TTI: 0-6932

Guidelines and Evaluation Framework for Horizontal Curve Wet-Surface Safety Analysis: A User Guide

Technical Report 0-6932-P1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
http://tti.tamu.edu/documents/0-6932-P1.pdf

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-18/0-6932-P1		

4. Title and Subtitle
GUIDELINES AND EVALUATION FRAMEWORK FOR HORIZONTAL CURVE WET-SURFACE SAFETY ANALYSIS: A USER GUIDE

5. Report Date
Published: November 2018

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.
Product 0-6932-P1

9. Performing Organization Name and Address
Texas A&M Transportation Institute
College Station, Texas 77843-3135

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
Project 0-6932

12. Sponsoring Agency Name and Address
Texas Department of Transportation
Research and Technology Implementation Office
125 E. 11th Street
Austin, Texas 78701-2483

13. Type of Report and Period Covered
Technical Report:
September 2016–August 2018

14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Developing Pavement Safety-Based Guidelines for Improving Horizontal Curve Safety
URL: http://tti.tamu.edu/documents/0-6932-P1.pdf

16. Abstract

The Texas Department of Transportation is increasing its efforts to improve rural highway curve safety by including high-friction surface treatments in the Highway Safety Improvement Program (HSIP). A handful of efforts are underway in the state to install these treatments or others that are intended to improve safety by increasing pavement skid resistance. However, HSIP funds are very limited. Hence, it is necessary to prioritize projects carefully to spend the limited funds where they would yield the greatest benefit in terms of crashes reduced and injuries and fatalities prevented.

Researchers calibrated detailed safety prediction models to account for the effects of key curve characteristics, including geometry, pavement variables (particularly skid resistance), and weather patterns. Additionally, researchers developed estimates of the service life for various surface treatments that may be used to increase skid resistance. By combining safety prediction models, weather data, and service life data, researchers created guidelines and a life-cycle benefit-cost evaluation framework to assist practitioners in choosing effective safety treatments for curves. This document describes the guidelines and spreadsheet-based evaluation framework and provides analysts with a User Guide for the framework.

17. Key Words
Highway Design, Highway Safety, Rural Highways, Highway Curves, Pavement, Skid Resistance, Crash, Crash Risk

18. Distribution Statement
No restrictions. This document is available to the public through NTIS:
National Technical Information Service
Alexandria, Virginia 22312
http://www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	41	

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Product 0-6932-P1
Project 0-6932
Project Title: Developing Pavement Safety-Based Guidelines for Improving Horizontal Curve Safety

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

Published: November 2018

TEXAS A&M TRANSPORTATION INSTITUTE
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DISCLAIMER

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NOTICE

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

TxDOT and FHWA sponsored this research project. Mr. Michael Pratt, Dr. Srinivas Geedipally, Mr. Bryan Wilson, and Dr. Dominique Lord prepared this document.

The researchers acknowledge the support and guidance that the project monitoring committee provided:

- Mr. Darrin Jensen, Project Manager (TxDOT, Research and Technology Implementation Office).
- Mr. Tommy Abrego (TxDOT, Policy & Standards).
- Mr. Epigmenio Gonzalez (TxDOT, Pharr District).
- Mr. John Bassett (TxDOT, Construction Division).
- Mr. Soojun Ha (TxDOT, Houston District).
- Ms. Patti Dathe, Contract Specialist (TxDOT, Research and Technology Implementation Office).

In addition, the researchers acknowledge the valuable contributions of Dr. Subasish Das, Mr. Marcus Brewer, Mr. Tom Freeman, Mr. Yash Menaria, Mr. Soheil Sohrabi, Ms. Ruth Iroanya, Mr. Pawan Dixit, and Ms. Katherine Lufkin, who assisted with various tasks during the conduct of the project.

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CHAPTER 1. OVERVIEW

INTRODUCTION

Horizontal curves are an essential part of the highway system, and they represent a small percentage of overall highway mileage, but they experience a disproportionate share of highway crashes. In particular, curves have been shown to be susceptible to run-off-road crashes and wet-weather crashes (*1*, *2*). Hence, efforts to reduce crash frequency on state-maintained highways need to consider rural highway curves.

Horizontal curve safety is influenced by various factors relating to geometry, traffic volume and speed, pavement, weather patterns, and traffic control devices. The Texas Department of Transportation (TxDOT) conducts several programs to identify high-crash locations and identify and implement safety treatments to reduce crashes. Two of these programs include the Highway Safety Improvement Program (HSIP) and the Wet-Surface Crash Reduction Program (WSCRP). These types of programs require identification of locations with safety concerns and evaluation of proposed treatments to assess cost-effectiveness. Since roadway safety improvement funding sources are limited, it is necessary to evaluate the effectiveness of treatments so the largest possible benefit (in terms of reduced crash frequency and/or severity) can be obtained with the limited resources.

In TxDOT research project 0-6932, researchers developed guidelines and an evaluation framework to assist practitioners in evaluating curve pavement safety issues and identifying cost-effective treatments. This document describes the procedures to apply these tools.

CURVE PAVEMENT SAFETY EVALUATION PROCESS

The *Pavement Design Guide* (*3*) provides the following description of TxDOT's approach to addressing wet-surface safety issues:

> The [WSCRP] allows the department to take advantage of the increased knowledge gained through our research efforts and to more effectively and efficiently address the various regional demands of Texas pavements. [WSCRP] addresses three separate but interrelated phases of pavement friction safety. The three phases are accident analysis, aggregate selection, and skid testing.

TxDOT's *Wet-Surface Crash Reduction Program Guidelines* (*4*) contains guidance for identifying roadway sections that are susceptible to increased wet-surface crash frequency based on examining the proportion of wet-surface crashes. This document contains a map that splits the state of Texas into three regions defined as having low, moderate, or high rainfall. Hence, the analyst is directed to consider both crash trends (in terms of wet-surface crash proportion) and geographic exposure to wet weather. The WSCRP guidelines also describe a process of sorting and ranking state-maintained highway sections (i.e., continuous stretches of both curves and tangents) by wet-surface crash proportion to identify candidate locations for safety countermeasures.

To assist practitioners in aggregate selection, TxDOT's Form 2088 (titled Surface Aggregate Selection Form) (*3*) provides calculation tables for conducting a qualitative margin-of-safety analysis. Generally, margin of safety is defined as friction supply minus friction demand (*5*). Form 2088 contains tables to estimate demand for friction (or friction demand) and available friction (or friction supply). In TxDOT research project 0-6714, researchers developed a quantitative margin-of-safety analysis tool in the form of an Excel®-based spreadsheet program called Texas Curve Margin of Safety (TCMS). Researchers in TxDOT research project 0-6932 updated and expanded the TCMS program to incorporate new safety prediction models, weather data, pavement material life span data (in terms of initial and terminal skid number and rate of change of skid number), and pavement treatment cost. These updates allow practitioners to conduct a detailed benefit-cost analysis for proposed pavement surface treatments on curves.

