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Safer by Design: Pavement Friction

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16. Abstract
Minimizing pavement impact on wet weather crashes is essential to the Wet Surface Crash Reduction Program (WSCRP). Currently, the Texas Department of Transportation has two methods to evaluate pavement friction: the Safer by Design (SBD) method and the pavement surface aggregate classification selection, Form 2088. The research team developed a framework to integrate Form 2088 with SBD pavement friction criteria. The combined criteria will bridge the gap between the approaches in the two current methods. The combined methods provide the benefits of streamlining the data inputs, avoiding duplication of efforts, and effectively improving the quality of the assessment of pavement friction safety. In addition, the research team developed a pavement risk assessment procedure and a crash modification factor to assist designers in understanding the risk associated with selecting the pavement type and materials. Overall, the inputs and framework of the SBD and the commonalities with Form 2088 were carefully combined to improve the SBD and the WSCRP.

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DISCLAIMER

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This report is not intended for construction, bidding, or permit purposes. The engineer (researcher) in charge of the project was Darlene C. Goehl, P.E. #80195.

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TABLE OF CONTENTS

Page

List of Figures ... **viii**
List of Tables ... **ix**
Chapter 1. Introduction ... **1**
Introduction ... 1
Background ... 1
Aggregate Characterization, TxDOT ... 3
History of Aggregate Requirements ... 3
Current Practice for Aggregates ... 4
TXDOT Wet Crashes Management Tools ... 5
Form 2088 ... 5
TxDOT SBD ... 10
SBD and Form 2088 ... 12
TxDOT Research Projects Summary ... 14
Literature Review Summary ... 17
Chapter 3. Risk Assessment Procedure ... **19**
Risk Assessment Procedure Background ... 19
Risk Assessment Criteria ... 19
Crash Data Analysis ... 20
Crash Data and Skid Number Analysis ... 21
Proposed Risk Assessment Procedure ... 28
Background SBD Modifications ... 29
Safety Analysis of Skid Numbers on Wet Crashes ... 29
SBD ... 39
Pavement Skid Number Utility Tool Development ... 40
Skid Number CMF Calculator ... 40
Skid Number Estimator ... 42
Integration with SBD Tool ... 43
Summary SBD Modifications ... 43
Risk Assessment Procedure ... 48
Future Work ... 48
Estimate of Skid Number ... 48
Update SBD ... 49
Chapter 7. Value of Research ... **50**
References ... **54**
Appendix A: Data Analysis Summary Statistics ... **55**
Distribution of Variables in the Dataset of Segments with Nonmissing Skid Numbers ... 55
Correlation Analysis ... 60
Appendix B. Wet Crash Modeling for CMF ... **61**

LIST OF FIGURES

Page

Figure 1. Original WWARP SAC Form 2088. 7
Figure 2. Revised WSCRP SAC Form 2088. 8
Figure 3. Safety Assessment Tool. 10
Figure 4. Output from Texas Curve Margin of Safety Worksheet [12]... 16
Figure 5. Annual Precipitation Totals and Frequency. 20
Figure 6. User Interface of Skid Number CMF Calculator. 41
Figure 7. Data Validation of Skid Number CMF Calculator. 42
Figure 8. Warning Message of Skid Number CMF Calculator. 42
Figure 9. User Interface of Skid Number Estimator. 43
Figure 10. ATL (left) and BRY (right) Project Locations. 46
Figure 11. FTW Project Locations.. 47
Figure 12. VOR Summary. 53

