then particular locations are identified and prioritized, not by their crash experience but by the strong possibility that crashes will happen there, so that a program of countermeasures can be applied where they are likely to prevent or reduce future crashes. These characteristics are referred to as *risk factors*.

Scoring for Prioritization

The individual risk factors are added together to generate a score for the location. The higher the score, the higher the risk that crashes of that type will occur there in the future. These risk factor computations can be carried out on a number of locations, and the resulting scores can be used to prioritize sites for appropriate countermeasure implementation.

Systemically Prioritizing Locations to Improve Pedestrian Safety

Pedestrian fatalities and injuries have been on the rise in Texas and across the nation for the past several years, and pedestrian safety is one of the seven emphasis areas included in the Texas Strategic Highway Safety Plan.

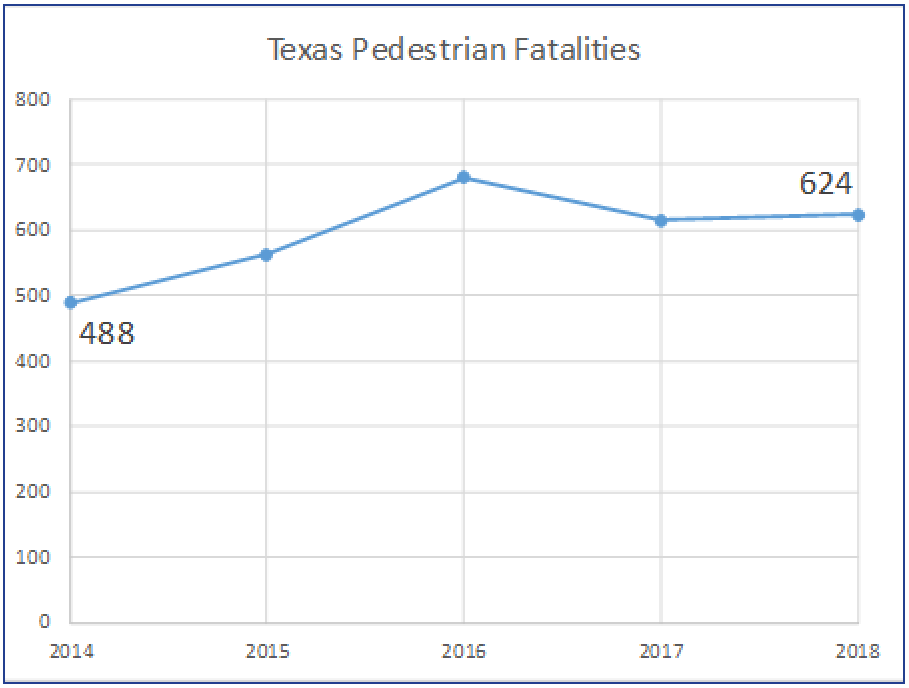


Figure 19. Texas Pedestrian Fatalities 2014–2018.

Systemic Approach

Pedestrian crashes are not often concentrated in any one given location, so a systemic approach is particularly appropriate for this type of crash issue. Rather than look for high concentrations of crashes, we look for locations with the *characteristics* or *risk factors* associated with pedestrian crashes for treatment. A value is assigned for each risk factor based on research into how likely a crash is, based on that characteristic's value.

Risk Factor Example

Risk factors are simply roadway characteristics that have an influence on crash likelihood. In the case of segment pedestrian crashes, pavement width is a risk factor, and the risk is different for different ranges of pavement width. Each range of risk is assigned a weight value (points), and the points for each risk factor are added to come up with a total for the segment. Four ranges are identified for widths with different weights for rural and urban conditions.

Table 2. Example Pedestrian Crash Risk Factor Values.

Risk Factor		Weight (Points)	
		Rural	**Urban**
Pavement width (ft)	≤16	9	10
	17–24	2	4
	25–50	23	21
	>50	23	23

Calculating a Roadway Segment Pedestrian Risk Score

The analyst can simply add the appropriate risk factor score in Table 3 for each element and add them together for a total score.

Table 3. Pedestrian Crash Risk Factor Values for Segments.

Risk Factor			Weight (Points)	
			Rural	Urban
Median type	No median		7	8
	Unprotected		21	12
	Curbed		10	13
	Barrier		17	19
Number of lanes	1 or 2		6	5
	3 or 4		23	22
	5 or more		11	21
Pavement width (ft)	≤16		9	10
	17–24		2	4
	25–50		23	21
	>50		23	23
Vehicle volume level	Low		2	2
	Moderate		9	5
	High		27	26
Truck percentage (%)	≤10	≤5	4	7
	10–20	5–10	22	19
	20–30	10–20	19	14
	>30	>20	21	10

The Safety Spreadsheet Toolkit includes a worksheet for calculating a pedestrian crash risk factor score.

Using the Segment Risk Factor Calculation Results

Comparing Segments

The scores can be used to compare segments to prioritize them for further study or implementation of countermeasures.

Percentiles

The analyst can also use the score's percentile compared to all state highway segments in Texas. The higher the percentile, the higher the risk. For example, only 5% of the comparison highway segments would have a higher score than the analyzed segment if the analyzed segment's score is in the 95th percentile.

Pedestrian Safety Countermeasures

Appendix C contains a list of potential pedestrian safety countermeasures.

Calculating a Signalized Intersection Pedestrian Risk Score

The analyst can simply add the appropriate risk factor score in Table 4 for each element and add them together for a total score.

Table 4. Pedestrian Crash Risk Factor Values for Signalized Intersections.

Risk Factor		Weight (Points) Rural
Pedestrian volume	Low (≤400)	6
	Moderate (400–1,000)	23
	High (≥1,000)	11
Median type	No median	18
	Partial	10
	Full (all approaches)	10
Land use	Commercial	18
	Residential	10
	Mixed	12

The Safety Spreadsheet Toolkit includes a worksheet for calculating a pedestrian crash risk factor score and its percentile compared to a sample of 150 urban signalized intersections in Houston and San Antonio.

Using the Intersection Risk Factor Calculation Results

Comparing Intersections

The scores can be used to compare intersections to prioritize them for further study or implementation of countermeasures.

The analyst can also use the score's percentile compared to a 150-intersection sample in Houston and San Antonio as an indicator of the degree of risk. The higher the percentile, the higher the risk. For example, only 5% of the comparison intersections would have a higher score than the analyzed intersection if the analyzed intersection's score is in the 95th percentile.

Pedestrian Safety Countermeasures

Appendix C contains a list of potential pedestrian safety countermeasures.

Systemically Prioritizing Locations to Reduce Wet-Weather Crashes on Two-Lane Highway Curves

Effect of Wet Weather

Weather events can act on roadway safety by impairing visibility, reduced traction and friction, high winds, and extreme temperature that may affect driver and vehicle performance. These impacts can increase crash risk and severity. Generally, research has found that both crash risk and severity increase in wet weather, as much as two to three times that of dry weather.[1]

Relationship between Rainfall and Crashes

Figure 20 depicts the effect of wet weather on crashes. The state average rainfall of 30 inches is used as the basis of comparison. The crash modification factor (CMF) is a multiplier used to determine how rainfall totals influence the number of wet-weather crashes. Wetter locations have more wet-weather-related crashes, and drier locations have fewer. By comparing the average rainfall in the state to that of a county or group of counties, we can determine the relationship between wet-weather crashes and the state average.

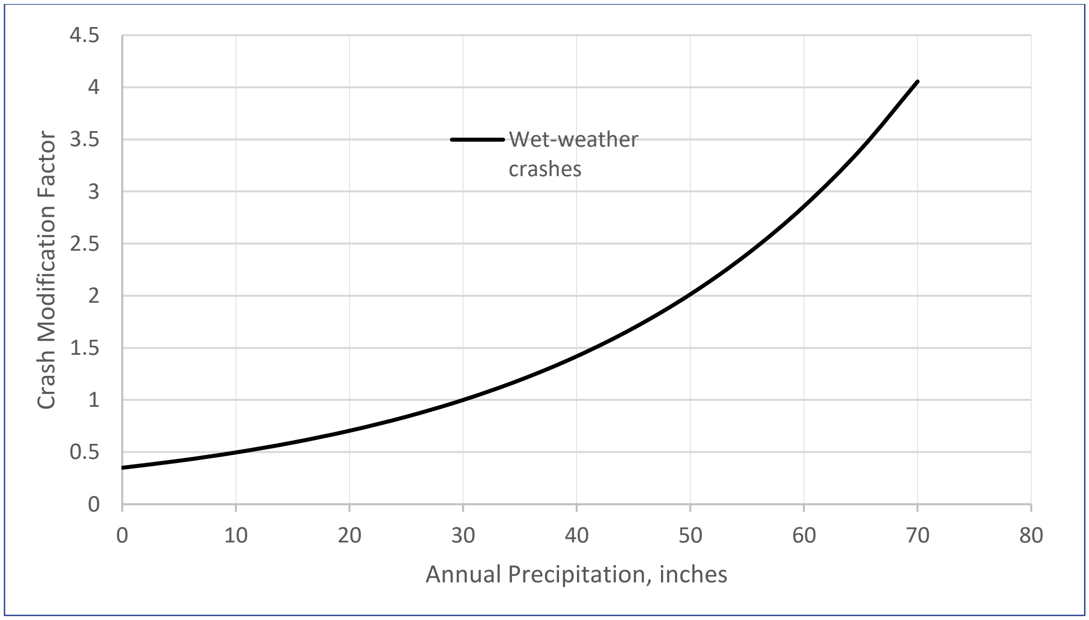


Figure 20. Effect of Wet Weather on Crashes.

Crash Modification Factors

CMFs tell us how crashes change in relation to changes in an influential factor, in this case rainfall. The CMF is multiplied by the number of crashes to determine the result:

- A value above 1 means that crashes will be more numerous.
- A value below 1 means that crashes will be less numerous.
- A value of 1.5 means that crashes will increase by 50%.
- A value of 0.75 means that crashes will decrease by 25%.

Example Use of the Chart

The counties in the Beaumont District experience on average 60 inches of rain. A value of 60 inches for annual precipitation results in a multiplier of just under 3. Therefore, wet-weather crashes in the Beaumont District are predicted to be almost three times the state average.

Annual precipitation values for Texas counties can be found in Appendix D.

Why the Systemic Approach Is Appropriate for Wet-Weather Curve Crashes

Wet-weather crashes are not often concentrated in any one given location, so a systemic approach is particularly appropriate for this type of crash issue. Rather than look for high concentrations of crashes, we are looking for locations with the *characteristics* or *risk factors* associated with pedestrian crashes for treatment. A value is assigned for each risk factor based on research into how likely a crash is, based on that characteristic’s value.

Wet-Weather Curve Crash Risk Factor Example

Risk factors are simply roadway characteristics that have an influence on crash likelihood. In the case of wet-weather curve crashes, the skid number is one of the risk factors, and the risk is different for different ranges of the skid number. Each range of the risk factor is assigned a weight value (points). The points for each risk factor are added to come up with a total for the segment. Points are assigned for a value, or range of values, in each risk factor category. For example, five ranges are identified and associated with a weight or number of points in the skid number category.

Table 5. Wet-Weather Curve Crash Risk Factors.

Wet-Weather Curve Crash Risk Factor		Weight (Points)
Skid number	≤30	23
	30–40	18
	40–50	12
	50–60	1
	>60	2
Traffic volume (vehicles/day)	≤400	0
	400–800	1
	800–1200	8
	1,200–1,600	15
	1,600–3,000	14
	3,000–5,000	22
	>5,000	20
Posted speed limit (miles/hour)	≤50	8
	55	23
	60	5
	65	9
	70	6
	75	15
Annual precipitation (inches)	≤56	13
	56–57	4
	57–58	11
	58–59	9
	59–60	23
	>60	4
Truck percentage (%)	≤10	22
	10–20	23
	> 20	2
Shoulder width (ft)	0	9
	1	6
	2	20
	3	18
	≥4	4
Curve radius (ft)	<1,000	23
	1,000–2,000	7
	2,000–5,000	5
	≥5,000	8

Calculating a Curve's Wet-Weather Crash Risk Score

The analyst can simply add the appropriate risk factor score in Table 6 for each element and add them together for a total score.

The Safety Spreadsheet Toolkit includes a worksheet for calculating a wet-weather crash risk score and its percentile compared to all the two-lane curves in the Beaumont District.

Using Wet-Weather Crash Risk Factor Calculation Results

Ranking Curves

The scores can be used to compare curve scores to prioritize them for further study or implementation of countermeasures.

Percentiles

The analyst can also use the score's percentile compared to all the two-lane curves in the Beaumont District. The higher the percentile, the higher the risk. For example, only 5% of the comparison curves would have a higher score than the analyzed curve if the analyzed curve's score is in the 95th percentile.

Table 6. Crash Rate for Horizontal Curves in Beaumont Based on Risk Factor Weights.

Total Weight (Points)	Number of Curves	Total Wet Crashes	Average Crash Rate
≤50	538	9	0.09
50–75	661	25	0.18
75–100	475	59	0.67
100–125	218	34	0.34
>125	57	24	0.96

Wet-Weather Curve Crash Countermeasures

Appendix D contains a list of potential wet-weather curve crash countermeasures. Appendix E contains performance and cost of skid resistance enhancement treatments.

Systemically Prioritizing Locations for Median Barrier Installation on Multilane Highways

Cross-Median Head-On Crashes

Head-on crashes are often severe. Those that involve a vehicle crossing a median are particularly severe. Despite their relative rarity, they comprise a high proportion of fatal and injury crashes. A 2001 study found that although these cross-median crashes represented less than 5% of all interstate crashes nationally, they accounted for more than 30% of fatalities on the interstate system.[2] Because these crashes are not often concentrated, the installation of a median barrier lends itself to a systemic analysis.

A study TTI performed for TxDOT in 2016 developed risk factors for prioritizing median barrier installation on both urban and rural divided highways with at least 4 feet of unprotected median.[3] Table 7 includes the values for risk factors segmented by ADT ranges.

Table 7. Crossover Crash Risk Factors.

Risk Factor		**Weight (Points)**		
		Low Volume (ADT ≤20,000)	**Moderate Volume (20,000 < ADT ≤ 30,000)**	**High Volume (ADT > 30,000)**
Median and inside shoulders (ft)	≤10	1	0	1
	11–20	3	11	2
	21–30	0	0	0
	31–40	4	0	0
	41–50	1	1	2
	51–60	6	6	1
	61–70	0	6	5
	71–80	7	1	1
	>80	1	0	6
Truck percentage	≤4%	0	1	11
	4–8%	7	8	5
	8–12%	2	0	2
	12-16%	3	0	0
	16–20%	0	4	0
	20–24%	0	0	0
	24–28%	1	8	0
	28–32%	0	0	1
	>32%	4	2	0

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[2] Hunter, W. W., J. R. Stewart, K. A. Eccles, H. F. Huang, F. M. Council, and D. L. Harkey. Three-Strand Cable Median Barrier in North Carolina — In-Service Evaluation. *Hydrology, Hydraulics, and Water Quality; Roadside Safety Features,* Vol. 1743, 2001, pp. 97–103.

[3] Geedipally, S. T. D. Walden, and L. Wu. A Systemic Approach for Selecting Median Barrier Installation Projects. Technical Memorandum-Task C TxDOT Project 58-6XXIA001. Texas A&M Transportation Institute, College Station, 2016.