The following two chapters describe the guidelines, which represent a planning-level analysis to identify curves that may benefit from the implementation of a pavement friction treatment, and the evaluation framework, which is a detailed analysis tool to quantify the benefit of a proposed pavement treatment. The guidelines focus on reduction of wet-weather crashes on curves, which are the crashes that are most affected by skid resistance. The evaluation framework applies to pavement surface treatments and treatments to increase the curve's superelevation rate.

CHAPTER 2. HORIZONTAL CURVE WET-WEATHER SAFETY SCREENING GUIDELINES

RATIONALE

Many horizontal curves exist on TxDOT-maintained rural highways, but due to limited resources, safety treatments can be implemented on only a small number of curves each year. Treatment options vary significantly in both effectiveness and cost. The most effective curve safety treatment is straightening (i.e., increasing the radius); however, it is also the most expensive treatment and can rarely be implemented. Treatments to improve curve delineation using traffic control devices (e.g., Chevrons or wider edgelines) are low-cost but also limited in their effectiveness. Pavement-based safety treatments represent a third category of treatments, which rank between straightening and traffic control devices in cost and effectiveness.

Pavement-based treatments are most likely to be effective in reducing wet-weather crashes, as it is rare for skid resistance to be inadequate in dry-weather conditions. Hence, to identify curves that are more likely to benefit from the implementation of a pavement friction treatment, guidelines should be applied to determine which curves may have inadequate skid resistance and are often exposed to wet-weather conditions. This exercise represents a safety screening method where a small list of candidate curves for treatment will be identified from a large list of curves. It can be considered as a planning-level safety analysis.

DESCRIPTION OF GUIDELINES

The guidelines are based on wet-weather crash prediction models that were calibrated using five years of crash, roadway inventory, and pavement data for TxDOT-maintained rural highway curves. These models are described by the following equations.

The annual wet-weather crash frequency for horizontal curves on two-lane highways can be estimated as follows:

$$\mu_{2U} = L \times y \times e^{-10.108} \times F^{0.841} \times CMF_{SW} \times CMF_{SK} \times CMF_{AP} \quad (1)$$

with:

$$CMF_{SW} = e^{-0.058(SW-8)} \quad (2)$$

$$CMF_{SK} = e^{-0.038(SK-40)} \quad (3)$$

$$CMF_{AP} = e^{0.031(AP-30)} \quad (4)$$

where:

μ_{2U}	=	estimated number of crashes per year per mile for curves on two-lane highways.
L	=	segment length, mi.
y	=	number of years of crash data, years.
F	=	traffic volume, vehicles per day.
CMF_{SW}	=	shoulder width crash modification factor.
CMF_{SK}	=	skid number crash modification factor.
CMF_{AP}	=	annual precipitation crash modification factor.

The annual wet-weather crash frequency for horizontal curves on four-lane undivided highways can be estimated as follows:

$$\mu_{4U} = L \times y \times e^{-7.097} \times F^{0.491} \times CMF_R \times CMF_{SK} \quad (5)$$

with:

$$CMF_R = 1 + 0.689(0.147V)^4 \frac{(1.47V)^2}{32.2R^2} \quad (6)$$

$$CMF_{SK} = e^{-0.034(SK-40)} \quad (7)$$

where:

μ_{4U} = estimated number of crashes per year per mile for curves on four-lane undivided highways.

CMF_R = horizontal curve radius crash modification factor.

The annual wet-weather crash frequency for horizontal curves on four-lane divided highways can be estimated as follows:

$$\mu_{4D} = L \times y \times e^{-9.843} \times F^{0.838} \times CMF_{SK} \times CMF_{AP} \quad (8)$$

with:

$$CMF_{SK} = e^{-0.0274(SK-40)} \quad (9)$$

$$CMF_{AP} = e^{0.014(AP-30)} \quad (10)$$

where:

μ_{4D} = estimated number of crashes per year per mile for curves on four-lane divided highways.

All three models (Equations 1, 5, and 8) include a crash modification factor (CMF) for skid number and a CMF for annual precipitation rate. The product of these two CMFs, $CMF_{sk|ap}$, represents a combined CMF that accounts for the safety effect of skid resistance given the amount of wet-weather exposure at the curve. Larger values are associated with curves that have a higher rate of wet-weather crashes. This quantity forms the basis for the thresholds that are listed in Table 1. The thresholds are described as follows:

- If a curve has a $CMF_{sk|ap}$ value below the first threshold (1 or less), its skid resistance is likely high enough to mitigate crash risk in wet-weather conditions.
- If a curve has a $CMF_{sk|ap}$ value between the first and second thresholds, it may represent an elevated risk for wet-weather crashes, so it should be monitored. If actual crash data reveal an elevated number of wet-weather crashes at the curve, or if the curve is located on a roadway section that is on the WSCRP location report for the district, it should be analyzed further to determine the potential benefit of a pavement friction treatment.
- If a curve has a $CMF_{sk|ap}$ value between the second and third thresholds, it should be analyzed further to determine the potential benefit of a pavement friction treatment.
- If a curve has a $CMF_{sk|ap}$ value above the third threshold, it should be considered a high priority for implementation of a pavement friction treatment.

Table 1. Recommended Combined CMF Thresholds.

Description	Combined CMF Range by Roadway Type (Nomograph Caption)		
	2-Lane (Figure 1)	**4-Lane Undivided (Figure 2)**	**4-Lane Divided (Figure 3)**
Friction treatments will not likely yield cost-effective wet-weather crash reduction	$CMF_{sk\|ap} \leq 1$	$CMF_{sk\|ap} \leq 1$	$CMF_{sk\|ap} \leq 1$
Monitor the curve for elevated wet-weather crash frequency	$1< CMF_{sk\|ap} \leq 2.5$	$1< CMF_{sk\|ap} \leq 1.5$	$1 < CMF_{sk\|ap} \leq 1.5$
Conduct a detailed analysis to determine potential benefit of a friction treatment	$2.5 < CMF_{sk\|ap} \leq 4$	$1. 5 < CMF_{sk\|ap} \leq 2$	$1.5 < CMF_{sk\|ap} \leq 2$
The curve is a high-priority location for a friction treatment	$CMF_{sk\|ap} > 4$	$CMF_{sk\|ap} > 2$	$CMF_{sk\|ap} > 2$

The thresholds are plotted in the nomographs shown in Figure 1, Figure 2, and Figure 3. The nomographs provide visual tools that allows the analyst to consider both variables (skid number and annual precipitation rate) that are needed to determine the $CMF_{sk|ap}$ value and evaluate the curve. As shown, a curve is more likely to be identified as a priority for pavement friction treatment if its skid number is low and/or if its annual precipitation rate is high. Since an annual precipitation CMF could not be developed for four-lane undivided highways, the thresholds and nomograph for four-lane undivided highways are based on a combination of the skid number CMF for four-lane *undivided* highways and the annual precipitation CMF for four-lane *divided* highways