LIST OF TABLES

Page

Table 1. Polish Value System. ... 3
Table 2. Surface Aggregate Classification Testing. ... 4
Table 3. Form 2088 Friction Demand Example. ... 5
Table 4. Form 2088 Available Friction Example. ... 6
Table 5. Frictional Demand Factors. ... 9
Table 6. Geometric Design Elements. ... 11
Table 7. Traffic and Roadside Design Elements. ... 11
Table 8. Factors for Project, Climate, and Crash Data. ... 12
Table 9. Factors for Geometric Design Elements. ... 12
Table 10. Factors for Traffic Elements. ... 13
Table 11. Factors for Roadside Elements. ... 13
Table 12. Skid Number Thresholds 6713-1. ... 14
Table 13. Crash Prediction Model Input Data. ... 14
Table 14. Additional SBD/SST Inputs. ... 17
Table 15. Estimates of Regression Coefficients of NB Regression Model Applied to Total Crash Data from 163,389 Segments. ... 23
Table 16. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 163,389 Segments. ... 23
Table 17. Estimates of Regression Coefficients of NB Regression Model Applied to Dry Crash Data from 163,389 Segments ... 23
Table 18. Estimates of Regression Coefficients of NB Regression Model Applied to Total Crash Data from 137,826 Segments Having Precipitation Data. ... 24
Table 19. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 137,826 Segments Having Precipitation Data. ... 24
Table 20. Estimates of Regression Coefficients of NB Regression Model Applied to Dry Crash Data from 137,826 Segments Having Precipitation Data. ... 25
Table 21. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 103,207 Segments Having Minskid < 40. ... 26
Table 22. Estimates of Regression Coefficients of NB Regression Model Applied to Dry Crash Data from 103,207 Segments Having Minskid < 40. ... 26
Table 23. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 34,619 Segments Having Minskid ≥ 40. ... 27
Table 24. Estimates of Regression Coefficients of NB Regression Model Applied to Dry Crash Data from 34,619 Segments Having Minskid ≥ 40. ... 27
Table 25. Risk Levels. ... 28
Table 26. RU_Lane Codes. ... 29
Table 27. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 26,654 Urban 2-Lane Segments. ... 31
Table 28. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 26,654 Urban 2-Lane Segments. ... 31
Table 29. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 26,654 Urban 2-Lane Segments. ... 31

Table 30. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 8,420 Urban Multi-Lane Undivided Segments. 32
Table 31. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 8,420 Urban Multi-Lane Undivided Segments. 32
Table 32. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 8,420 Urban Multi-Lane Undivided Segments. 33
Table 33. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 10,220 Urban Multi-Lane Divided Segments. 33
Table 34. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 10,220 Urban Multi-Lane Divided Segments. 33
Table 35. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 10,220 Urban Multi-Lane Divided Segments. 34
Table 36. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 75,185 Rural 2-Lane Segments. 34
Table 37. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 75,185 Rural 2-Lane Segments. 35
Table 38. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 75,185 Rural 2-Lane Segments. 35
Table 39. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 4,133 Rural Multi-Lane Undivided Segments. 35
Table 40. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 4,133 Rural Multi-Lane Undivided Segments. 36
Table 41. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 84,133 Rural Multi-Lane Undivided Segments. 36
Table 42. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 13,214 Rural Multi-Lane Divided Segments. 37
Table 43. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 13,214 Rural Multi-Lane Divided Segments. 37
Table 44. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 13,214 Rural Multi-Lane Divided Segments. 37
Table 45. Skid Number Regression Coefficients and CMF Estimates. 38
Table 46. Skid Number CMF Estimates by Urban Roadway Categories. 39
Table 47. Skid Number CMF Estimates by Rural Roadway Categories. 39
Table 48. Ratio of Wet, FI_Wet, and PDO_Wet Crashes and Base Skid Number for Different Roadway Categories. 40
Table 49. Case Study Summary. 45
Table 50. HSIP Work Codes for 303 Resurfacing Projects. 51
Table 51. Research Benefit Areas. 52
Table 52. Quantiles for Crash Types. 55
Table 53. Summary Statistics for Crash Types. 55
Table 54. Quantiles for Pavement Condition and Climate. 56
Table 55. Summary Statistics for Pavement Condition and Climate. 56
Table 56. Quantiles for Pavement Friction. 57
Table 57. Summary Statistics for Pavement Friction. 57
Table 58. Quantiles for Traffic Data. 58
Table 59. Summary Statistics for Traffic Data. 58

Table 60. Quantiles for Traffic Data. 59
Table 61. Summary Statistics for Traffic Data. 59
Table 62. Multivariate Correlations among Roadway Characteristic Variables. 60
Table 63. Multivariate Correlations among Crashes, Skid Numbers, and Roadway Characteristic Variables. 60
Table 65. Quantiles for Crashes. 61
Table 66. Summary Statistics for Crashes. 61

CHAPTER 1. INTRODUCTION

INTRODUCTION

Safety of the travelling public is and has been a priority for the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). FHWA issued the Highway Safety Program Standard 12 on June 27, 1967, and states that, "every State shall have a program of design, construction and maintenance to improve highway safety." From the 1960s to current practice, TxDOT's policies and procedures to reduce wet weather accidents have evolved. There are currently two methods to evaluate pavement friction, the safer by design (SBD) method and the wet surface crash reduction program (WSCRP).