Calculating a Divided Roadway Segment's Cross-Median Crash Risk Score

The analyst can simply add the appropriate risk factor score in Table 8 for each element and add them together for a total score.

The Safety Spreadsheet Toolkit includes a worksheet for calculating a cross-median crash risk score and its percentile compared to all multi-lane state divided highways and freeways with a median width greater than 4 feet.

Using Cross-Median Crash Risk Calculation Results

Ranking Curves

The scores can be used to compare curve scores to prioritize them for further study or implementation of countermeasures.

Percentiles

The analyst can also use the score's percentile compared to all multi-lane state divided highways and freeways in Texas with a median width greater than 4 feet. The higher the percentile, the higher the risk. For example, only 5% of the comparison curves would have a higher score than the analyzed curve if the analyzed curve's score is in the 95th percentile.

Systemically Prioritizing Locations to Improve Horizontal Curve Safety on Two-Lane Highways

Why the Systemic Approach Is Appropriate

Horizontal curves are necessary and inevitable part of roadways, but a disproportionate share of crashes occur on them based on their portion of highway miles. In particular, rural two-lane roads account for almost 70% of fatal curve-related crashes. More than 85% of these crashes are single-vehicle roadway departure crashes or head-on lane departure crashes.[4] As is the case with other rural crash issues, these crashes are not always concentrated at particular locations, and a systemic approach is applicable.

Two-Lane Horizontal Curve Risk Factors

A 2016 study TTI prepared for TxDOT identified the risk factors and potential countermeasures associated with curve crashes on two-lane rural highways.[4] The risk factors included in Table 8 are grouped by ADT ranges. Lane width, shoulder width, percentage of trucks, curve radius, and deflection angle all influence curve crashes. The risk factor calculations can be used to prioritize a group of curves. The study also identified the curves with the greatest risk and found that they all had scores of 80 or above.

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[4] Geedipally, S., D. Lord, and L. Wu. *A Systemic Approach to Project Selection for Improving Horizontal Curve Safety*. Technical Memorandum, Task C TxDOT Project 58-6XXIA002. Texas A&M Transportation Institute, College Station, 2016.

Table 8. Two-Lane Horizontal Curve Crash Risk Factors.

Risk Factor		Weight (Points)		
		Low Volume (ADT ≤500)	Moderate Volume (500 < ADT ≤ 1,500)	High Volume (ADT > 1,500)
Lane width* (ft)	<10	9	9	9
	10	12	12	14
	11	18	14	16
	12	9	14	9
	≥13	11	9	9
Shoulder width (ft)	0–2	16	12	16
	2–4	11	16	15
	4–6	11	11	13
	≥6	9	8	6
Truck percentage (%)	<8	14	14	16
	8–15	14	12	14
	≥15	10	12	7
Radius (ft)	<500	16	16	11
	500–1000	17	17	23
	1000–1500	5	4	5
Deflection angle	<20	2	2	3
	20–40	11	12	14
	40–60	17	17	16
	60–80	14	12	13
	80–100	12	14	13
	≥100	11	11	11

* Lane width needs to be rounded (e.g., 9.4 ft should be rounded to 9 ft, and 10.5 ft to 11 ft).

The Safety Spreadsheet Toolkit includes a worksheet for calculating a two-lane horizontal curve crash risk score and its percentile compared to two-lane horizontal curves in Texas.

Using the Horizontal Curve Risk Factor Calculation Results

Comparing Curves

The scores can be used to compare curves to prioritize them for further study or implementation of countermeasures.

Percentiles

The analyst can also use the score's percentile compared to all curves on two-lane state highways in Texas. The higher the percentile, the higher the risk. For example, only 5% of the comparison curves would have a higher score than the analyzed curve if the analyzed curve's score is in the 95th percentile.

Curve Crash Countermeasures

Appendix F contains a list of potential curve crash countermeasures.

Integrating Safety into the Project Development Process

Safety performance should be considered during all stages of the life of a project. This is particularly important when considering the project development process (PDP). Though the PDP may differ by district, it is important for each district to explore suitable safety assessment methods that will help it inform, justify, and defend safety-based decisions.

Purpose

These recommendations are provided to help TxDOT transportation professionals select suitable safety assessments methods throughout the project development tasks. As the project life cycle shows (Figure 21), this documentation is primarily focused on safety assessment methods for the following project development phases:

- Planning and scoping.
- Alternatives identification and analysis.
- Preliminary design.
- Final design.

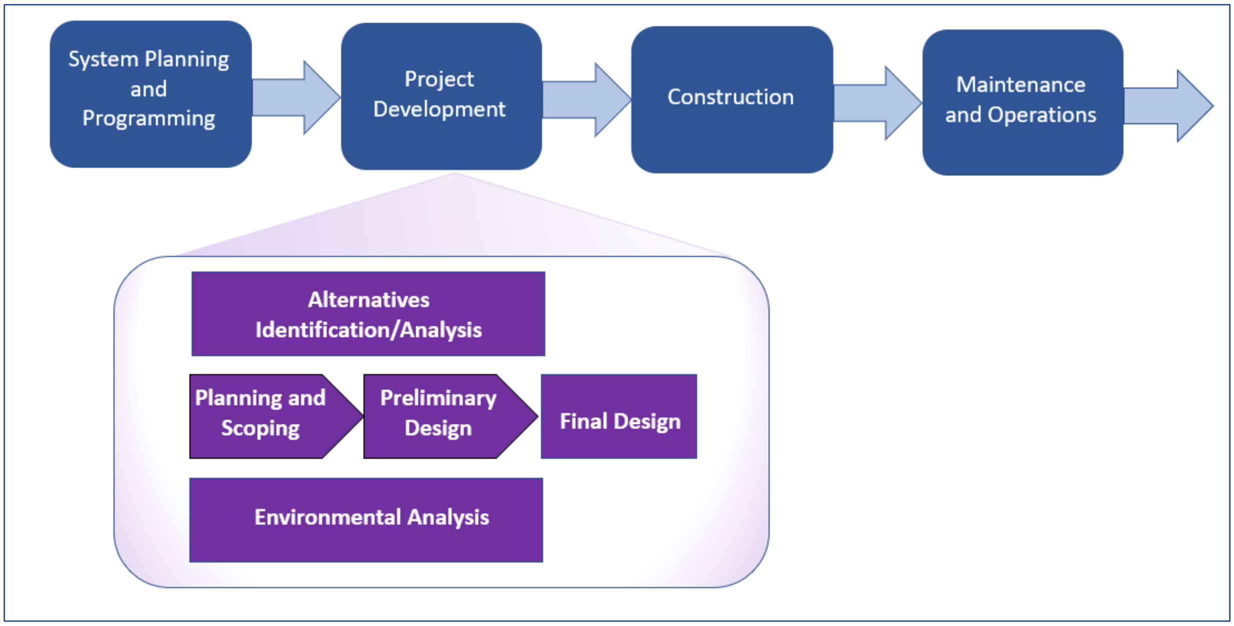


Figure 21. Project Life Cycle.

Safety Assessment Methods for Varying Project Applications

The transportation profession does not have a single *magic bullet* safety assessment method suitable for all project types or PDP phases. Instead, the transportation professional must uniquely evaluate safety at each individual PDP step. Safety assessments can range from the straightforward basic methods and extend to intermediate and advanced procedures. Though the more advanced methods can offer statistically reliable results, in many cases a more straightforward basic approach will give the same result. This section summarizes potential assessment methods an analyst can apply for the four project development phases.

Foundational Elements for Safety Assessment Methods

The safety assessment methods described in the American Association of State Highway and Transportation Officials *Highway Safety Manual* and presented in this guide use one or more of the following basic foundational elements:

- Observed crashes.
- Crash modification factors/functions.
- Safety performance functions.

An ***observed crash*** refers to one or more years of crash history for a location. Safety assessments that focus on observed crashes can provide meaningful information for existing facilities. In this guide, the section “Describing TxDOT District Safety Issues” uses historic (observed) crashes.

A ***crash modification factor*** is a measure of the safety effectiveness for a particular roadway treatment or design element. For example:

- A CMF value of 0.85 would suggest that the presence of that treatment or element would result in a 15 percent decrease in crashes compared to its absence.
- A CMF value of 1.0 suggests that a particular feature would have no effect on the number of crashes.

There are CMFs for a wide variety of roadway treatments and alternative design element dimensions. These CMFs are available in Part D (Volume 3) of the *Highway Safety Manual* at the Crash Modification Factors Clearinghouse (www.cmfclearinghouse.org), or in state-specific guidelines in which some state departments of transportation have customized CMFs for their regional conditions.

Each CMF is uniquely defined by associated base conditions, road type, and crash type.

A ***safety performance function*** is a statistically derived equation that estimates (or predicts) the average number of crashes per year likely to occur on a roadway of a particular type (e.g., two-way two-lane roadways or urban arterials) with a particular traffic volume. Using SPFs can enhance a safety assessment method’s predictive reliability by taking advantage of crash information for other similar roadways and not relying solely on recent crash history for the specific roadway in question.

Three Common Levels of Analysis

- Observed crashes.
- Predicted crashes.
- Expected crashes.

Note: The source material for this summary is from the Federal Highway Administration document *Scale and Scope of Safety Assessment Methods in the Project Development Process.*

Planning and Scoping

Planning and scoping activities occur early in the PDP and involve identifying the needs and range of actions, alternatives, and impacts to be addressed as part of the specific project scope. The following three general categories identify planning and scoping related tasks:

- Conduct preliminary planning and needs assessment.
- Establish project purpose and need.
- Establish project scope.

Table 9. Planning and Scoping Safety Assessment Objective.

Related Task	Objective	Basic				Intermediate		Advanced
		Site Evaluation or Audit	**Historical Crash Data Evaluation**	**CMF Applied to Observed Crashes**	**CMF Relative Comparison**	**AADT-Only SPF**	**SPF with CMF Adjustment**	**SPF with CMF Weighted with Observed Crashes**
		Observed Crashes				*Predicted Crashes*		*Expected Crashes*
Safety Assessments:		Increasing Level of Predictive Reliability						
Conduct Preliminary Planning and Needs Assessment	Characterize Existing Safety Performance	✓	✓[1]					
Establish Project Purpose and Need	Diagnose Safety Issues the Project Should Address	✓	✓[1]			✓[2]	✓	✓
Establish Project Scope	Refine Extent of Project and Safety Assessment Needs	✓	✓	✓[3]	✓[3]	✓	✓[3]	✓

[1] Refer to “Describing TxDOT District Safety Issues” section.

[2] See “Screening the Network to Identify Locations with Potential for Safety Improvement” section and Appendices A and B for AADT-only SPFs unique to the Beaumont District.

[3] Review prioritizing targeted categories of safety improvements by assessing the CMF and associated countermeasure.

Alternatives Identification and Analysis

The alternatives analysis phase is typically conducted after a project need has been determined but before a solution has been identified. This phase may coincide with the planning and scoping phase and can extend into the early stages of preliminary design. The purpose of safety assessments in the alternatives analysis phase is to estimate the impact of each alternative on safety. The following three general categories identify planning and scoping related tasks:

- Conduct preliminary planning and needs assessment.
- Establish project purpose and need.
- Establish project scope.

Table 10. Alternatives Evaluation and Identification Safety Assessment Objective.

		Basic				**Intermediate**		**Advanced**
Related Task	**Objective**	**Site Evaluation or Audit**	**Historical Crash Data Evaluation**	**CMF Applied to Observed Crashes**	**CMF Relative Comparison**	**AADT-Only SPF**	**SPF with CMF Adjustment**	**SPF with CMF Weighted with Observed Crashes**
		Observed Crashes				*Predicted Crashes*		*Expected Crashes*
Safety Assessments:	Increasing Level of Predictive Reliability							
Alternative Selection	Estimate the safety performance of alternatives			✓[3]	✓[3]	✓[2]	✓[3]	✓
Interchange Access Justification	Estimate the safety performance impact of new or modified points of access			✓[3]	✓[3]	✓[2]	✓[3]	✓

[2] See “Screening the Network to Identify Locations with Potential for Safety Improvement” section and Appendices A and B for AADT-Only SPFs unique to the Beaumont District.

[3] Review prioritizing targeted categories of safety improvements by assessing the CMF and associated countermeasure.

Preliminary and Final Design

The preliminary and final design phases are clearly defined for most jurisdictions, yet key elements of these two phases can differ for each transportation agency. Therefore, this guide combines the preliminary and final design into a single section. During the design phase, design decisions must be refined and finalized prior to construction. In general, safety assessments in the design phase focus on documenting design decisions, including those that require exceptions to the design standards, and calculating the estimated number of crashes that can be anticipated for the final facility design.

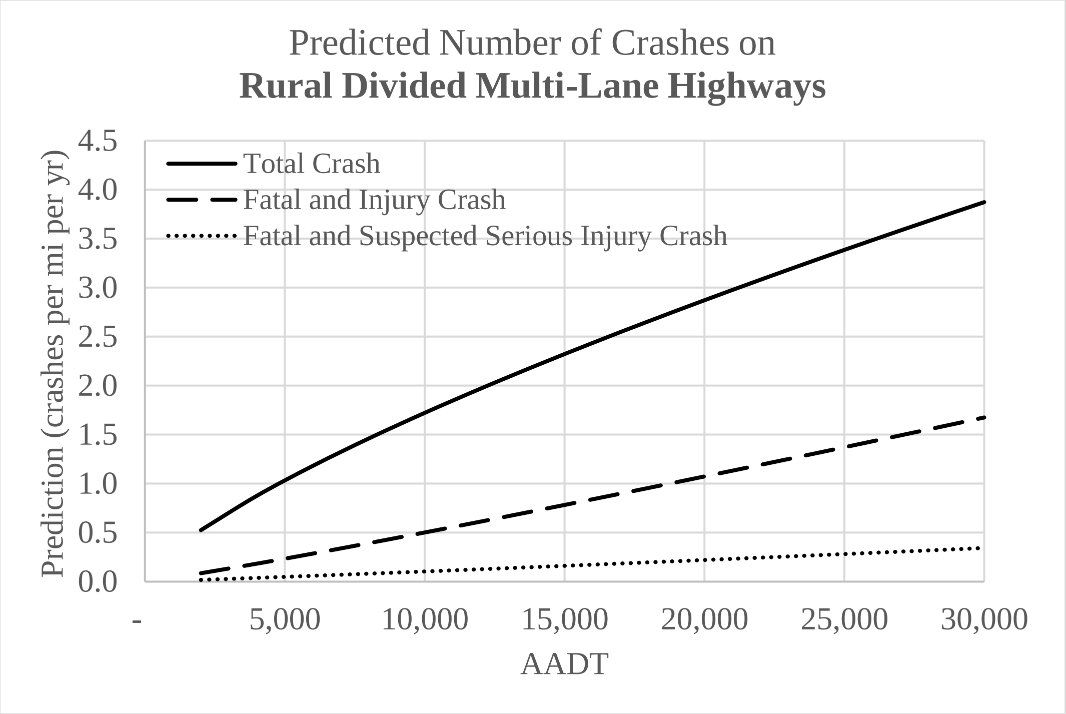
This section provides information to help select safety assessment methods suitable for addressing safety performance related questions that arise during these preliminary and final design activities based upon the related task and project type. This guide describes the design tasks in four general categories:

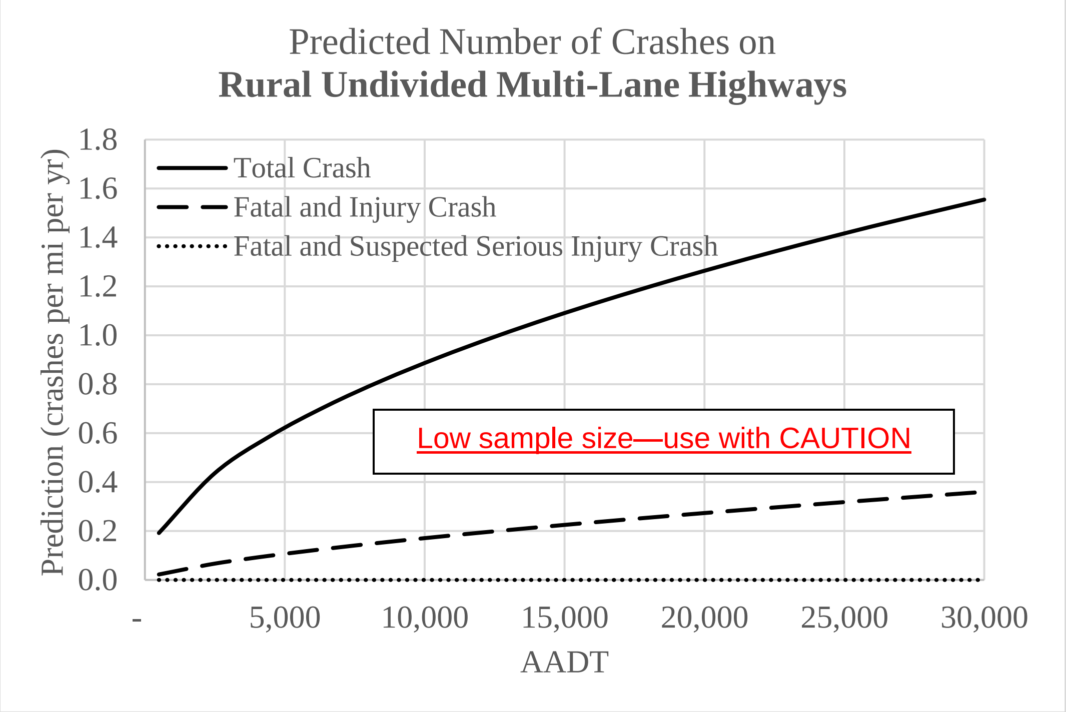
- Selection of specific design elements and their dimensions.
- Design exceptions.
- Value engineering.
- The work zone transportation management plan.

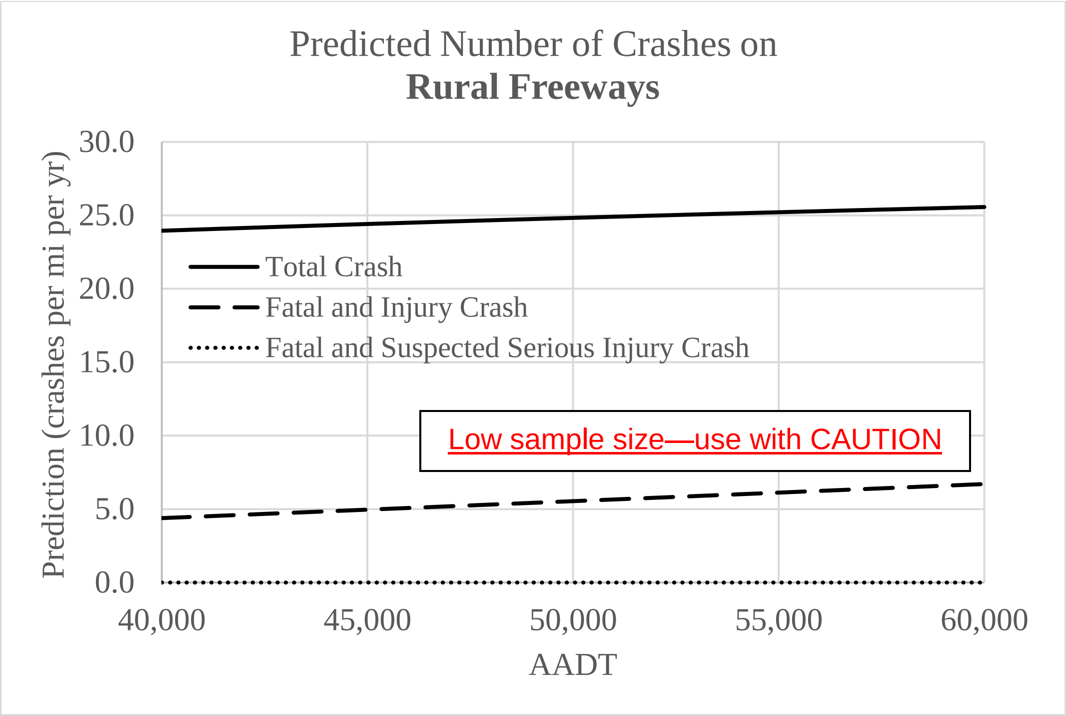
Table 11. Preliminary and Final Design Safety Assessment Objective.

Related Task	**Objective**	**Basic**				**Intermediate**		**Advanced**
		Site Evaluation or Audit	**Historical Crash Data Evaluation**	**CMF Applied to Observed Crashes**	**CMF Relative Comparison**	**AADT-Only SPF**	**SPF with CMF Adjustment**	**SPF with CMF Weighted with Observed Crashes**
		Observed Crashes				*Predicted Crashes*		*Expected Crashes*
Safety Assessments:	Increasing Level of Predictive Reliability →							
Selection of Specific Design Elements and Their Dimensions	To compare safety impacts of alternative dimensions	✓	✓	✓	✓	✓	✓	✓
Design Exception	To estimate how the design exception impacts safety performance and to identify and evaluate strategies for mitigation			✓	✓	✓	✓	✓
Value Engineering	To quantify safety performance so that it can be weighed with other project considerations			✓	✓	✓	✓	✓
The Work Zone Transportation Management Plan	To compare safety impacts of traffic control strategies	✓			✓			

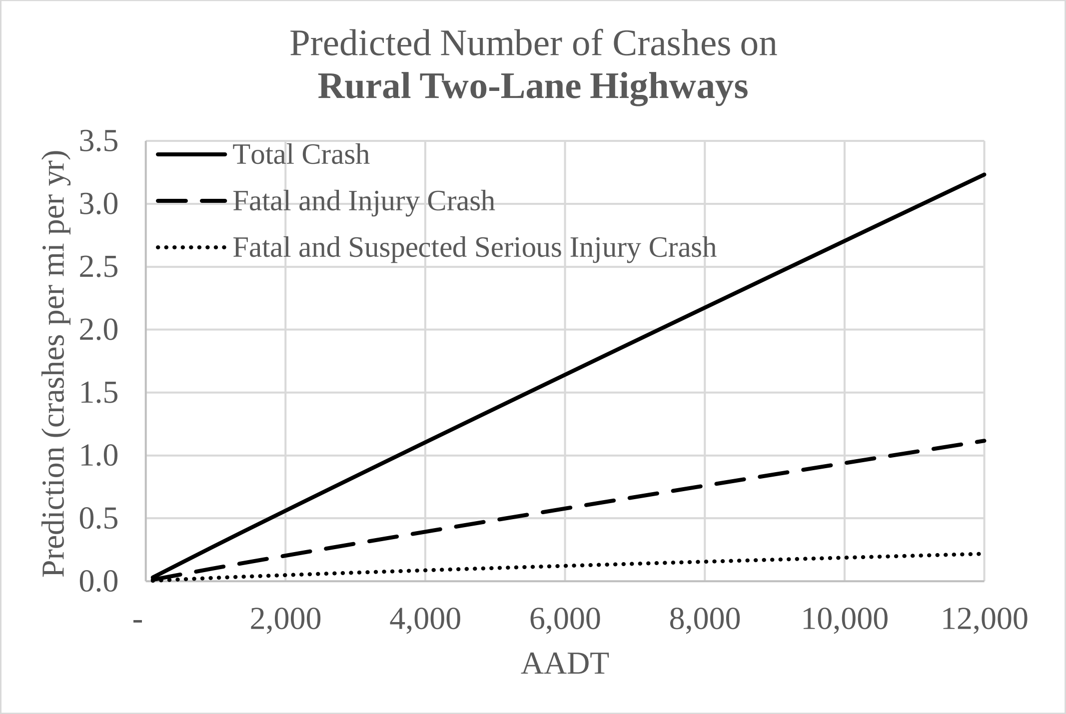
Appendix A. Roadway Segment Benchmark Curves