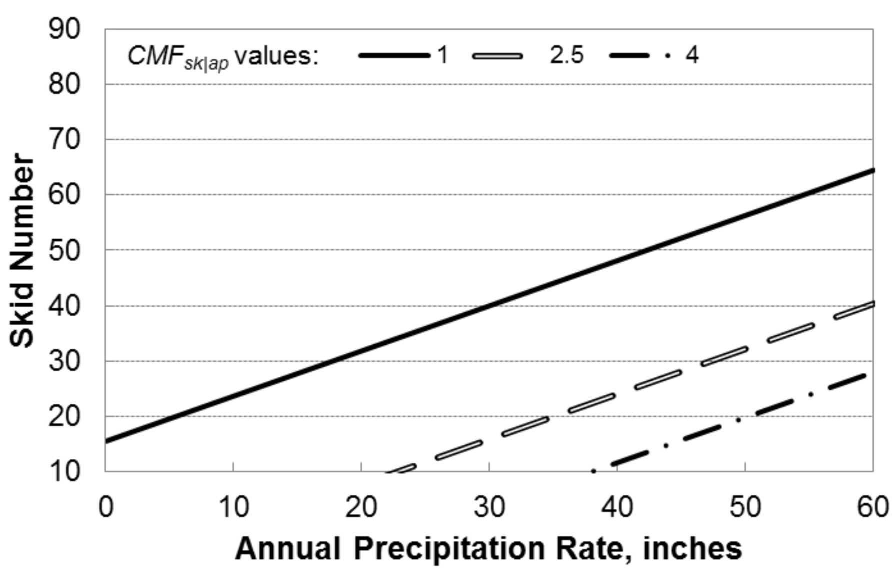

Figure 1. Combined Skid Number and Annual Precipitation Rate Nomograph for Two-Lane Highways.

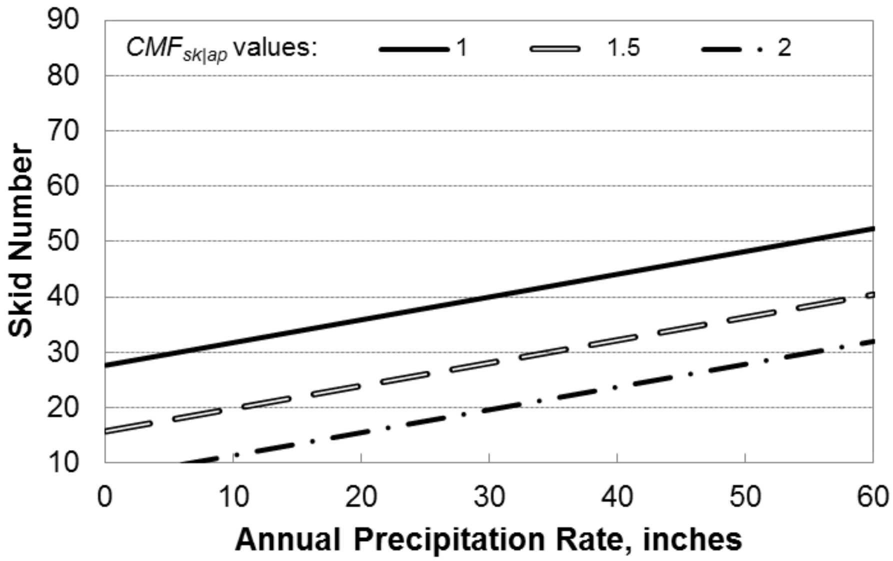

Figure 2. Combined Skid Number and Annual Precipitation Rate Nomograph for Four-Lane Undivided Highways.

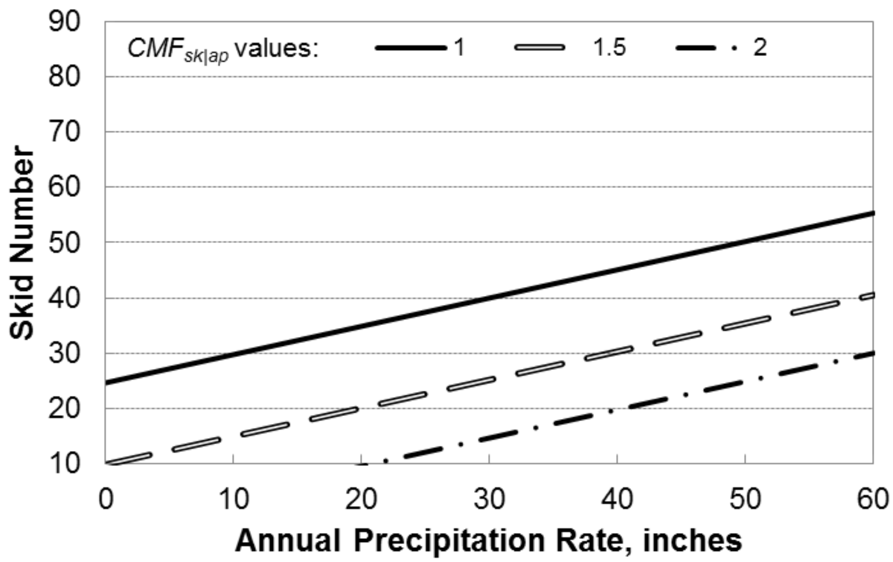

Figure 3. Combined Skid Number and Annual Precipitation Rate Nomograph for Four-Lane Divided Highways.

APPLICATION

The guidelines should be considered as the first step in a process to rank and prioritize curves that may be good candidates for pavement friction treatments. The second step is to apply a more detailed evaluation framework, which is described in the next section. Practitioners *may* apply the evaluation framework for any curve of interest, but *should* apply the evaluation framework if one or more of the conditions are met:

1. The skid number and annual precipitation rate for the curve plot into either of the bottom regions of the nomographs (curves in the bottommost region are considered highest priority).
2. The curve is located on a roadway section that is on the district's WSCRP location report and its skid number and annual precipitation rate plot into the second nomograph region from the top. That is, the curve's $CMF_{sk|ap}$ value exceeds 1.
3. The curve has a radius less than or equal to 1146 ft, or a degree of curve of 5 or greater. Crash frequency increases notably when curve radius decreases below this value.
4. The curve has been identified as having elevated crash frequency based on another type of analysis, crash data query, or citizen complaints.

Note that the WSCRP location reports are mentioned in conjunction with these guidelines. Researchers recommend that the guidelines be applied in parallel with the efforts to generate and analyze the WSCRP location reports for each district.