BACKGROUND

From the 1960s to current practice, FWHA's guidance has evolved along with TxDOT's policies and procedures to reduce wet weather accidents. FHWA has issued programs and technical advisories related to pavement safety, such as the following:

- July 19, 1973, IM 21-2-73 [1]: This provided the basic guidelines for a skid accident reduction program.
- December 23, 1980, FHWA Technical Advisory (T) 5040.17, "Skid Accident Reduction Program" [2].
    - Additional requirements for skid resistant pavements were published.
    - This advisory stated, "The State's program shall provide that there are standards for pavement design and construction with specific provision for high skid resistant qualities."
- June 17, 2005, FHWA Technical Advisory T5040.36 [3].
    - Both microtexture and macrotexture are necessary to provide wet pavement friction at low- and high-speed conditions.
    - The selection of the surface texture type to be provided at a specific location should be based on existing conditions at that site.
    - When selecting a texturing method or establishing a threshold value for a friction-related parameter, an agency should consider many factors including splash and spray, climate, traffic, speed, geometry, conflicting movements, materials and costs, and the presence of noise sensitive receptors.
- June 17, 2010, FHWA Technical Advisory T 5040.38, "Pavement Friction Management Technical Advisory" [4].
    - Provides guidance to state and local highway agencies on managing pavement surface friction.
    - The 2010 advisory supersedes the 1980 FHWA Technical Advisory 5040.17, "Skid Accident Reduction Program."

    - The Pavement Friction Management Technical Advisory (T 5040.38) website recommends several reference materials for pavement surface texture and friction.
- The current advisory is T 5040.38, which covers topics such as test equipment for measuring pavement friction, identification and classification of roadway locations with elevated crash rates, prioritizing projects for improving pavement friction, appropriate frequency and extent of friction testing on a highway network, and determining a pavement friction management program's effectiveness. It has guidance for the factors that should be considered when selecting pavement surface techniques or thresholds. These include splash and spray, climate, traffic volume and composition, speed limit, roadway geometry, potential conflicting movements or maneuvers (frictional demand), materials quality and cost, and the presence of noise-sensitive receptors.

TxDOT has followed FHWA guidance along with developing ways to improve its safety program through research. TxDOT's Form 2088, "Surface Aggregate Selection" was developed and implemented in 1999 under the Wet Weather Accident Reduction Program (WWARP) [1]. The WWARP included three phases, wet weather accident analysis, aggregate selection, and skid testing. Form 2088 was developed to assist with the program's flexible pavement aggregate selection phase. The program described the frictional demand and availability of a roadway pavement surface. The WWARP name was changed in August 2011 to WSCRP [5]. Also, in August of 2011, the Traffic Safety Division took over the oversight of the program from Materials and Testing. In November 2011, the percentage of wet surface crash criteria was added to the friction demand area.

With the intent to track the safety impacts of its system-wide investments, since February 2020 TxDOT has required that all roadway design projects on two-lane and four-lane rural highways utilize the Safety Scoring Tool (SST). The SST has evolved into the SBD method. The SBD method was developed to provide roadway designers with a reliable yet simple numeric assessment of the expected safety effectiveness that could be used at various stages of the project design process.

Although the SBD has a broader scope of application, its intent and design are aligned with TxDOT's WSCRP and its objective to provide a practical way to assess expected safety effectiveness.

The research team developed a framework to integrate Form 2088 with SBD pavement friction criteria. The combined criteria will bridge the gap between the approaches in the two current methods. The combined methods provide the benefits of streamlining the data inputs, avoiding duplication of efforts, and effectively improving the quality of the assessment of pavement friction safety.

CHAPTER 2. LITERATURE REVIEW

A literature review was performed to determine the current state of the practice and emerging research for the criteria used to determine pavement friction demand and availability. In general, the research team reviewed the following:

- National, international, and local current procedures or practices for characterizing aggregates for pavement surface friction.
- Existing relevant TxDOT test methods, specifications, policies, and procedures. The research team summarized their commonality and any deviations from other information in the literature for pavement friction safety programs and aggregate selection practices.
- Sources and data availability used in the criteria for the factors included in Form 2088 and SBD.