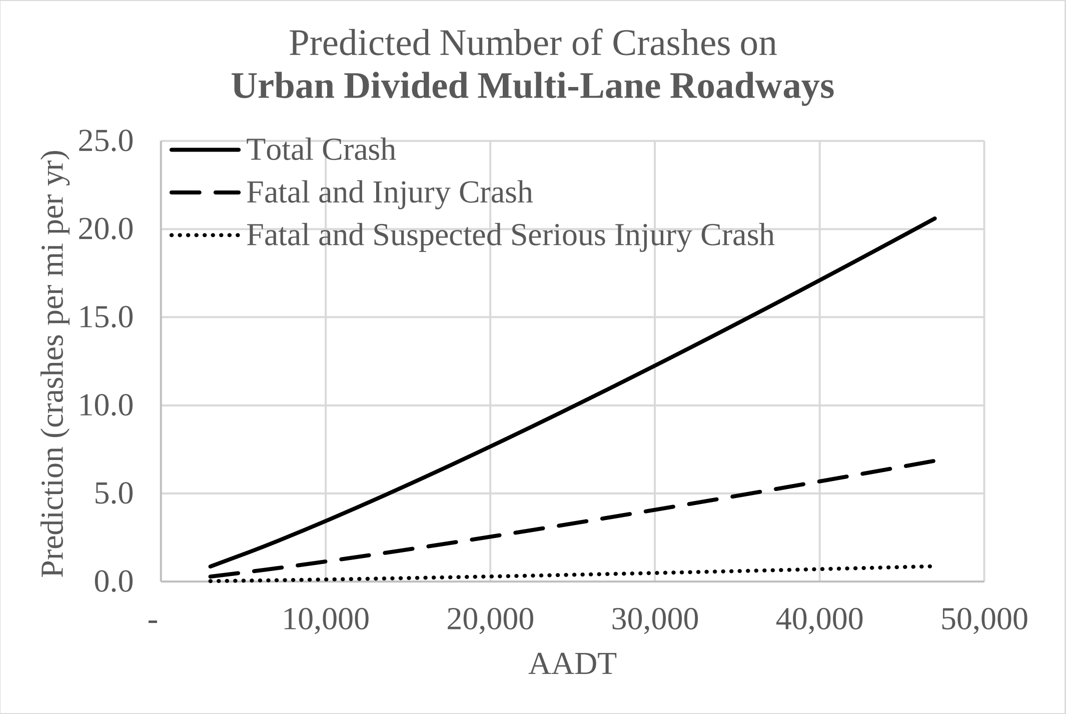


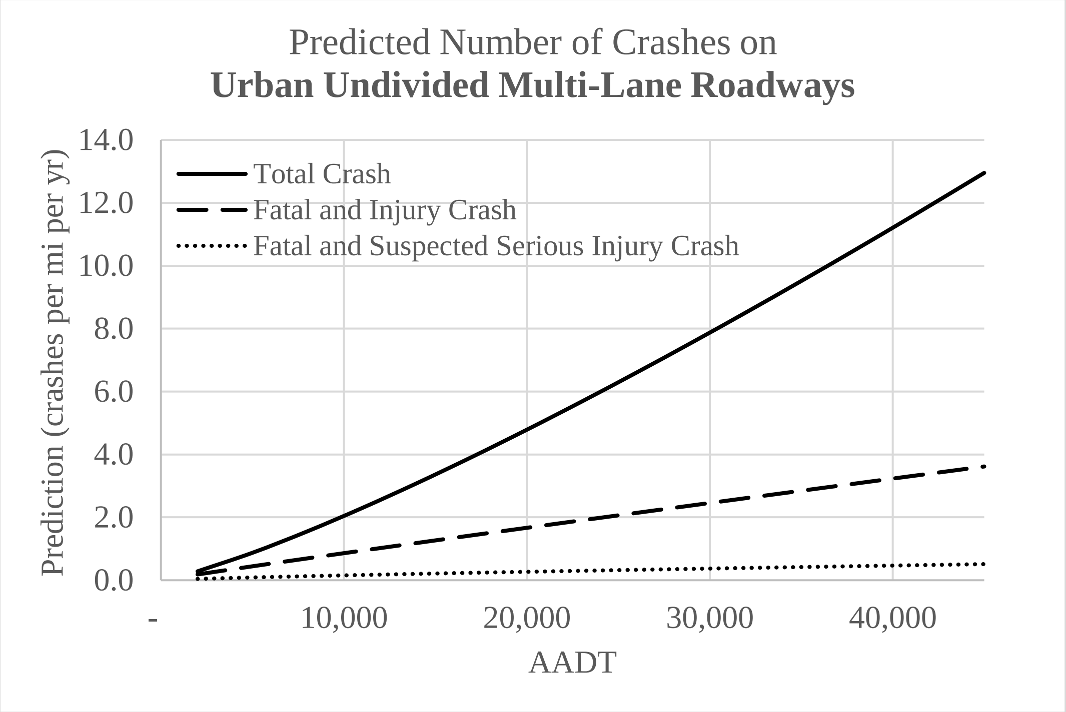


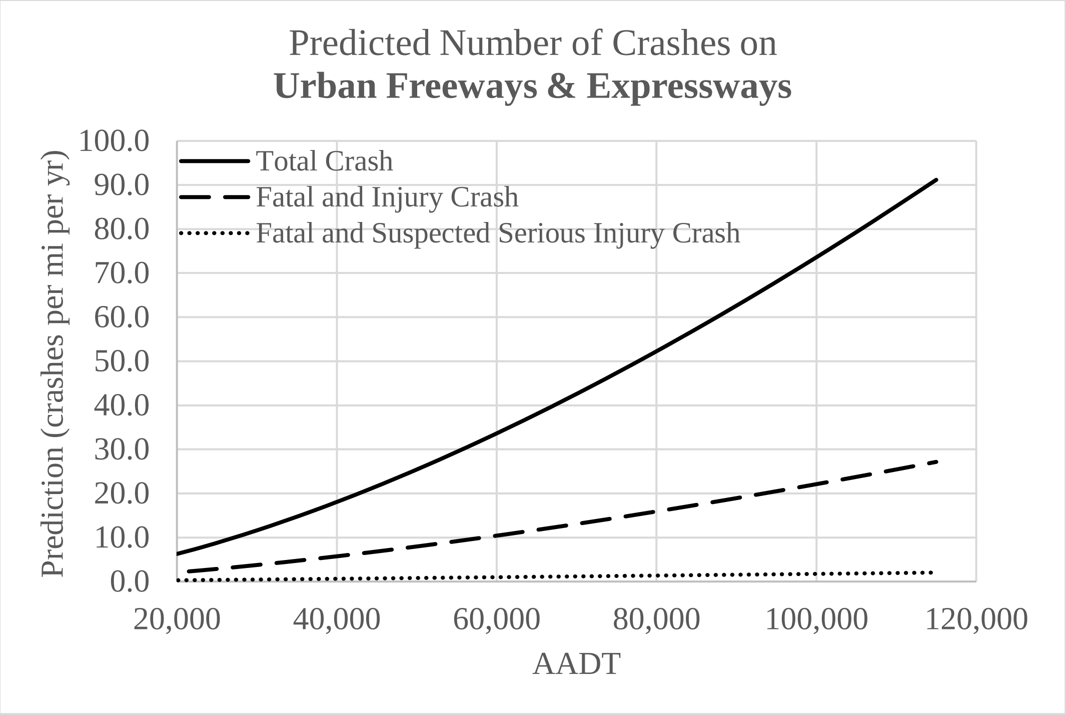


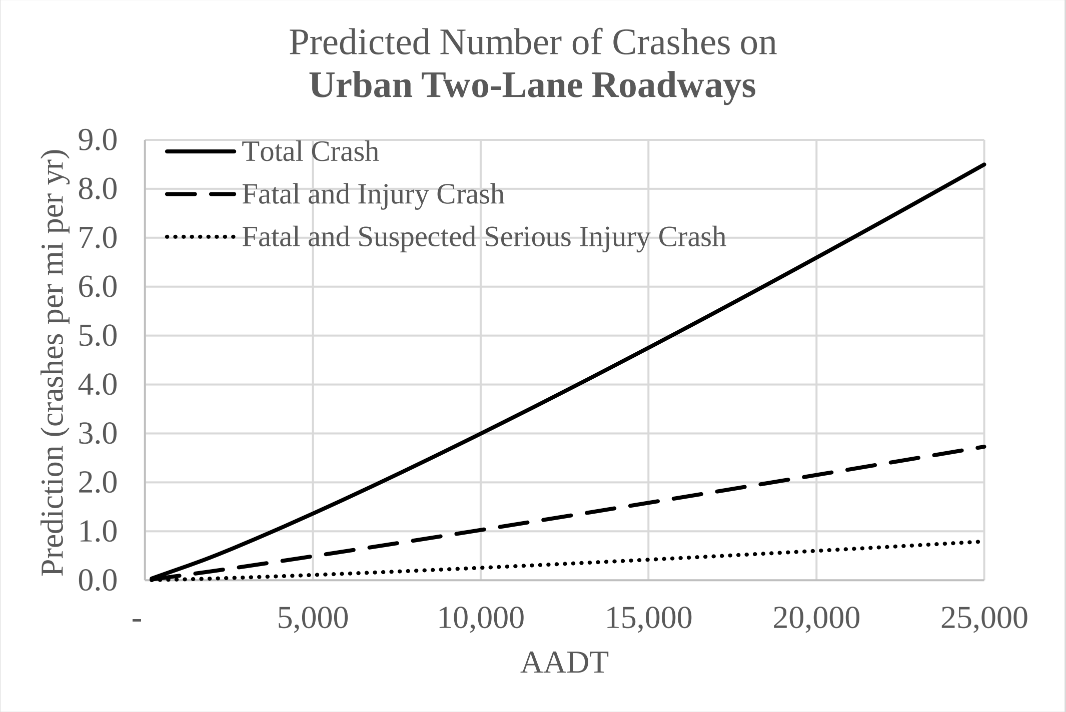
Low sample size—use with CAUTION



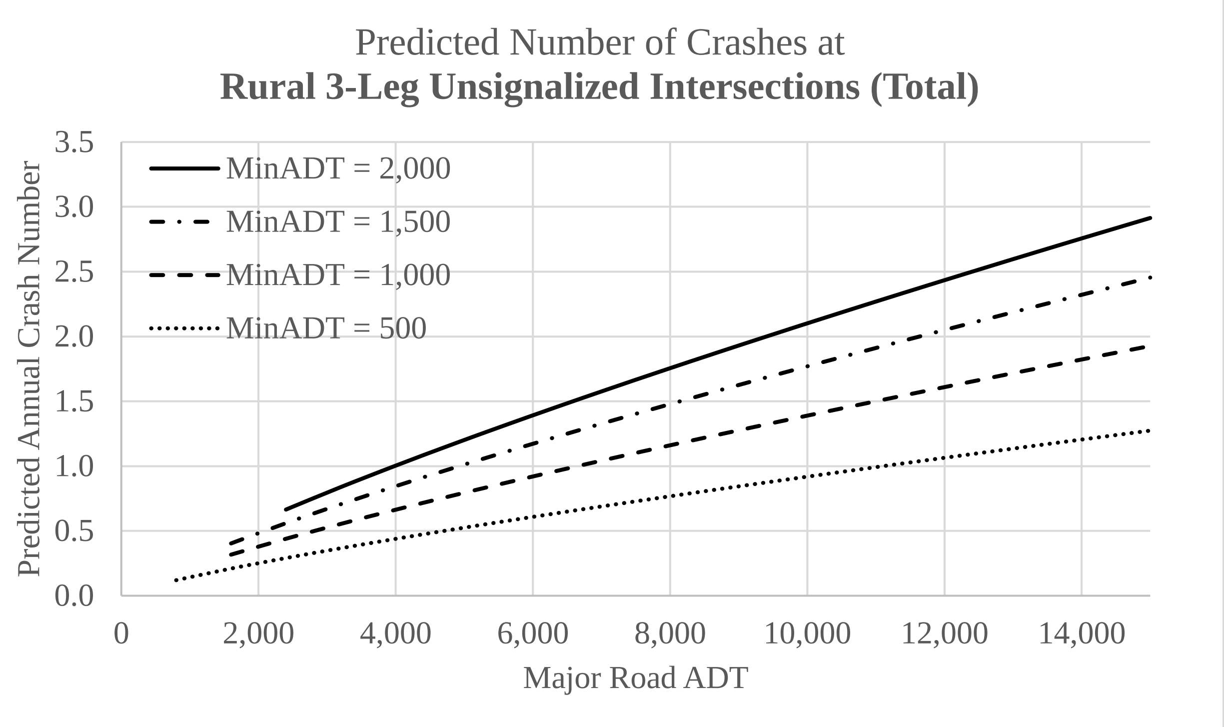

Predicted Number of Crashes on
Urban Divided Multi-Lane Roadways
Total Crash
Fatal and Injury Crash
Fatal and Suspected Serious Injury Crash
Prediction (crashes per mi per yr)
25.0
20.0
15.0
10.0
5.0
0.0
-
10,000
20,000
30,000
40,000
50,000
AADT

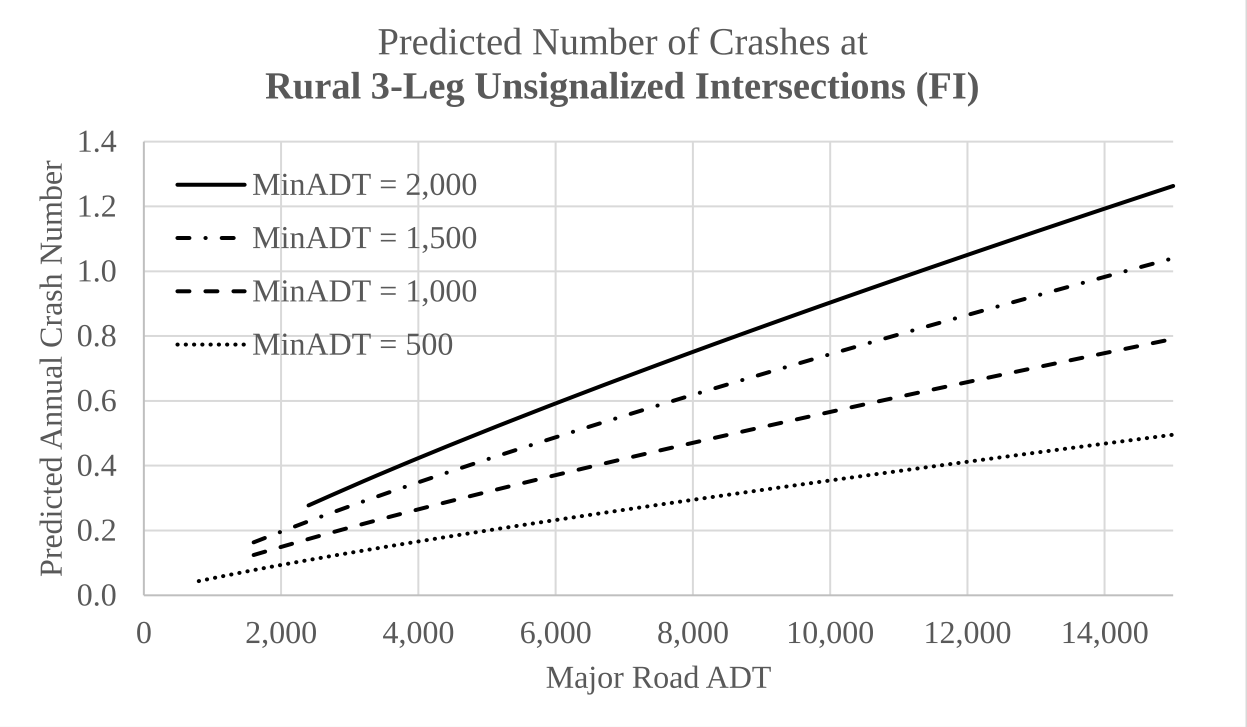

Predicted Number of Crashes on
Urban Undivided Multi-Lane Roadways
Total Crash
Fatal and Injury Crash
Fatal and Suspected Serious Injury Crash
Prediction (crashes per mi per yr)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-
10,000
20,000
30,000
40,000
AADT

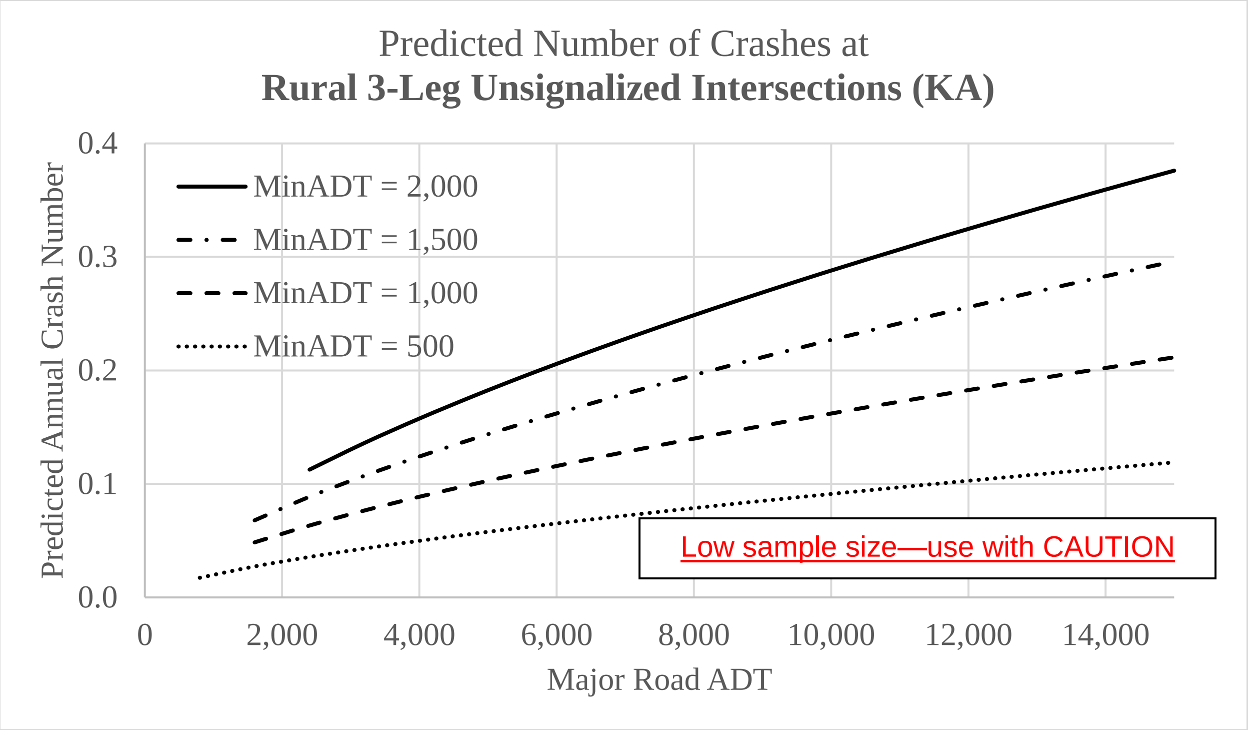

Predicted Number of Crashes on
Urban Freeways & Expressways
Prediction (crashes per mi per yr)
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
20,000
40,000
60,000
80,000
100,000
120,000
AADT
Total Crash
Fatal and Injury Crash
Fatal and Suspected Serious Injury Crash

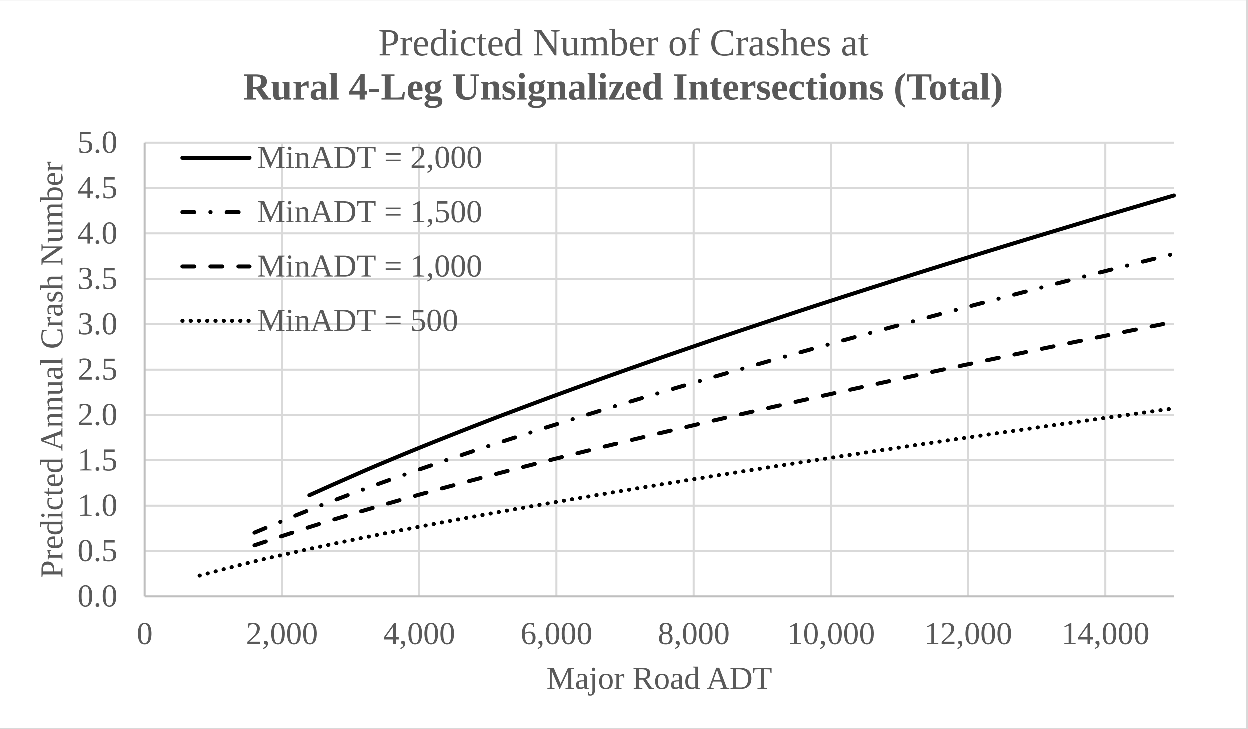

Predicted Number of Crashes on
Urban Two-Lane Roadways
Prediction (crashes per mi per yr)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-
5,000
10,000
15,000
20,000
25,000
AADT
Total Crash
Fatal and Injury Crash
Fatal and Suspected Serious Injury Crash