CHAPTER 3. USER GUIDE: TEXAS CURVE MARGIN OF SAFETY EVALUATION FRAMEWORK TOOL

RATIONALE

The safety performance of a horizontal curve is influenced by various factors, including curve geometry, pavement friction, and vehicle speed, the latter of which is influenced by the former. Though drivers generally reduce to a safe speed by the time they arrive at the middle of a curve, they often misjudge the sharpness of the curve before entering it, and are compelled to decelerate or make correcting maneuvers while in the curve. Excessive deceleration or braking on a curve can lead to a sliding failure of the tire-pavement interface and result in a crash.

A margin of safety analysis represents a good method for evaluating curve safety as a function of geometry and pavement friction. Margin of safety is defined as the side friction supply minus the side friction demand. Because vehicle speeds and the superelevation rate change along the length of a curve, it is necessary to evaluate the margin of safety along the entire length of the curve. This type of analysis requires estimation of vehicle speed at key points along the curve length, such as the point of curvature (PC), the midpoint of curve (MC), and the point of tangency (PT). Furthermore, consideration must be given to the occurrence of correcting maneuvers, which are associated with side friction demands well in excess of demands incurred by vehicles tracking the curve with geometric exactness.

Researchers developed an evaluation framework to help practitioners assess the potential safety benefit of curve pavement improvements. This framework is in the form of a spreadsheet program called the TCMS worksheet. TCMS is designed to compute the benefits of increasing pavement friction through the provision of a high-friction surface treatment (HFST) or increasing superelevation rate. The computation methodology and the application of the TCMS program are described below.

CALCULATION METHODS

This section describes the calculation methods used by the TCMS program. Specifically, the methods used to compute margin of safety, crash prediction, treatment life span, and life-cycle cost are detailed in the following subsections.

Margin of Safety Analysis

A detailed margin of safety analysis requires knowledge of the side friction supply and the side friction demand. These quantities are influenced by curve geometry, pavement characteristics, and vehicle speeds. Development of the margin-of-safety calculations is described in detail in Chapter 5 of TxDOT research report 0-6714-1 (*2*). The margin-of-safety concept is summarized by the following equations:

$$M.S = f_s - f_D \qquad (11)$$

$$f_s = f(SK) \qquad (12)$$

$$f_D = \frac{v^2}{gR_p}\cos\left(\frac{e}{100}\right) - \sin\left(\frac{e}{100}\right)\cos G \quad (13)$$

where:

M.S.	=	margin of safety.
f_s	=	side friction supply.
f_D	=	side friction demand.
SK	=	skid number.
v	=	vehicle speed, ft/s.
g	=	gravitational constant (= 32.2 ft/s^2).
R	=	curve radius, ft.
e	=	superelevation rate, percent.
G	=	vertical grade, ft/ft.

The margin of safety analysis framework is formulated to account for changes to skid number and superelevation rate between the before and after periods, consistent with the installation of a new pavement surface or an increase in superelevation.

The margin of safety is computed as the side friction demand subtracted from the side friction supply as shown in Equation 11. Glennon (*5*) suggested that the margin of safety should be at least 0.08–0.12 along the entire length of the curve.

Crash Prediction

Predicted crash counts are obtained using the crash prediction models that were documented in Chapter 5 of TxDOT research report 0-6932-R1. The way the worksheet is formulated, the only CMF that would change based on the input data is the skid number CMF. Hence, the worksheet provides estimates of the predicted change in crash count (in percent) based on the change in skid number CMF that would result from the specified changes to skid number. The skid number used for the computation of this CMF is the skid number measured at 50 mph.

The analyst may apply an empirical Bayes adjustment to the predicted crash count if desired. The evaluation framework uses the empirical Bayes methodology that Bonneson et al. described (*6*).

Pavement Service Life

The service life for a pavement friction treatment is computed based on the following key quantities:

- Initial skid number (immediately after installation).
- Rate of change of skid number.
- Terminal skid number.

The evaluation framework includes these quantities for the following treatment options:

- Seal coat (or chip seal).
- Hot-mix asphalt (HMA).
- Permeable friction course (PFC).
- High-friction surface treatment (HFST).

The derivation of the initial and terminal skid numbers and rates of change for the treatments is described in detail in Chapter 4 of TxDOT research report 0-6932-R1.

Benefit-Cost Analysis

The benefit-cost analysis compares the expected cost to implement one of the pavement treatment products to the benefit of reducing crashes over the life of the treatment. Table 2 gives costs for various treatments. The HFST and seal coat costs come from the literature. The asphalt overlay costs come from asphalt production data from TxDOT for the year 2015.

Table 2. Unit Cost for Various Pavement Treatments.

Treatment Type	Thickness (inches)	Approximate Unit Cost	
		$/ton	$/yd^2
HFST	Not applicable	NA	19–25
Seal Coat	Not applicable	NA	2.50
Asphalt Overlay			
Dense Graded	1.5–2.0	79	6.50–8.75
Super Pave	1.5–2.0	86	7.25–9.75
Stone Matrix Asphalt	1.5–2.0	105	7.25–8.75
Thin Overlay Mix	1.0–1.25	116	6.50–8
Permeable Friction Course (SAC A)	1.5	110	9

To compute a benefit-cost ratio for a proposed curve pavement treatment, the following steps are required:

1. Estimate the fatal-and-injury crash frequency of the curve for a time period before the treatment is implemented. This estimated crash frequency is based on the curve’s characteristics, particularly its skid number, in the before period.
2. Identify a proposed pavement treatment and determine the increase in skid number that can be obtained from the treatment.
3. Estimate the fatal-and-injury crash frequency of the curve for a time period after the treatment is implemented. The crash frequency will change between the before and after periods due to the change in skid number, but no other variables (and hence no other CMF values) will change. This crash frequency can be improved using the empirical Bayes adjustment (*6*) if actual crash data are available for the before period.
4. Compute the reduction in fatal-and-injury crashes between the before and after periods.
5. Using default crash severity distribution proportions, compute the number of property-damage-only (PDO) crashes in both time periods and the reduction in these crashes between the time periods.

6. Using crash cost values for all severity levels (K [fatal], A [incapacitating injury], B [non-incapacitating injury], C [possible injury], and PDO), compute the treatment benefit in terms of crash costs reduced following installation of the treatment.
7. Compute the proposed treatment cost.
8. Compute the benefit-cost ratio by dividing the benefit obtained in step 6 by the cost obtained in step 7.

Table 3 provides the default crash costs and severity distribution used in TCMS. These values are identical to those used in the Value of Research technical memorandum that researchers submitted in October 2016. Researchers derived the severity distributions from a query of the Texas Reference Marker (TRM) and Crash Records Information System (CRIS) databases, the fatal-and-injury crash costs from U.S. Department of Transportation guidance (*7*), and the PDO crash costs from the guidance provided by Council et al. (*8*).

Table 3. Crash Costs and Severity Distribution.