AGGREGATE CHARACTERIZATION, TXDOT

History of Aggregate Requirements

Before the WWARP/WSCRP program was established, TxDOT designers used a general note to establish the criteria for aggregates used in surface courses of all pavement types except concrete. The polish value (PV) test results of an aggregate and the present annual daily traffic (ADT) were the criteria used to determine the aggregate allowed on the surface course of a flexible pavement. The criteria used by TxDOT designers are shown in Table 1.

Table 1. Polish Value System.

Present ADT	PV
< 750	n/a
750–2000	28
2000–5000	30
> 5000	32

The initial material testing used to determine the surface aggregate classification (SAC), which is used in the WWARP/WSCRP, were the following:

- Tex-411-A, Soundness of Aggregate Using Sodium Sulfate or Magnesium Sulfate [6], which measures aggregate resistance to disintegration.
- Tex-438-A, Accelerated Polish Test for Coarse Aggregate [6], estimates coarse aggregate's polish and relative wear. In March 2001, the polish value test was changed from cross-hatched to smooth tire.
- Tex-612-J, Acid Insoluble Residue for Fine Aggregate [6], determines the percentage by weight of hydrochloric acid insoluble residue in a fine aggregate.

The initial criteria based on the material testing for determining the SAC were as follows:

I. All bituminous coarse aggregates that have both an acid insoluble residue of 70.0 percent or greater and magnesium sulfate soundness loss of 30.0 percent or less will be classified as class “A” sources.
II. All aggregate sources that do not meet the criteria defined in criteria I will be classified based on a combination of their residual solid tire polish value and magnesium sulfate soundness loss.

Over time, the surface aggregate classification criteria have changed. The current criteria are shown in Table 2 and are part of TxDOT test method Tex-499-A [6].

Table 2. Surface Aggregate Classification Testing.

Property Test Method	SAC A	SAC B	SAC C
Acid insoluble residue, % min Tex-612-J	55	—	—
5-cycle Mg, % max Tex-411-A	25	30	35
Crushed faces, 2 or more, % min Tex-460-A	85	85	85

The 2004 special specification 3150, “Warranted Microsurfacing (WMS),” has performance requirements for skid resistance (SN50S) of 25 and a two-year warranty period. Current TxDOT specifications do not have skid resistance criteria in any of the pavement items.

Current Practice for Aggregates

Texas uses SAC A aggregates for pavement surfaces with the highest friction demand. On the other hand, SAC B sources (typically limestones) are used when less friction demand is warranted. SAC B aggregates are abundant in Texas and mostly meet the requirements achieved by SAC A except for the acid insoluble residue test. Per ASTM 3042, this test determines the percentage of insoluble residues in carbon aggregates that separate the aggregates that may polish excessively.

Studies show that the acid-insoluble residues on the rock (limestone) increase with increased polish resistance quality [7-9]. However, correlations between the acid-insoluble residues and other aggregate polishing tests are relatively poor [7]. In addition, Kandhal et al. (1993) studied the acid-insoluble test on Alabama limestone aggregates. They concluded that the acid-insoluble residue should not be used to screen limestone rocks because of variations. Variabilities have also been observed for Texas limestone aggregates.

TXDOT WET CRASHES MANAGEMENT TOOLS

Form 2088

The safety of road users is a major priority for TxDOT and FHWA. In line with FHWA guidelines, in 1999, TxDOT developed and implemented Form 2088 (Aggregate Surface Selection) under WWARP. Form 2088 was revised in 2012, including a name change to WSCRP. Form 2088 has criteria that allow pavement designers to select appropriate aggregate that will provide adequate friction over the life of the pavement surface.

Currently, Form 2088 compares the demand for friction to the available friction. The total credit for the available friction should be greater than or equal to the demand for friction. The nine friction demand factors are shown in Table 3. The nine factors are weighted equally when compared to the other factors for demand. Each factor is assigned several points based on a rating of low (1), moderate (2), or high (3). The criteria thresholds are shown in Table 3. Furthermore, TxDOT research report 0-7077, "Synthesis: Evaluation Selection Criteria for TxDOT Form 2088" included recommendations for changes to the low, moderate, and high criteria.

Table 3. Form 2088 Friction Demand Example.