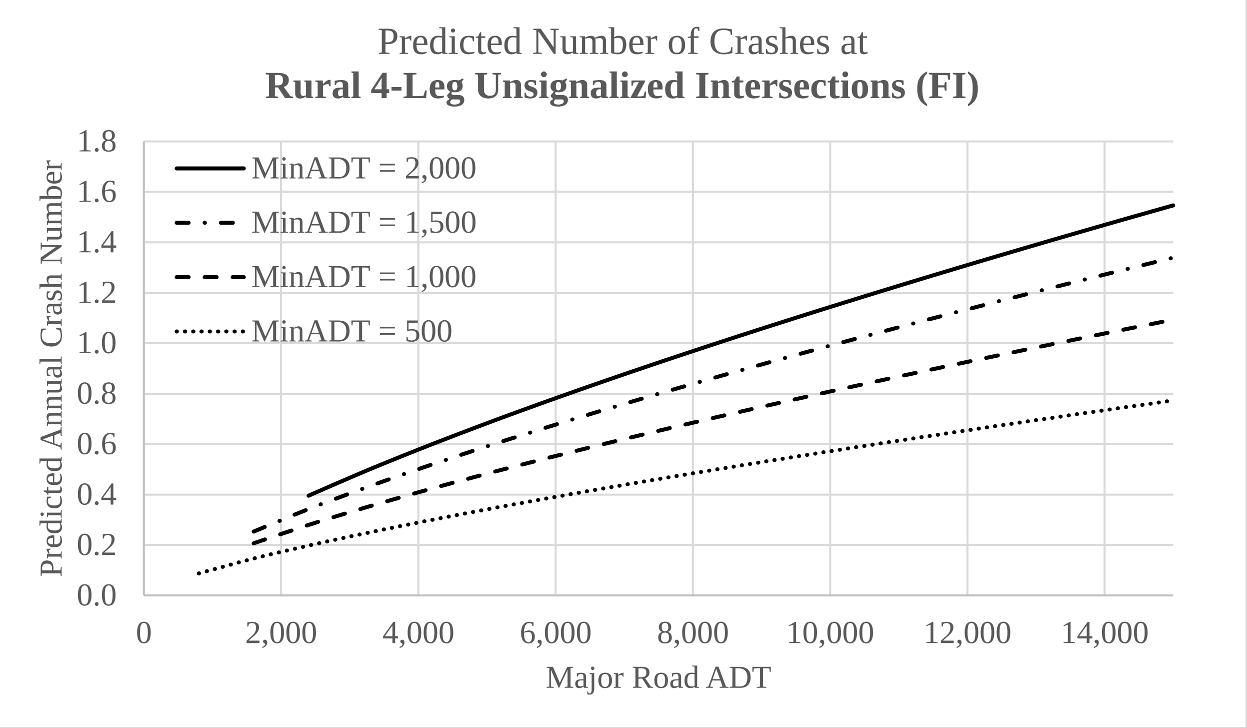
Appendix B. Intersection Benchmark Curves

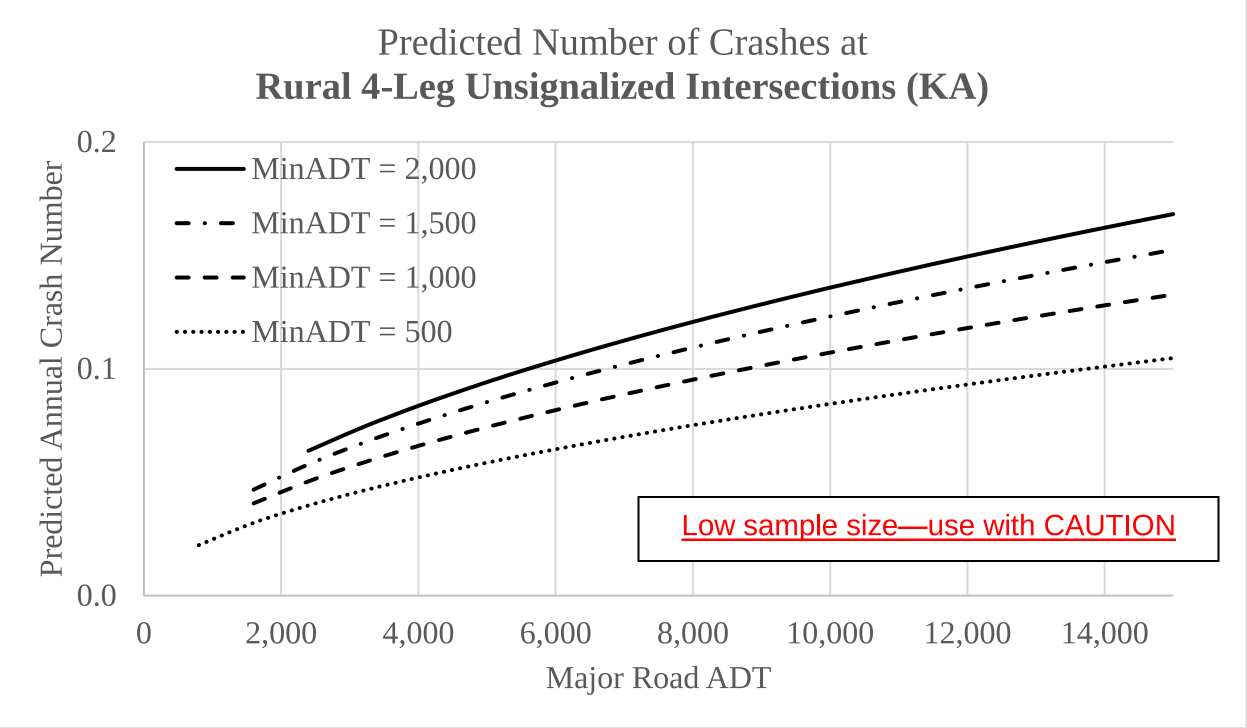


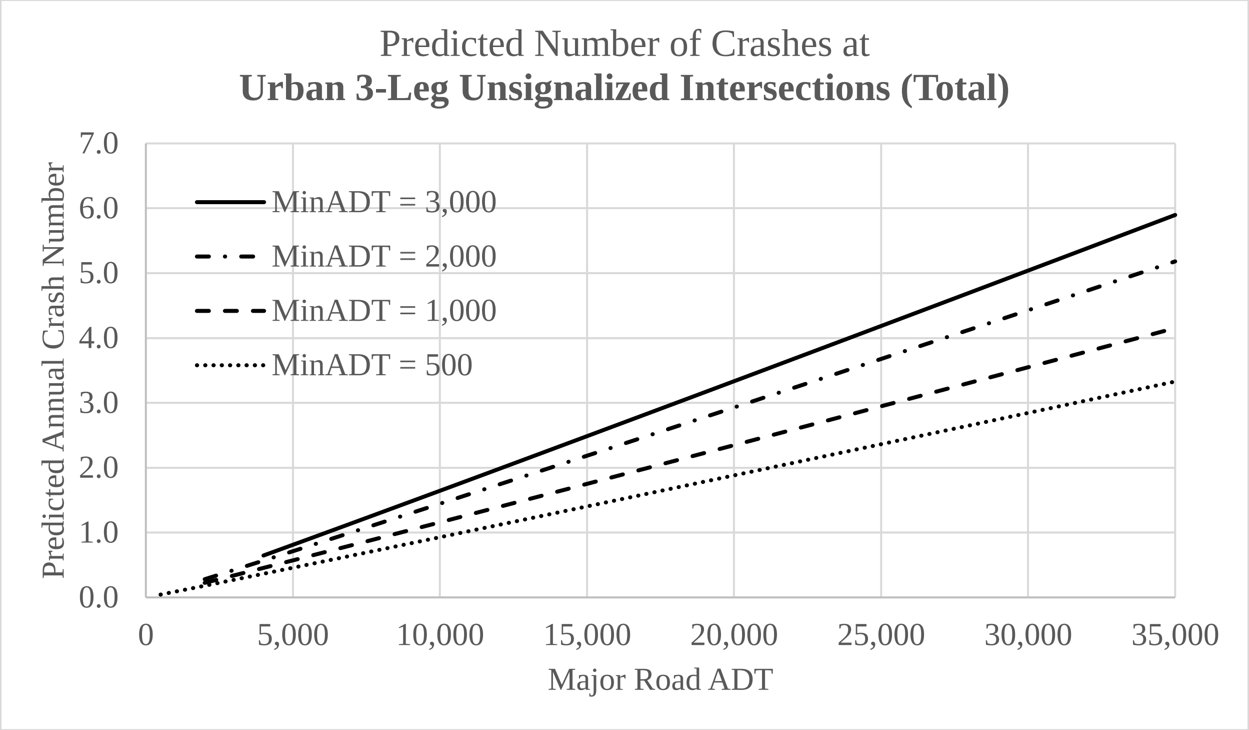


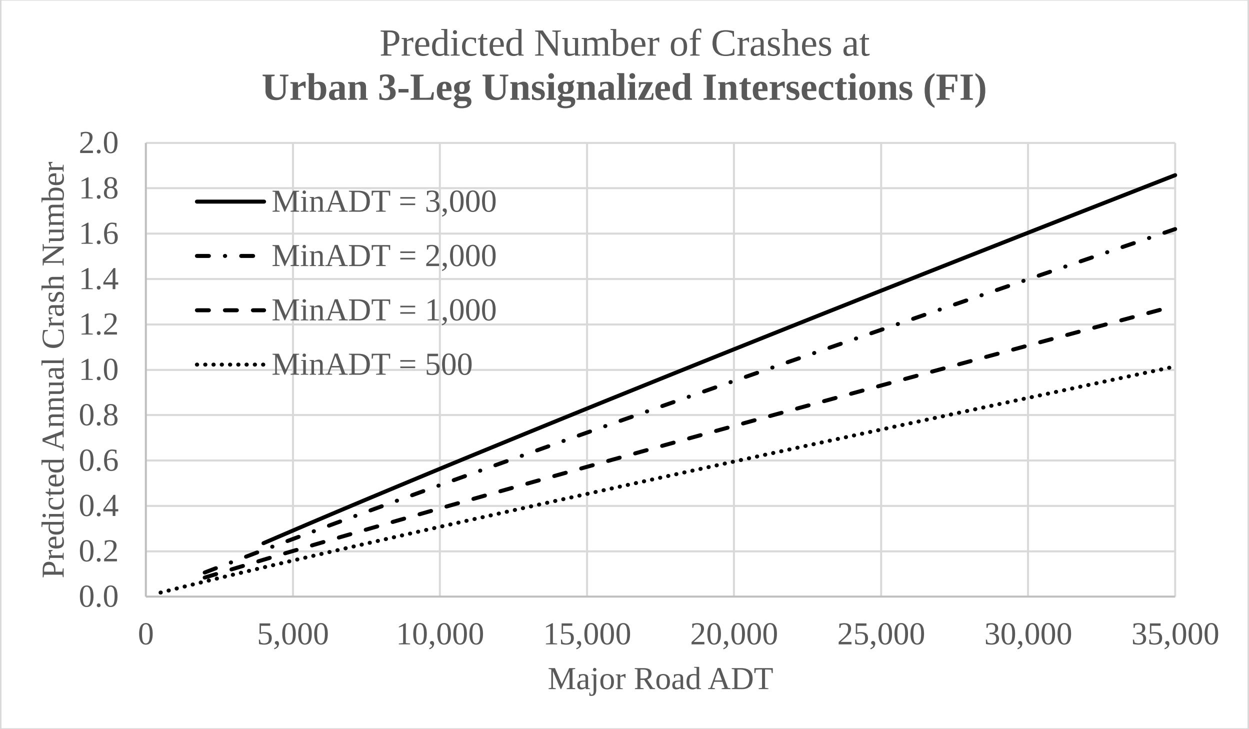

Predicted Number of Crashes at
Rural 3-Leg Unsignalized Intersections (KA)
Predicted Annual Crash Number
0.0
0.1
0.2
0.3
0.4
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
Major Road ADT
MinADT = 2,000
MinADT = 1,500
MinADT = 1,000
MinADT = 500
Low sample size—use with CAUTION

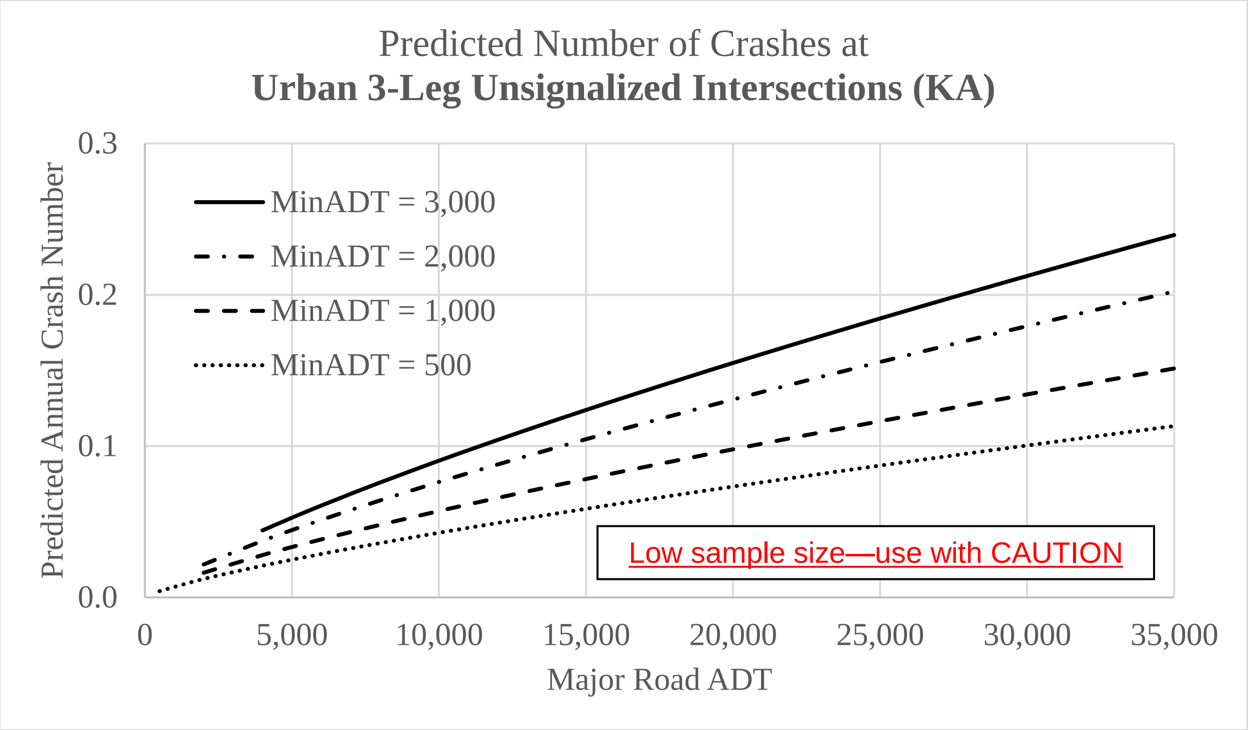

Predicted Number of Crashes at
Rural 4-Leg Unsignalized Intersections (Total)
Predicted Annual Crash Number
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
Major Road ADT
MinADT = 2,000
MinADT = 1,500
MinADT = 1,000
MinADT = 500