Crash Severity	Crash Cost	Severity Distribution (proportion)
K	$9,100,000	0.0335
A	$3,908,450	0.0626
B	$691,600	0.1567
C	$27,300	0.1449
PDO	$10,350	0.6023

DESCRIPTION OF TEXAS CURVE MARGIN OF SAFETY PROGRAM

The TCMS program is an Excel®-based spreadsheet program. It was developed to automate the calculations required to facilitate a margin of safety analysis and life-cycle benefit-cost analysis of a proposed pavement-based curve safety treatment. TCMS incorporates crash prediction models and pavement service life calculations. The organization of the program is described in the next section, followed by discussion of the required input data and explanation of the output data.

Organization

The TCMS program is organized so the entire worksheet can be printed on six pages. The first page contains input data entry cells, output cells, and calculation of skid number at the curve advisory speed. The second page provides a table and a chart to illustrate margin of safety trends throughout the curve and the change in skid number for a proposed pavement friction treatment over time. The remaining pages contain calibration coefficients and intermediate calculations that are used to produce the output calculations on the first and second pages.

Figure 4 provides a screenshot of a portion of the first page of TCMS. The cells are color-coded so the analyst can easily identify data entry cells and output data cells. The main set of data entry cells is blue. With the exception of the general information data entry cells (describing quantities like district, highway, and curve location), the blue cells must be filled. Several additional data entry cells are orange. The orange cells differ from the blue cells in that the program requires the quantities that are entered into the orange cells, but can estimate the quantities if the analyst leaves the cells blank. The key output data cells are colored rose. The cells containing calibration factors on the later pages of the program are yellow.

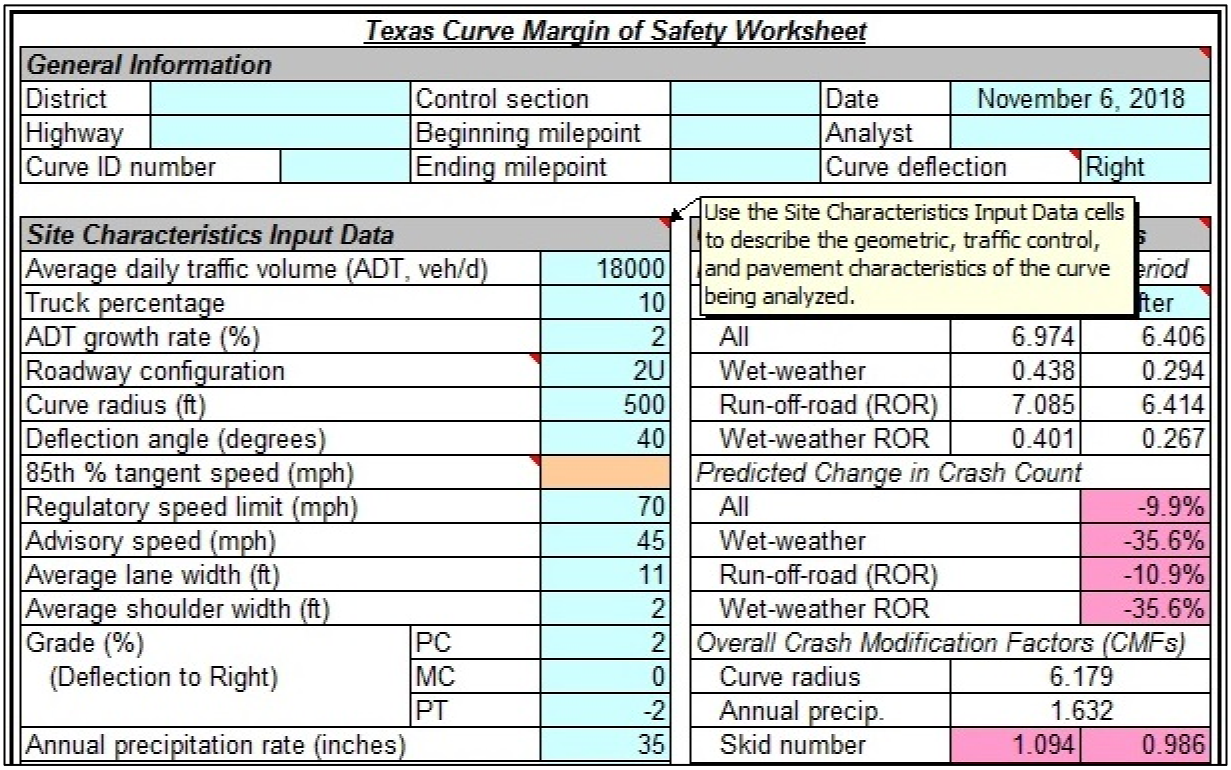

Figure 4. TCMS Screenshot.

Some of the cells, data boxes, or graphs in TCMS have comment boxes that provide additional clarification about the needed input data or interpretation of the output data. Red triangles indicate the presence of these comments. The comments can be viewed by placing the cursor on top of the red triangles. In Figure 4, a comment is shown for the Site Characteristics Input Data box.

The input and output data cells are organized into logical groups. For example, the site characteristics and pavement treatment input data cells are each contained within a box, and additional output data boxes are provided for margin of safety analysis calculations, crash prediction model calculations, benefit-cost calculations, and calculations of the skid number at the specified curve advisory speed.

Most of the output data cells are white. These cells do not represent key output quantities but are made visible because their contents may be of interest. The output data cells are protected so the analyst cannot inadvertently alter an equation and obtain erroneous calculations from the program.

The input data cells are configured with data validation features to prevent illogical values from being entered. For example, regulatory speed limit and advisory speed must be multiples of 5 mph, and the skid numbers must be between 0 and 100.

Input Data

Cells containing general information are located on the upper portion of the TCMS worksheet (see Figure 4). These cells can be used to document the location of the curve, the date, the analyst's name, and the direction of curve deflection (left or right) corresponding to the grade data that are entered into the Input Data box. Of these quantities, only the curve deflection direction affects the calculations performed by the program.

Figure 5 shows the box containing the site characteristics input data cells. The following data are needed:

- Average daily traffic volume (ADT, veh/d).
- Truck percentage.
- ADT growth rate (%).
- Roadway configuration, described by the following codes:
  - 2U = two-lane undivided.
  - 4U = four-lane undivided.
  - 4D = four-lane divided (all types of medians, including flush-paved, depressed, unpaved, or raised, with or without a positive barrier).
- Curve radius (ft). Enter the geometric radius of the curve.
- Deflection angle (degrees). Enter the total deflection angle for the curve.
- 85^{th}-percentile tangent speed (mph). Enter the field-measured 85^{th}-percentile tangent speed, if available. This speed should be measured at a location sufficiently far upstream of the curve that the curve geometry does not affect vehicle speeds. If this quantity is not entered, the program will estimate the 85^{th}-percentile tangent speed using a model described by Equation 71 in Reference *2*.
- Regulatory speed limit (mph). Enter the regulatory speed limit. This quantity is used to estimate the 85^{th}-percentile tangent speed if a field-measured value is not available.
- Advisory speed (mph). Enter the curve advisory speed, or the regulatory speed limit if no advisory speed is posted.
- Average lane width (ft). Enter the average lane width that exists along the length of the curve.
- Average shoulder width (ft). Enter the average shoulder width that exists along the length of the curve.
- Grade (%). Enter the roadway grade, as measured at the centerline of the roadway in the direction of travel, for the PC, the MC, and the PT. The entered grade numbers should be measured in the direction of travel corresponding with the curve deflection direction that was entered in the General Information box.
- Annual precipitation rate (inches). Rates are provided in the Appendix for TxDOT districts and Texas counties. The analyst may use these rates or rates from a different data source if available.
- Superelevation rate (%). Enter the superelevation rate observed at the MC, and optionally the value observed at the PC and PT. A positive superelevation rate value corresponds to a cross slope that decreases side friction demand. If values are not provided for the PC and the PT, the program estimates the superelevation rate at these points using the default proportion of 0.5, which can be adjusted in the calibration factor cells if desired. A

proportion of 0.5 means that the superelevation rate at the PC and the PT is equal to 0.5 times the value observed at the MC. Cells are provided for the before and after cases so the effects of changing the superelevation rate can be computed. Cells are also provided for the two travel directions so differences in superelevation rate between the two directions can be accommodated.

Site Characteristics Input Data			
Average daily traffic volume (ADT, veh/d)			18000
Truck percentage			10
ADT growth rate (%)			2
Roadway configuration			2U
Curve radius (ft)			500
Deflection angle (degrees)			40
85th % tangent speed (mph)			
Regulatory speed limit (mph)			70
Advisory speed (mph)			45
Average lane width (ft)			11
Average shoulder width (ft)			2
Grade (%) (Deflection to Right)		PC	2
		MC	0
		PT	-2
Annual precipitation rate (inches)			35
Superelevation rate (%)		Before	After
Deflection to Left	PC	4.5	6.5
	MC	6	8
	PT	4.5	6.5
Deflection to Right	PC	6.5	8.5
	MC	8	10
	PT	6.5	8.5

Figure 5. Site Characteristics Input Data Cells.

In the example described by the input data in Figure 5, a safety improvement project is being considered for a curve with a 500-ft radius and a 40° deflection angle. The proposed project will involve increasing the superelevation rate by 2 percent along the entire length of the curve.

Figure 6 shows the box containing the pavement treatment input data cells. The following data are needed:

- Skid number for the existing surface, which corresponds to the before period.
- Treatment type for the proposed surface, which corresponds to the after period. Table 4 lists the options and categories for each treatment type.
- Aggregate type and percent contribution to coarse aggregate: Describe up to two aggregates to be used in the proposed pavement treatment by specifying the type and the percent contribution that the material makes to the coarse aggregate in the treatment. Coarse aggregate is the portion of aggregate that is retained on the #4 sieve during the standard sieve test. Table 5 lists the options for aggregate type and the treatment categories for which each aggregate type may be used. Note that the drop-down menus

are programmed to allow only the aggregate types that are appropriate for the specified treatment type.

- Economic discount rate: Enter the discount rate to be used in the economic calculations to determine benefit-cost ratio. This value is used to convert the future value of treatment benefits (i.e., the costs of future crashes) to present value.
- Treatment cost: Enter the cost of installing the proposed pavement treatment.

Pavement Treatment Input Data	
Skid number for existing surface	30
Proposed treatment type	PFC
Aggregate type 1	Siliceous Gravel
% contribution to coarse aggregate	50
Aggregate type 2 (optional)	Dolomite
% contribution to coarse aggregate	50
Economic discount rate	3.0%
Treatment cost	$50,000

Figure 6. Pavement Treatment Input Data Cells.

Table 4. Treatment Type Options.

Option	Category
Type C (DG, SP)	
Type D (DG, SP)	
Type F (DG, SP)	
CAM	
SMA (Type C or D)	Asphalt overlay
TOM	
CMHB-F	
Thin PFC	
PFC	
Seal Coat (Gr. 3, 4, 5)	Seal coat
High-friction treatment	High-friction surface treatment

Table 5. Aggregate Type Options.

Option	Applicable Treatment Category
Calcined bauxite	High-friction surface treatment
Limestone	Asphalt overlay or seal coat
Dolomite	Asphalt overlay or seal coat
Sandstone	Asphalt overlay or seal coat
Siliceous Gravel	Asphalt overlay or seal coat
Limestone Gravel	Asphalt overlay or seal coat
Igneous	Asphalt overlay or seal coat
Flint	Asphalt overlay or seal coat
Lightweight Agg.	Seal coat

Figure 7 shows the box containing the crash analysis input data cells. The following data are needed:

- Analysis period (yr). Enter the number of years included in the analysis period. This quantity defines the time period for the calculation of predicted crash counts and also the time period for which the benefit (or disbenefit) of the proposed treatment will be computed.
- Crash data period (yr). If empirical Bayes adjustment to the predicted crash counts is desired, enter the number of crashes observed during the time period for which historical crash data are available. If empirical Bayes adjustment is not desired, enter 0.
- Reported crash count in analysis period. If empirical Bayes adjustment to the predicted crash counts is desired, enter the number of crashes observed during the crash data period. Separate cells are provided for four different categories of crashes—all crashes, wet-weather crashes, run-off-road crashes, and wet-weather run-off-road crashes. Leave these cells blank if empirical Bayes adjustment is not desired.

Crash Analysis Input Data		
Analysis period (yr)		7
Crash data period (yr)		7
Reported crash count by type	All	10
	Wet-weather	3
	Run-off-road (ROR)	9
	Wet-weather ROR	2

Figure 7. Crash Analysis Input Data Cells.

Output Data

Calculation results are provided on the first and second pages of the TCMS worksheet. These results include margin of safety analysis, crash prediction model calculations, pavement service life (in terms of skid number over time), and benefit-cost calculations. Details are provided in the following subsections.

Margin of Safety Analysis

Figure 8 shows the margin of safety analysis results in tabular and graphical form. Results are provided in the rose-colored cells for the two directions of travel to compare the before period to the after and terminal periods. These calculations can be made for the ideal or correcting travel path types, as indicated in the blue cell.

In the example shown, the existing configuration (described by the before period) has a margin of safety of 0.000 for correcting travel path type in both travel directions at the PC. This result indicates that there is no margin of safety if a driver makes a correcting maneuver at the PC. The margin of safety at the PT is also borderline acceptable for the before case, based on the suggested minimum of 0.08–0.12 (*5*). In the after period, the entire curve has a margin of safety of at least approximately 0.09, while the PC still has the lowest margin of safety of any point along the curve. However, in the terminal period, the margin of safety at the PC has degraded to 0.05 in one direction and 0.07 in the other direction.