Predicted Number of Crashes at
Rural 4-Leg Unsignalized Intersections (FI)
Predicted Annual Crash Number
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
MinADT = 2,000
MinADT = 1,500
MinADT = 1,000
MinADT = 500
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
Major Road ADT

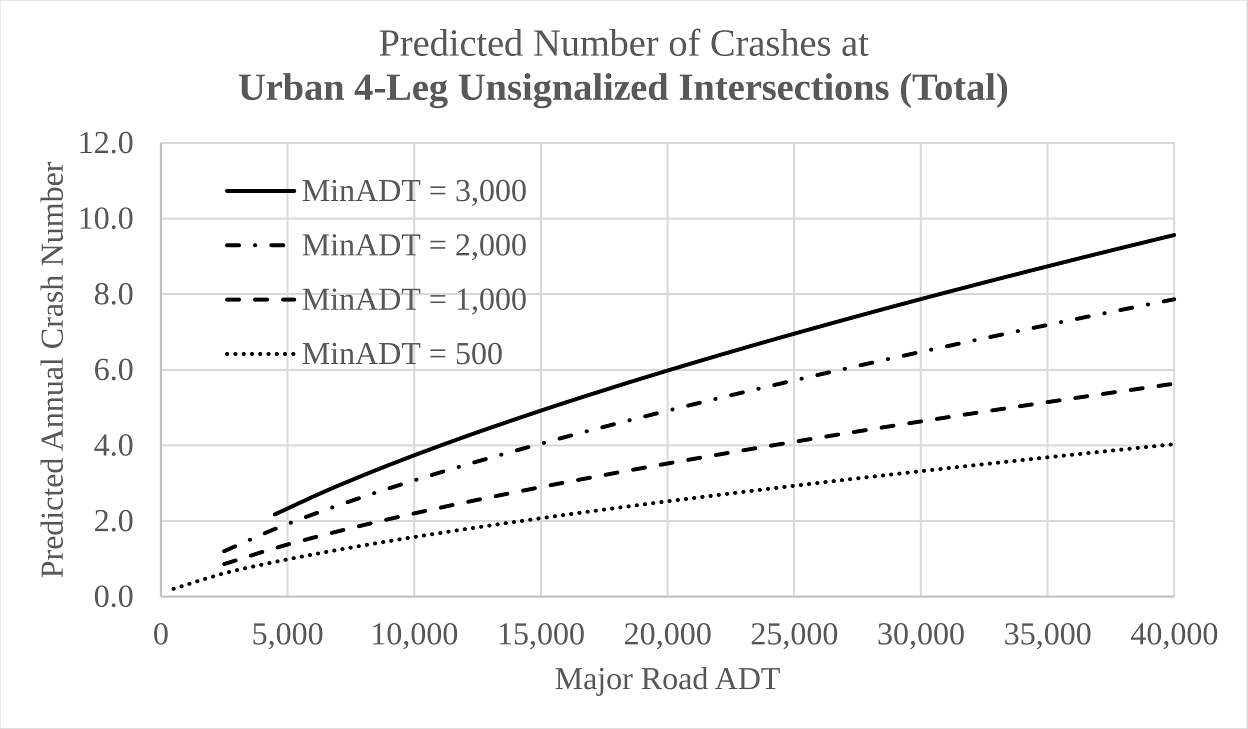

Predicted Number of Crashes at
Rural 4-Leg Unsignalized Intersections (KA)
Predicted Annual Crash Number
0.2
0.1
0.0
MinADT = 2,000
MinADT = 1,500
MinADT = 1,000
MinADT = 500
Low sample size—use with CAUTION
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
Major Road ADT

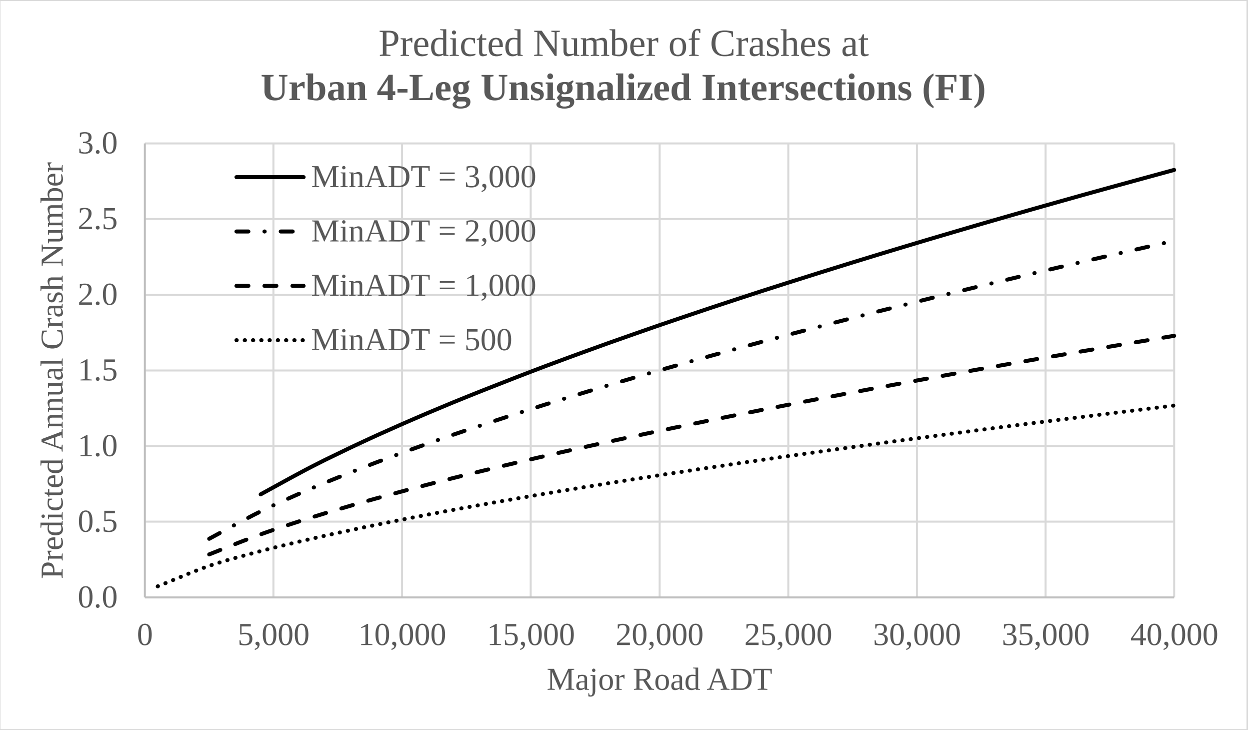

Predicted Number of Crashes at
Urban 3-Leg Unsignalized Intersections (Total)
Predicted Annual Crash Number
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
MinADT = 3,000
MinADT = 2,000
MinADT = 1,000
MinADT = 500
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Major Road ADT

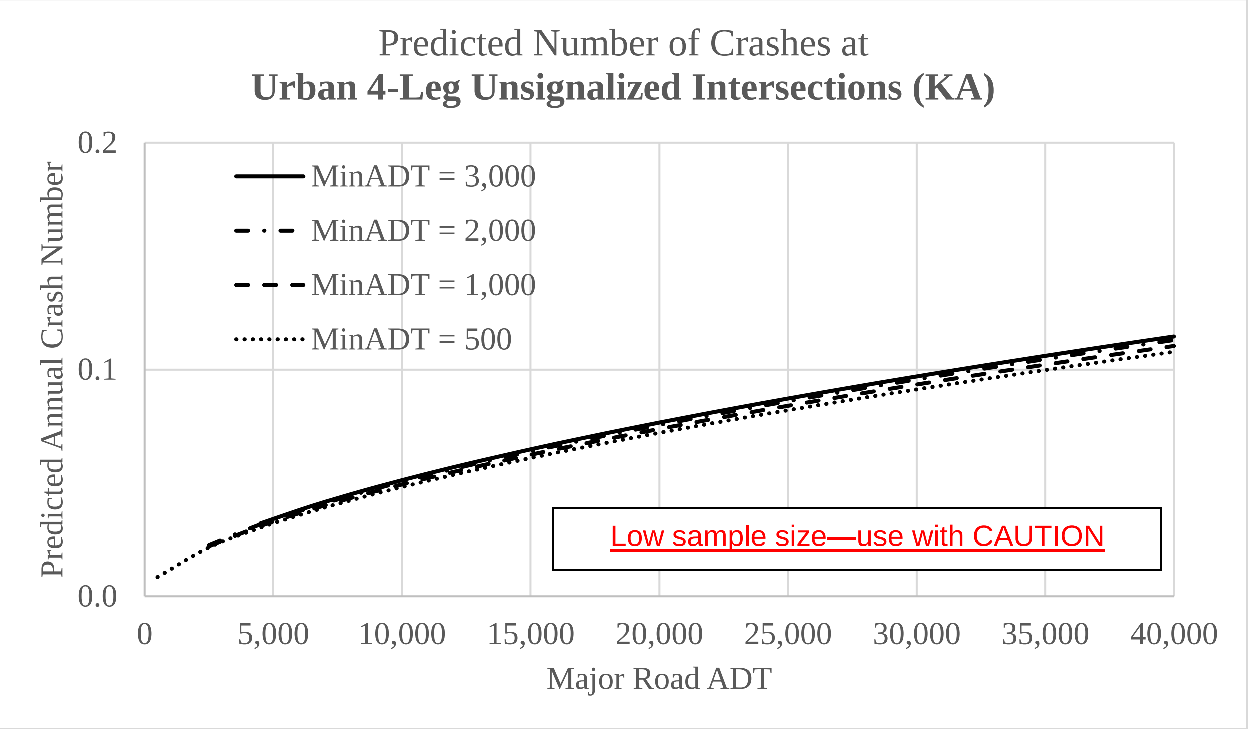

Predicted Number of Crashes at
Urban 3-Leg Unsignalized Intersections (FI)
Predicted Annual Crash Number
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
MinADT = 3,000
MinADT = 2,000
MinADT = 1,000
MinADT = 500
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Major Road ADT