Texas Curve Margin of Safety Worksheet

Margin of Safety Analysis — Tabular Results

Correcting		Before	After	Terminal	Change before-after	Change before-terminal
Deflection	PC	0.000	0.094	0.050	+ 0.094	+ 0.05
to	MC	0.172	0.306	0.258	+ 0.133	+ 0.086
Left	PT	0.126	0.252	0.206	+ 0.125	+ 0.08
Deflection	PC	0.000	0.115	0.071	+ 0.115	+ 0.071
to	MC	0.164	0.296	0.249	+ 0.132	+ 0.085
Right	PT	0.086	0.209	0.164	+ 0.123	+ 0.078

Margin of Safety Analysis — Graphical Results

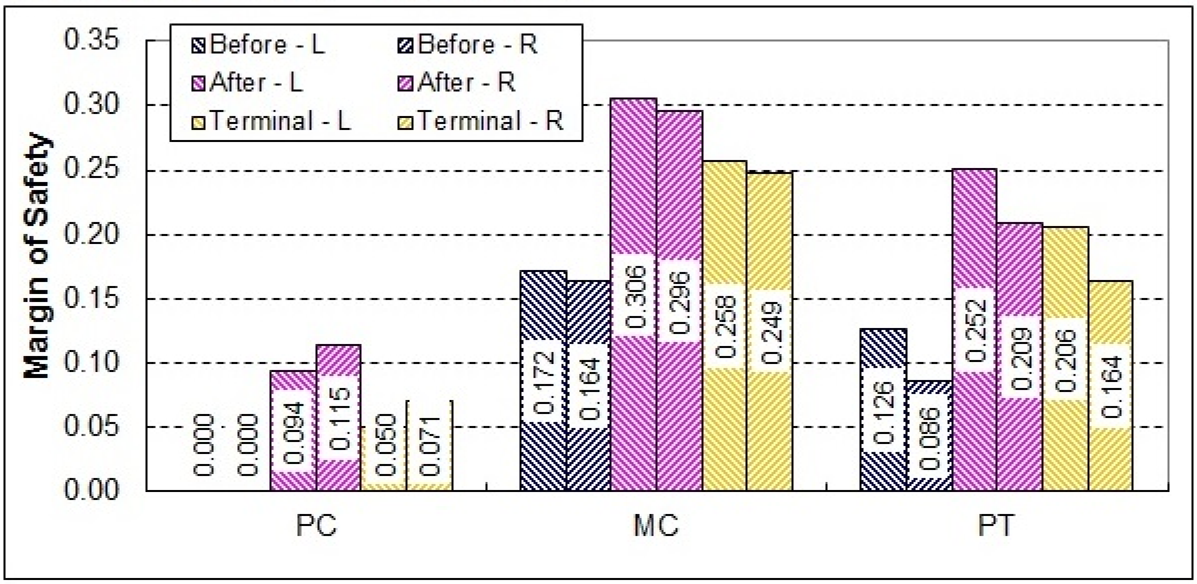

Figure 8. Margin of Safety Analysis Calculations.

The margin of safety analysis results are shown in graphical form on the second page of the TCMS worksheet. The blue, pink, and yellow bars on the graph illustrate the before, after, and terminal cases, respectively. The direction of the hatch lines corresponds to the direction of travel (curve deflecting to the left or the right). In all cases, the pink bars are taller than the blue bars, indicating an improvement in margin of safety following the installation of the safety treatment, with the benefit decreasing between the after and terminal periods but never below the margin of safety that existed in the before period.

Crash Prediction Model Calculations

The crash prediction model calculations are provided on the right side of the first page of the Analysis worksheet. Figure 9 shows these calculations. Crash counts are provided for the four crash categories (all crashes, wet-weather crashes, run-off-road crashes, and wet-weather run-off-road crashes), along with the curve radius, annual precipitation, skid number, and combined skid number–annual precipitation CMFs associated with the four models. The rose-colored cells show the change in skid number and combined skid number–annual precipitation CMFs and resulting change in predicted crash count due to the installation of the friction surface treatment.

Crash Prediction Model Calculations		
Predicted Crash Counts in Analysis Period		
	Before	After
All	6.974	6.406
Wet-weather	0.438	0.294
Run-off-road (ROR)	7.085	6.414
Wet-weather ROR	0.401	0.267
Predicted Change in Crash Count		
All		-9.9%
Wet-weather		-35.6%
Run-off-road (ROR)		-10.9%
Wet-weather ROR		-35.6%
Overall Crash Modification Factors (CMFs)		
Curve radius	6.179	
Annual precip.	1.632	
Skid number	1.094	0.986
Skid x Precip.	1.786	1.609
Wet-Weather CMFs		
Curve radius	1.000	
Annual precip.	2.959	
Skid number	1.462	0.942
Skid x Precip.	4.328	2.787
Run-off-Road CMFs		
Curve radius	7.895	
Annual precip.	1.632	
Skid number	1.105	0.984
Skid x Precip.	1.804	1.607
Wet-Weather Run-off-Road CMFs		
Curve radius	1.000	
Annual precip.	3.065	
Skid number	1.462	0.942
Skid x Precip.	4.482	2.886

Figure 9. Crash Prediction Model Calculations.

One data input cell exists within the crash prediction model calculations. This cell allows the analyst to choose the time period to compare with the before period. The options include:

- After: Immediately after treatment.
- End: The end of the last year of the specified analysis period.
- Terminal: The end of the year in which the effective skid number is reached. Effective terminal skid number is defined as the skid number at the end of the first year when the skid number drops to within 1 *SK* of the terminal value.

Skid Number and Treatment Service Life

For the purpose of computing a benefit-cost ratio, it is necessary to compute the service life of the proposed pavement friction treatment in terms of the skid number's change over time. Figure 10 shows a typical trend for the skid number over time. The initial skid number corresponds to year 0, when the treatment is newly installed. The terminal skid number is the final, minimum value on the rightmost portion of the graph.

The Analysis worksheet provides the following numerical outputs below the skid number graph (bottom portion of Figure 10):

- Years to effective terminal skid number: Number of years until the effective terminal skid number is reached.
- Effective terminal skid number: The effective terminal skid number is defined as the skid number at the end of the first year when the skid number drops to within 1 *SK* of the terminal value.