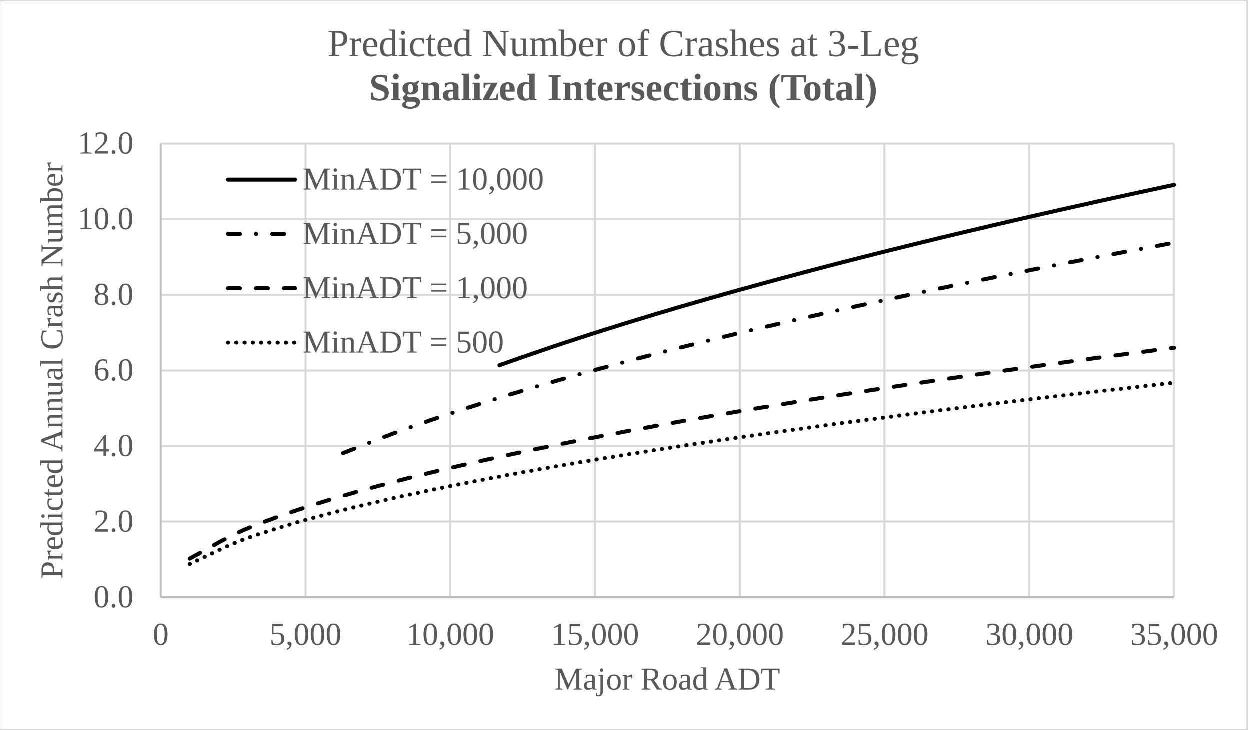


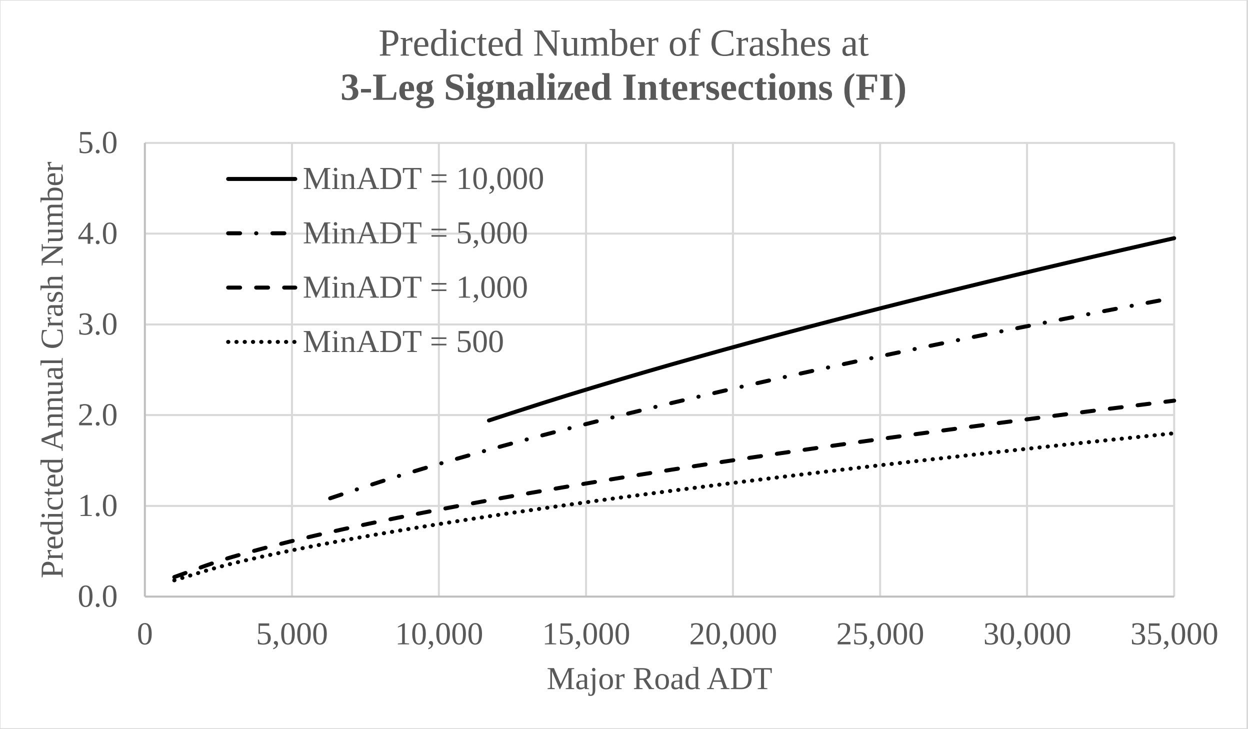
Low sample size—use with CAUTION

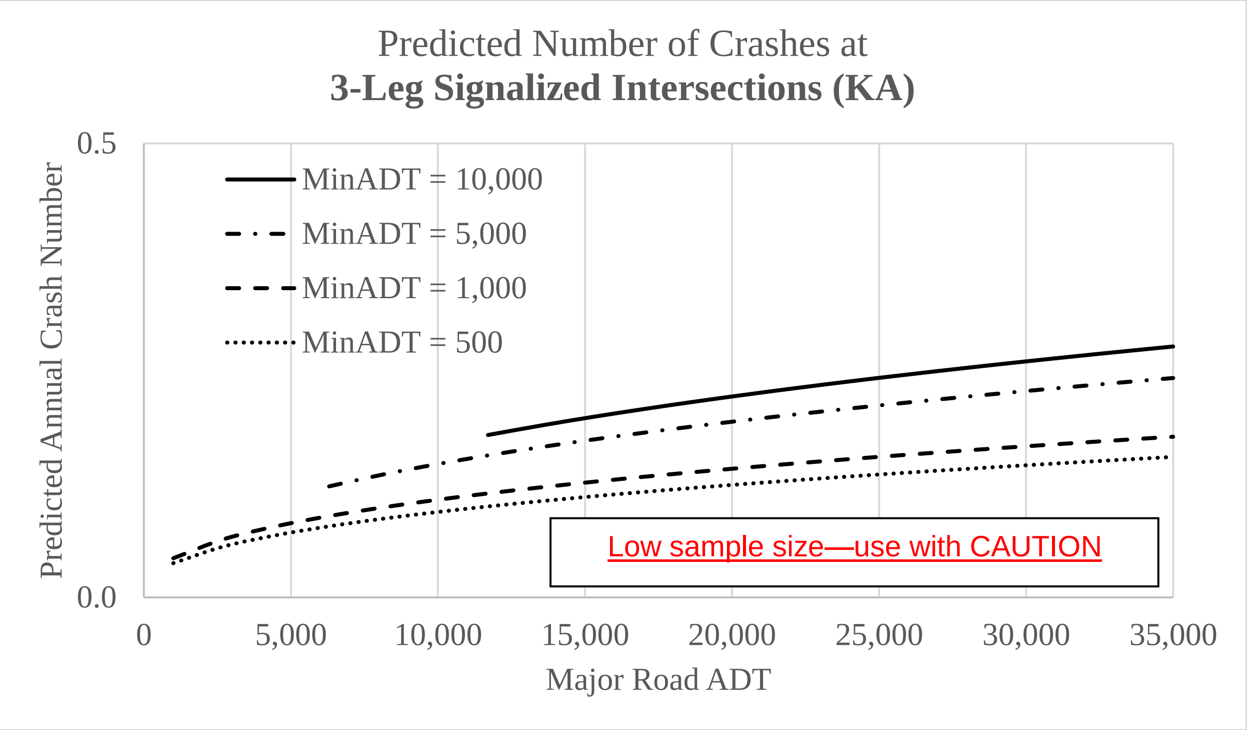


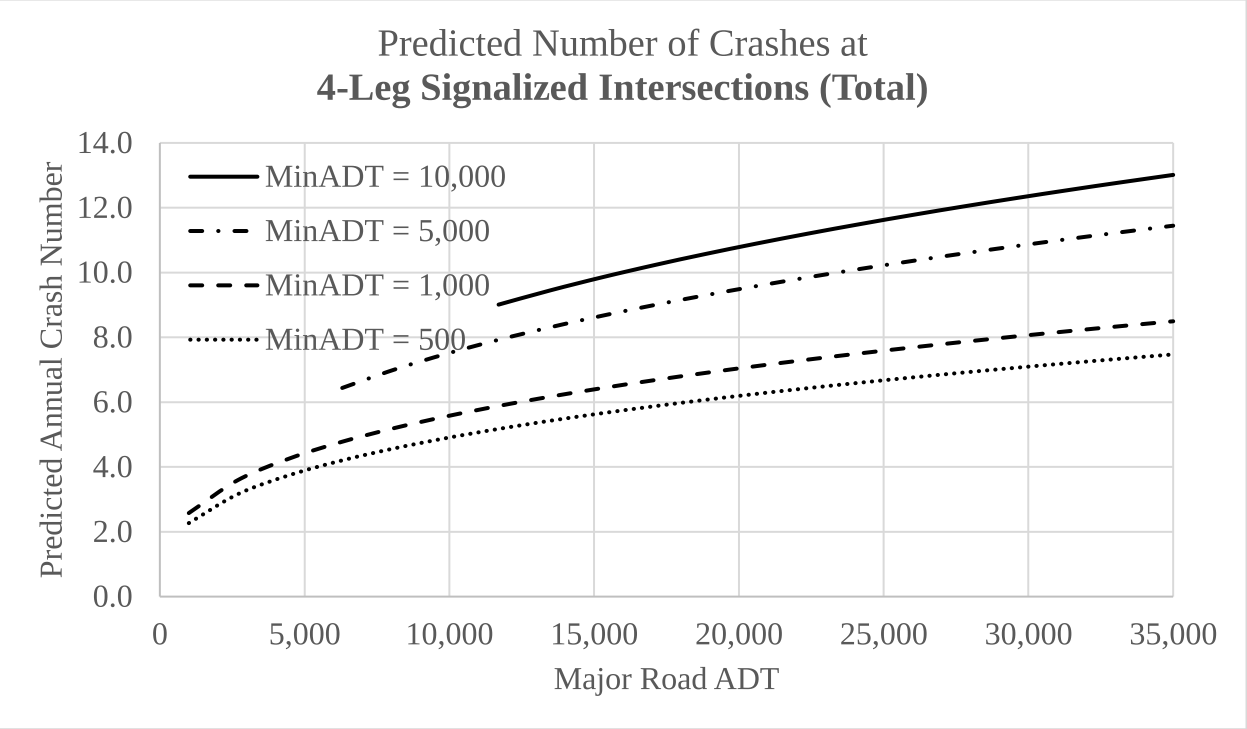

Predicted Number of Crashes at
Urban 4-Leg Unsignalized Intersections (FI)
Predicted Annual Crash Number
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
Major Road ADT
MinADT = 3,000
MinADT = 2,000
MinADT = 1,000
MinADT = 500

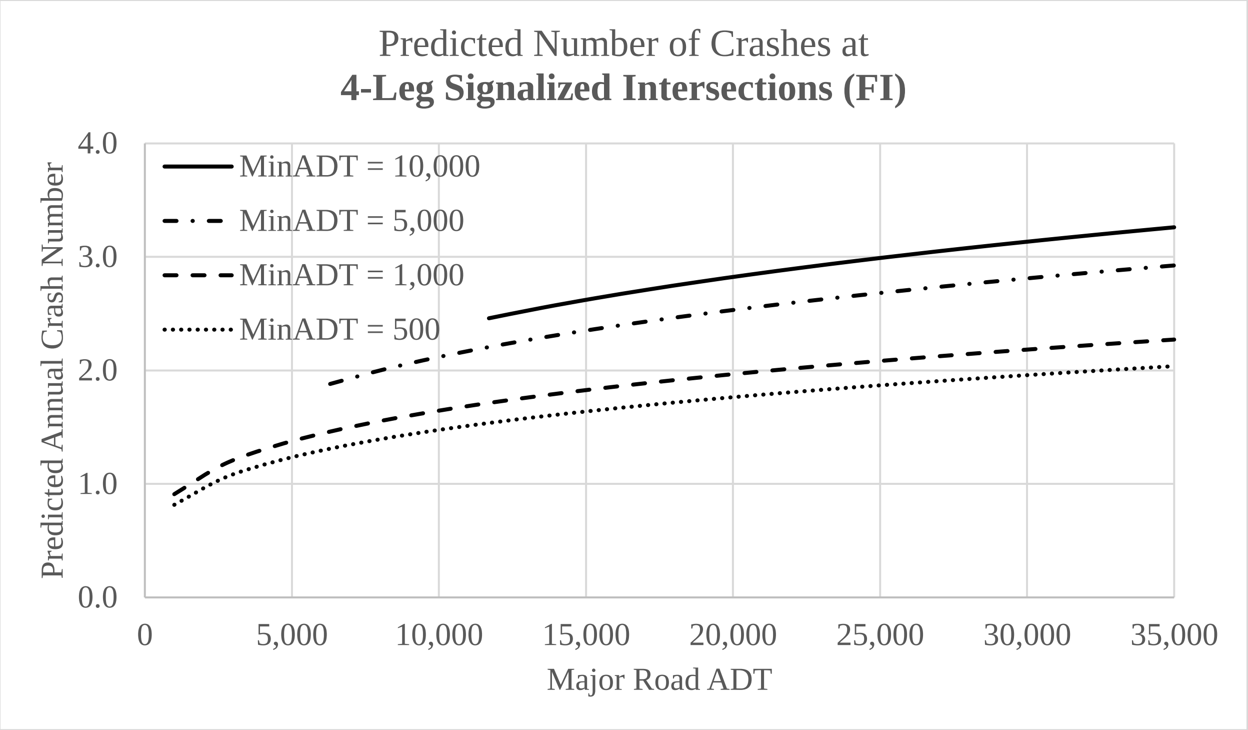

Predicted Number of Crashes at
Urban 4-Leg Unsignalized Intersections (KA)
Predicted Annual Crash Number
0.0
0.1
0.2
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
Major Road ADT
MinADT = 3,000
MinADT = 2,000
MinADT = 1,000
MinADT = 500
Low sample size—use with CAUTION

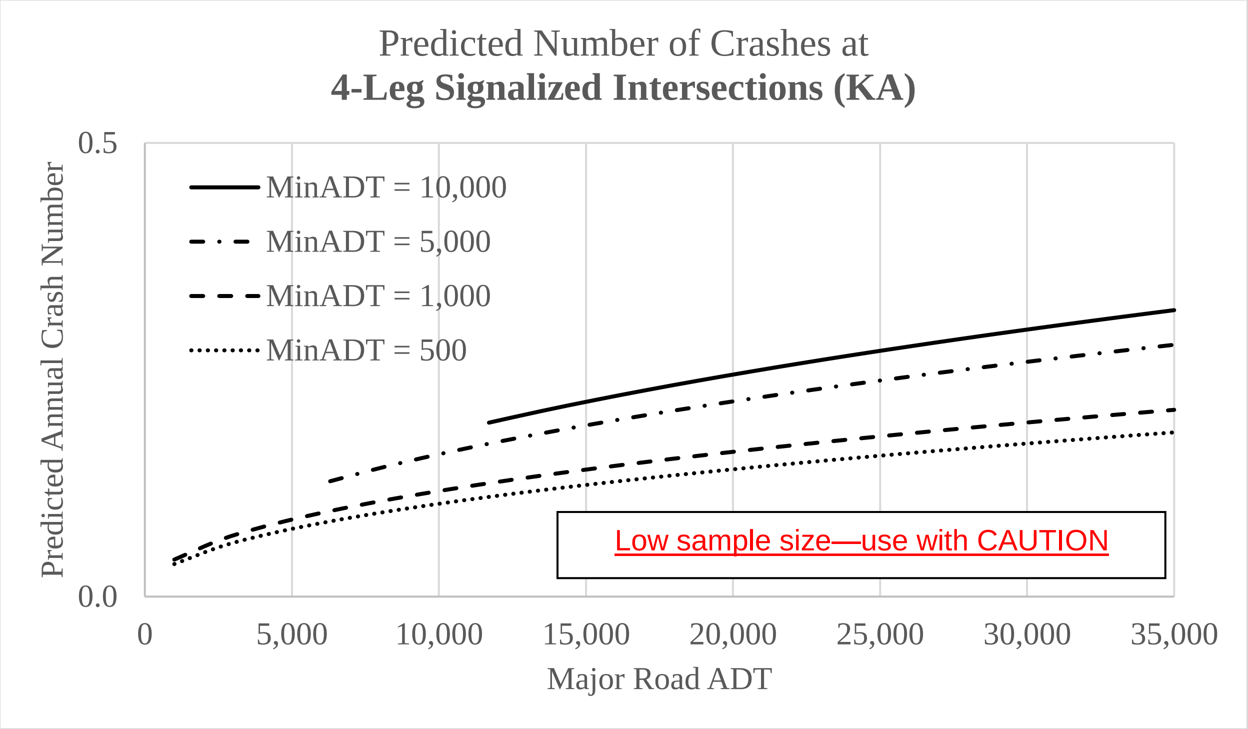

Predicted Number of Crashes at 3-Leg
Signalized Intersections (Total)
MinADT = 10,000
MinADT = 5,000
MinADT = 1,000
MinADT = 500
Predicted Annual Crash Number
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Major Road ADT


Predicted Number of Crashes at
3-Leg Signalized Intersections (FI)
MinADT = 10,000
MinADT = 5,000
MinADT = 1,000
MinADT = 500
Predicted Annual Crash Number
5.0
4.0
3.0
2.0
1.0
0.0
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Major Road ADT


Predicted Number of Crashes at
3-Leg Signalized Intersections (KA)
Predicted Annual Crash Number
0.5
0.0
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Major Road ADT
MinADT = 10,000
MinADT = 5,000
MinADT = 1,000
MinADT = 500
Low sample size—use with CAUTION


Predicted Number of Crashes at
4-Leg Signalized Intersections (Total)
Predicted Annual Crash Number
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Major Road ADT
MinADT = 10,000
MinADT = 5,000
MinADT = 1,000
MinADT = 500


Predicted Number of Crashes at
4-Leg Signalized Intersections (FI)
MinADT = 10,000
MinADT = 5,000
MinADT = 1,000
MinADT = 500
Predicted Annual Crash Number
4.0
3.0
2.0
1.0
0.0
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Major Road ADT


Predicted Number of Crashes at
4-Leg Signalized Intersections (KA)
MinADT = 10,000
MinADT = 5,000
MinADT = 1,000
MinADT = 500
Low sample size—use with CAUTION
Predicted Annual Crash Number
0.5
0.0
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Major Road ADT

Appendix C. Pedestrian Safety Countermeasures

Table 12. Potential Pedestrian Safety Countermeasures.

Category	Countermeasure
Along the roadway	Sidewalks, walkways, and paved shoulders
	Street furniture/walking environment
At crossing locations	Curb ramps
	Marked crosswalks and enhancements
	Curb extensions
	Crossing islands
	Raised pedestrian crossings
	Lighting and Illumination
	Parking restrictions (at crossing locations)
	Pedestrian overpasses/underpasses
	Automated pedestrian detection
	Leading pedestrian interval
	Advance yield/stop lines
Transit	Transit stop improvements
	Access to transit
	Bus bulb-outs
Roadway design	Bicycle lanes
	Lane narrowing
	Lane reduction (road diet)
	Driveway improvements
	Raised medians
	One-way/two-way street conversions
	Improved right-turn slip-lane design
Intersection design	Roundabouts
	Modified T-intersections
	Intersection median barriers
	Curb radius reduction
	Modify skewed intersections
	Pedestrian accommodations at complex interchanges
Traffic calming	Temporary installations for traffic calming
	Chokers
	Chicanes
	Mini-circles
	Speed humps
	Speed tables
	Gateways
	Landscaping
	Specific paving treatments
	Serpentine design

Category	Countermeasure
Traffic management	Diverters
	Full street closure
	Partial street closure
	Left turn prohibitions
Signals and signs	Traffic signals
	Pedestrian signals
	Pedestrian signal timing
	Traffic signal enhancements
	Right-turn-on-red restrictions
	Advanced stop lines at traffic signals
	Left turn phasing
	Push buttons and signal timing
	Pedestrian hybrid beacon
	Rectangular rapid flash beacon
	Puffin crossing
	Signing
Other measures	School zone improvement
	Neighborhood identity
	Speed monitoring
	On-street parking enhancements
	Pedestrian/driver education
	Police enforcement
	Automated enforcement systems
	Pedestrian streets/malls
	Work zones and pedestrian detours
	Pedestrian safety at railroad crossings
	Shared streets
	Streetcar planning and design

Listed in Harkey, D. L., and C. V. Zegeer. *PEDSAFE: Pedestrian Safety Guide and Countermeasure Selection System.* FHWA-SA-04-003. University of North Carolina, 2004.

Appendix D. Annual Average Precipitation for Texas Counties

County	Annual Avg. Precipitation (in.) 1981–2010 National Oceanic and Atmospheric Administration Normal
Anderson	45.14
Andrews	14.74
Angelina	49.25
Aransas	41.01
Archer	30.72
Armstrong	22.25
Atascosa	26.57
Austin	41.75
Bailey	18.38
Bandera	37.37
Bastrop	36.53
Baylor	25.64
Bee	31.97
Bell	33.08
Bexar	34.86
Blanco	34.87
Borden	19.06
Bosque	33.51
Bowie	54.11
Brazoria	53.50
Brazos	40.06
Brewster	17.00
Briscoe	22.41
Brooks	26.47
Brown	30.43
Burleson	39.50
Burnet	33.09
Caldwell	35.19
Calhoun	42.39
Callahan	27.42
Cameron	27.49
Camp	45.10
Carson	21.78
Cass	48.84
Castro	21.22
Chambers	57.11
Cherokee	47.01
Childress	26.43
Clay	32.39
Cochran	18.93
Coke	23.20
Coleman	29.82
Collin	42.07

County	Annual Avg. Precipitation (in.) 1981–2010 National Oceanic and Atmospheric Administration Normal
Collingsworth	22.26
Colorado	43.93
Comal	34.42
Comanche	31.28
Concho	26.99
Cooke	42.70
Coryell	33.66
Cottle	22.63
Crane	15.60
Crockett	22.70
Crosby	23.34
Culberson	21.24
Dallam	16.73
Dallas	38.67
Dawson	19.14
Deaf Smith	20.05
Delta	45.00
Denton	38.09
DeWitt	36.08
Dickens	22.71
Dimmit	22.37
Donley	24.02
Duval	25.99
Eastland	29.02
Ector	16.61
Edwards	25.21
El Paso	10.54
Ellis	38.74
Erath	34.53
Falls	38.46
Fannin	46.13
Fayette	37.68
Fisher	24.76
Floyd	21.60
Foard	26.40
Fort Bend	50.13
Franklin	47.42
Freestone	43.12
Frio	24.88
Gaines	17.52
Galveston	56.81
Garza	20.89
Gillespie	31.69

County	Annual Avg. Precipitation (in.) 1981–2010 National Oceanic and Atmospheric Administration Normal
Glasscock	17.57
Goliad	36.54
Gonzales	33.09
Gray	21.63
Grayson	41.27
Gregg	48.09
Grimes	43.51
Guadalupe	33.54
Hale	20.79
Hall	22.59
Hamilton	31.47
Hansford	20.34
Hardeman	27.34
Hardin	61.70
Harris	46.84
Harrison	51.34
Hartley	21.02
Haskell	26.40
Hays	35.74
Hemphill	22.79
Henderson	42.94
Hidalgo	24.07
Hill	36.06
Hockley	19.84
Hood	35.08
Hopkins	44.80
Houston	45.18
Howard	20.70
Hudspeth	11.11
Hunt	44.46
Hutchinson	22.85
Irion	20.15
Jack	32.11
Jackson	43.25
Jasper	54.75
Jeff Davis	17.47
Jefferson	60.42
Jim Hogg	23.79
Jim Wells	28.79
Johnson	37.28
Jones	26.06
Karnes	30.14
Kaufman	40.15
Kendall	38.10

County	Annual Avg. Precipitation (in.) 1981–2010 National Oceanic and Atmospheric Administration Normal
Kenedy	28.40
Kent	23.51
Kerr	33.63
Kimble	24.53
King	24.82
Kinney	23.56
Kleberg	31.94
Knox	26.43
La Salle	24.70
Lamar	47.07
Lamb	18.87
Lampasas	32.23
Lavaca	41.06
Lee	37.99
Leon	42.29
Liberty	59.92
Limestone	40.34
Lipscomb	21.39
Live Oak	26.36
Llano	27.70
Loving	9.10
Lubbock	21.09
Lynn	21.21
Madison	45.12
Marion	48.96
Martin	17.56
Mason	29.19
Matagorda	48.89
Maverick	20.41
McCulloch	27.63
McLennan	33.34
McMullen	23.87
Medina	30.32
Menard	25.09
Midland	14.80
Milam	36.97
Mills	30.49
Mitchell	20.42
Montague	37.56
Montgomery	48.77
Moore	18.37

County	Annual Avg. Precipitation (in.) 1981–2010 National Oceanic and Atmospheric Administration Normal
Morris	46.79
Motley	23.85
Nacogdoches	55.52
Navarro	39.78
Newton	57.45
Nolan	22.42
Nueces	32.93
Ochiltree	21.09
Oldham	19.45
Orange	59.13
Palo Pinto	32.19
Panola	51.43
Parker	36.01
Parmer	20.14
Pecos	15.25
Polk	57.98
Potter	21.14
Presidio	13.72
Rains	44.47
Randall	20.15
Reagan	19.29
Real	27.38
Red River	52.61
Reeves	13.54
Refugio	34.43
Roberts	24.08
Robertson	39.70
Rockwall	38.58
Runnels	24.04
Rusk	49.36
Sabine	54.60
San Augustine	51.89
San Jacinto	50.68
San Patricio	34.28
San Saba	27.33
Schleicher	23.21
Scurry	21.59
Shackelford	28.36
Shelby	54.20
Sherman	17.77
Smith	46.63
Somervell	36.87
Starr	20.60
Stephens	29.98

County	Annual Avg. Precipitation (in.) 1981–2010 National Oceanic and Atmospheric Administration Normal
Sterling	20.46
Stonewall	23.77
Sutton	23.03
Swisher	21.57
Tarrant	39.60
Taylor	27.15
Terrell	14.72
Terry	19.58
Throckmorton	27.67
Titus	47.70
Tom Green	24.34
Travis	34.89
Trinity	49.31
Tyler	56.18
Upshur	46.84
Upton	15.14
Uvalde	25.63
Val Verde	18.81
Van Zandt	45.80
Victoria	41.08
Walker	49.08
Waller	38.20
Ward	14.40
Washington	45.14
Webb	22.68
Wharton	46.38
Wheeler	26.49
Wichita	31.39
Wilbarger	27.94
Willacy	25.91
Williamson	33.58
Wilson	27.35
Winkler	14.61
Wise	36.83
Wood	48.20
Yoakum	19.20
Young	31.51
Zapata	22.52
Zavala	23.09
All counties	32.13

Appendix E. Performance and Cost of Skid Resistance Enhancement Treatments

Table 13. Skid Resistance for Various Pavement Treatments.

Treatment Type	Test Method*	Approximate Skid Number		Comments
		Initial	Terminal	
High-friction surface treatment (HFST)	SK40R	<70	<60	Calcined bauxite
			55	Flint
Seal coats	SK60	60	55	
Thin asphalt overlays	SK (smooth)	50	30	
Permeable friction course (PFC)	SK40R	35–65	20–55	6-year term
Shot blasting	N/A	53	48 (11 mo.)	
Abrading	N/A	48	38 (11 mo.)	
Water blasting	N/A	N/A	N/A	

* SK: skid number
N/A: not available

Source: Srinivas Geedipally. *Technical Memorandum, Task C: Safety Analysis in Support of Traffic Operations: TxDOT Project 58-6XXIA002, A Systemic Approach to Project Selection for Improving Horizontal Curve Safety.* Texas A&M Transportation Institute, 2016.

Table 14. Mean Texture Depth for Various Pavement Treatments.

Treatment Type	Approximate Mean Texture Depth, mm
HFST	>1.5
Seal coats	>1.0
Thin asphalt overlays	0.4–0.6 (dense-graded), >1.0 (stone-matrix asphalt)
PFC	1.5–3.0
Abrading and texturing	0.7–1.2 (grinding), 0.9–1.4 (grooving)
Water blasting	Varies (depends on aggregate)

Source: Srinivas Geedipally. *Technical Memorandum, Task C: Safety Analysis in Support of Traffic Operations: TxDOT Project 58-6XXIA002, A Systemic Approach to Project Selection for Improving Horizontal Curve Safety.* Texas A&M Transportation Institute, 2016.

Table 15. Service Life for Various Pavement Treatments.

Treatment Type	Approximate Service Life, yr
HFST	7–12
Seal coats	3–15
Thin asphalt overlays	8–15
PFC	10–15
Diamond grinding	8
Abrading and shot blasting	2
Water blasting	Data not available

Source: Michael P. Pratt, Srinivas R. Geedipally, Bryan Wilson, Subasish Das, Marcus Brewer, and Dominique Lord. *Pavement Safety-Based Guidelines for Horizontal Curve Safety.* Report 0-6932-R1. Texas A&M Transportation Institute, 2018.

Table 16. Unit Cost for Various Pavement Treatments.

Treatment Type	Approximate Unit Cost
HFST	$\$21/\text{yd}^2$
Seal coats	$\$1–\$2.50/\text{yd}^2$
Thin asphalt overlays	$\$3–\$6/\text{yd}^2$
PFC	$7/yd2
Diamond grinding	$\$1.70–\$6.70/\text{yd}^2$
Shot blasting (48-in. width)	$\$3/\text{yd}^2$
Abrading (72-in. width)	$\$2/\text{yd}^2$
Water blasting	$\$1/\text{yd}^2$ less expensive than the average strip/spot sealing

Source: Michael P. Pratt, Srinivas R. Geedipally, Bryan Wilson, Subasish Das, Marcus Brewer, and Dominique Lord. *Pavement Safety-Based Guidelines for Horizontal Curve Safety.* Report 0-6932-R1. Texas A&M Transportation Institute, 2018.

Table 17. Crash Reduction Performance for Various Pavement Treatments.

Treatment Type	Section Type	Crash Type	Approximate CMF Value[1]	
			Average	Range
HFST	Curves and ramps, generally high-accident locations	Wet	0.34	0.14–0.48
		Total	0.72	0.65–0.75
Seal coats	Two-way and multilane roads (not high-accident specific)	Wet	0.76	0.42–1.60
		Total	1.15	0.83–1.52
Thin asphalt overlays	Multilane roads and freeways	Wet	0.87	0.53–1.27
		Total	0.99	0.93–1.20
PFC	Freeways (California and North Carolina)	Wet	0.68	0.51–1.04
		Total	0.94	0.74–1.10
Abrading and texturing	California freeways	Wet	2.03	N/A
		Total	0.77	N/A
Water blasting	N/A	N/A	N/A	N/A

Notes:
[1] CMF = 1 – crash reduction factor / 100
N/A = not available

Source: Michael P. Pratt, Srinivas R. Geedipally, Bryan Wilson, Subasish Das, Marcus Brewer, and Dominique Lord. *Pavement Safety-Based Guidelines for Horizontal Curve Safety.* Report 0-6932-R1. Texas A&M Transportation Institute, 2018.

Appendix F. Candidate Countermeasures for Reducing Curve-Related Crashes

Table 18. List of Candidate Countermeasures for Reducing Curve-Related Crashes.

Treatment	Road Type	Crash Type (Severity)	CMF	App. Cost	Service Life (yr)
Install centerline markings	Unspecified	All (injury)	0.99	$650 per mi	2
Place edgeline markings	Rural two lane	All (injury)	0.73	$650 per mi	2
Install post-mounted delineators	Rural two lane undivided	All (injury)	0.70	$3,000 per curve	2
Install horizontal alignment signs	Unspecified	All (all)	0.82	$300 per unit	6
Install combination horizontal alignment/advisory speed signs	Unspecified	All (injury)	0.87	$300 per unit	6
Install chevrons (curve)	Unspecified	SVROR (all)	0.86	$3,000 per curve	10
Install raised pavement markers	Rural two-lane (r ≤ 1,640 ft)	Nighttime (all)	1.43*	$1,360 per mi	3
Safety treat fixed objects	Unspecified	SVROR (injury)	0.50	$300,000 per mi	20
Dynamic curve warning system	Unspecified	All (all)	0.59	$18,000 per unit	10
Speed advisory marking in lane	Unspecified	All (all)	0.94	$300 per unit	2
Install rumble strips	Rural two-lane highway	SVROR and head-on (all)	0.61	$2,640 per mi	10
Flatten side slope (provide an embankment side slope of 6:1 or flatter)	Unspecified	SVROR (all)	0.54	$300,000 per mi	20
Install high-friction surface treatment (curve)	Unspecified	All (all)	0.55	$20/sq yd	5
Increase superelevation	Unspecified	All (all)	0.35	$200,000 per mi	10

* A CMF greater than 1.0 indicates that nighttime crashes on sharp curves will increase after installing raised pavement markers.

Table 19. Cost, Effectiveness, and Time Frame for Implementation of Potential Countermeasures for SVROR Crashes.

Countermeasure	Cost[1]	Effectiveness[2]	Time Frame for Implementation[3]
Install centerline markings	Low	Low	Short
Place edgeline markings	Low	Moderate	Short
Install post-mounted delineators	Low	High	Short
Install horizontal alignment signs	Low	Moderate	Short
Install combination horizontal alignment/advisory speed signs	Low	Moderate	Short
Install chevrons (curve)	Low	Moderate	Short
Install raised pavement markers	Low	Low	Short
Safely treat fixed objects	High	High	Short to medium
Dynamic curve warning system	Moderate	High	Short
Speed advisory marking in lane	Low	Low	Short
Install rumble strips	Low	High	Short
Flatten side slope (provide an embankment side slope of 6:1 or flatter)	High	High	Short to medium
Install high-friction surface treatment (curve)	High	High	Short
Increase superelevation	High	High	Short to medium

Notes:

[1] **Cost:** low: <$10,000 per mile or implementation; moderate: $10,000 to $100,000 per mile or implementation; high: >$100,000 per mile or implementation.

[2] **Effectiveness:** low: CMF > 0.9; moderate: 0.7 < CMF ≤ 0.9; high: CMF ≤ 0.7.

[3] **Implementation (construction period):** short: less than a year; medium: 1 to 2 years; long: more than 2 years.