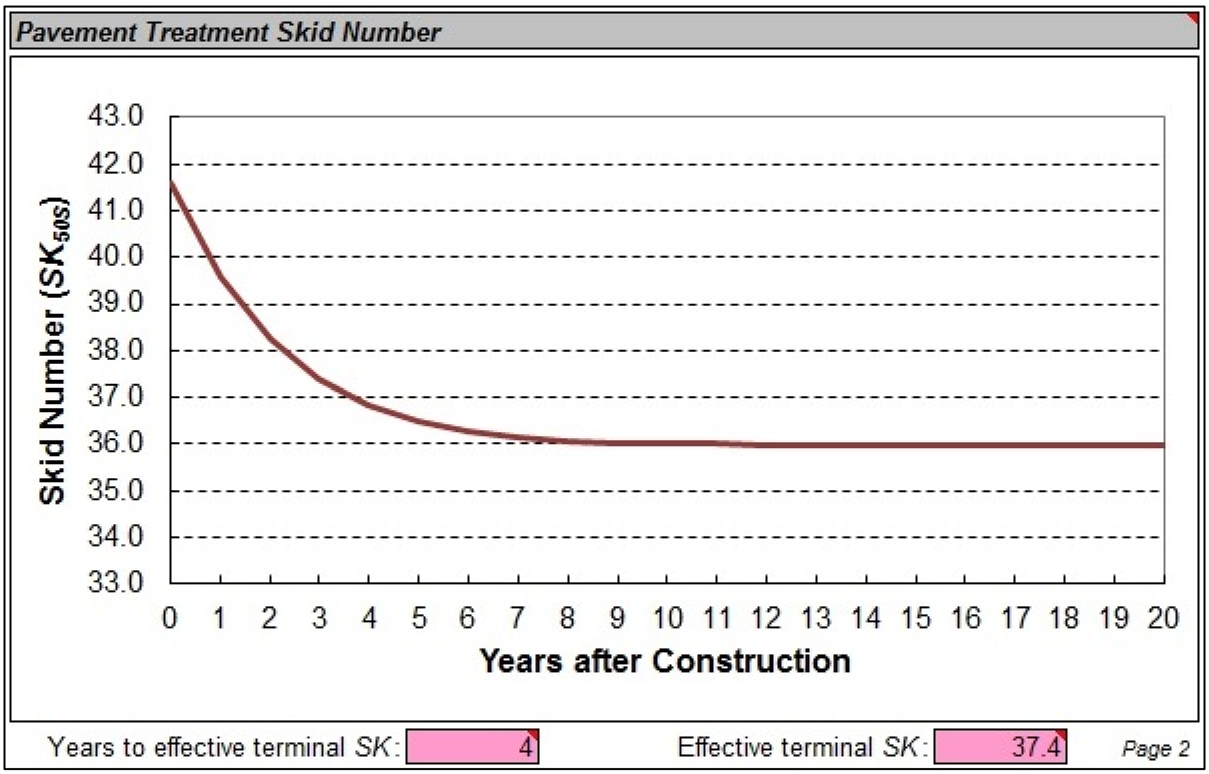

Figure 10. Pavement Treatment Skid Number Change over Time.

Figure 11a shows a set of calculations that provides the skid number at the advisory speed and at the skid test speed for three time periods (before, after, and terminal). These numbers are provided so the analyst can assess skid resistance at typical traffic speeds, which will often vary from the speed used to field-measure skid number (50 mph).

Skid Number Calculations			
Skid number	Before	After	Terminal
at advisory speed	31.8	44.0	39.6
at skid test speed	30.0	41.6	37.4

a. Skid Number

Benefit-Cost Analysis Calculations	
Average crash cost	$668,082
Analysis period (yr)	7
SK at end of analysis period	36.3
Benefit-cost ratio	4.48
Net benefit	$174,146
Period of improved *SK* (yr)	21
SK at end of improved period	36.0
Benefit-cost ratio	8.79
Net benefit	$389,285

b. Benefit-Cost Analysis

Figure 11. Skid Number and Benefit-Cost Calculations.

The benefit-cost analysis results are provided in a table on the bottom of the first page, as shown in Figure 11b. The following quantities are given:

- Average crash cost: This number provides the cost of the average crash that occurs on rural highway curves. This cost depends on the distribution of crashes by severity and the costs of crashes by severity.
- For the analysis period:
  - Analysis period duration (yr).
  - Benefit-cost ratio for the proposed treatment. The treatment benefit is computed as the value of the crashes reduced, and the treatment cost is provided by the analyst.
  - Net benefit for the proposed treatment, which is defined as benefit minus cost.
- For the period of improved skid number:
  - Duration of period of improved skid number (yr).
  - Benefit-cost ratio for the proposed treatment.
  - Net benefit for the proposed treatment.

The provision of calculations for both time periods allows the analyst to consider the service life of the proposed surface treatment. In the example shown, the proposed surface treatment reaches a terminal skid number of about 36, which exceeds the skid number of 30 for the before period, suggesting that the treatment would continue to yield safety benefits even after the end of the specified seven-year analysis period.

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2 Pratt, M., S. Geedipally, A. Pike, P. Carlson, A. Celoza, and D. Lord. *Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves.* Report FHWA/TX-14/0-6714-1, Texas A&M Transportation Institute, College Station, Texas, 2014.

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8 Council, F., E. Zaloshnja, T. Miller, and B. Persaud. *Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometries*. Report FHWA-HRT-05-0-051, Pacific Institute for Research and Evaluation, Calverton, Maryland, 2005.

APPENDIX

Table 6. Annual Average Precipitation by TxDOT District.

District (Number)	Annual Avg. Precipitation (in.)
Paris (1)	45.91
Fort Worth (2)	35.61
Wichita Falls (3)	31.95
Amarillo (4)	20.76
Lubbock (5)	20.19
Odessa (6)	14.67
San Angelo (7)	23.15
Abilene (8)	23.97
Waco (9)	34.99
Tyler (10)	46.65
Lufkin (11)	52.07
Houston (12)	49.04
Yoakum (13)	41.42
Austin (14)	33.68
San Antonio (15)	30.88
Corpus Christi (16)	32.84
Bryan (17)	42.45
Dallas (18)	39.44
Atlanta (19)	49.01
Beaumont (20)	58.33
Pharr (21)	24.91
Laredo (22)	22.7
Brownwood (23)	29.8
El Paso (24)	15.18
Childress (25)	24.49
All Districts	33.76

Table 7. Annual Average Precipitation by County.

County	Annual Avg. Precipitation (in.)
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
Collingsworth	22.26
Colorado	43.93
Comal	34.42
Comanche	31.28

Table 7. Annual Average Precipitation by County (cont'd.).

County	Annual Avg. Precipitation (in.)
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
Glasscock	17.57
Goliad	36.54
Gonzales	33.09
Gray	21.63
Grayson	41.27
Gregg	48.09

Table 7. Annual Average Precipitation by County (cont'd.).

County	Annual Avg. Precipitation (in.)
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
Kenedy	28.40
Kent	23.51
Kerr	33.63
Kimble	24.53
King	24.82
Kinney	23.56
Kleberg	31.94

Table 7. Annual Average Precipitation by County (cont'd.).

County	Annual Avg. Precipitation (in.)
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
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

Table 7. Annual Average Precipitation by County (cont'd.).

County	Annual Avg. Precipitation (in.)
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
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

Table 7. Annual Average Precipitation by County (cont'd.).

County	Annual Avg. Precipitation (in.)
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