Demand For Friction	Low	Moderate	High	Designer's Rating	Points
Rain Fall (inches/year)	≤ 20	> 20 ≤ 40	> 40	> 40	3
Traffic (ADT)	≤ 5000	> 5000 ≤ 15,000	> 15,000	≤ 5000	1
Speed (mph)	≤ 35	> 35 ≤ 60	> 60	> 35 ≤ 60	2
Trucks (%)	≤ 8	> 8 ≤ 15	> 15	≤ 8	1
Vertical Grade (%)	≤ 2	> 2 ≤ 5	> 5	> 2 ≤ 5	2
Horizontal Curve (Degrees)	≤ 3	> 3 ≤ 7	> 7	> 7	3
Driveways (per mile)	≤ 5	> 5 ≤ 10	> 10	≤ 5	1
Intersecting Roadways (ADT)	≤ 500	> 500 ≤ 750	> 750	> 500 ≤ 750	2
Wet Surface Crashes (%)	≤ 5	> 5 < 15	≥ 15	≥ 15	3
SUMMARY OF TOTAL DEMAND FOR FRICTION					**18**

The available friction is determined by four factors with a point system based on a low (2), moderate (5), and high (8) criteria. The pavement surface design life points are determined by combining the surface design life and macro texture. Each factor is weighted the same compared to the other factors for available friction. The demand has points ranging from a minimum total of 9 to a maximum of 27. The available friction points range from 11 to 32. The minimum total point is 11 since SAC C is not an option. Table 4 is an example of the available friction compared to the friction demand in Table 3.

Table 4. Form 2088 Available Friction Example.

***Available Friction**	**Low**	**Moderate**	**High**	**Designer's Rating**	**Points**
Cross Slope (%)	< 2	2-3	3-4	< 2	2
Aggregate Microtexture	SAC C	SAC B	SAC A	SAC A	8
Pavement	Final Riding Surface			Surface Design Life	5
HMA Mixture Type	Item 344 Superpave Mixtures (SP)			Macro Texture	5
SUMMARY OF TOTAL AVAILABLE FRICTION					**20**
DOES TOTAL AVAILABLE FRICTION EXCEED TOTAL FRICTION DEMAND?					**Yes**

The original and revised Form 2088 criteria and associated friction demand are shown in Figure 1 and Figure 2, respectively, along with Table 5.

Texas Department of Transportation

Surface Aggregate Selection Form
WWARP

Form 2088
(8/2002)
Page 1 of 1

CSJ:

Date:

Highway:

Limits:

County:

District:

Designer's Name:

FRICTION DEMAND

Attribute	Low	Moderate	High	DESIGNER'S RATING L	M	H
Rain Fall (inches/year)	≤ 20	>20≤ 40	>40	☐	☐	☐
Traffic (ADT)	≤ 5000	>5000≤ 15,000	>15,000	☐	☐	☐
Speed (mph)	≤ 35	>35≤ 60	>60	☐	☐	☐
Trucks (%)	≤ 8	>8≤ 15	>15	☐	☐	☐
Vertical Grade (%)	≤ 2	>2≤ 5	>5	☐	☐	☐
Horizontal Curve ()	≤ 3	>3≤ 7	>7	☐	☐	☐
Driveways (per mile)	≤ 5	>5≤ 10	>10	☐	☐	☐
Intersecting Roadways (ADT)	≤ 500	>500≤ 750	>750	☐	☐	☐
Parameters set by the designer that affect pavement friction	**Low**	**Moderate**	**High**	**L**	**M**	**H**
Cross Slope (inches/foot)	3/8 - ½	¼ - 3/8	≤ ¼	☐	☐	☐
Surface Design Life (years)	≤ 3	>3≤ 7	>7	☐	☐	☐
Macro Texture (of proposed surface)	Coarse (Such as: Seal Coat Surface Treatment, OGFC)	Medium (Such as: HMAC Type "C" and "D", CMHB, SuperPave)	Fine (Such as: Slurry Seal "F" HMAC)	☐	☐	☐

Additional considerations include visibility restrictions (sight distance), accident history, skid performance, and material availability.

OVERALL FRICTIONAL DEMAND			SELECTION OF AGGREGATE CLASSIFICATION		
Low	Moderate	High	A	B	C
☐	☐	☐	☐	☐	☐

Comments and/or Justification:

Contact/Help **Submit**

Figure 1. Original WWARP SAC Form 2088.

Surface Aggregate Selection Form

Form 2088
(Rev. 05/12)
Page 1 of 1

Texas Department of Transportation

CSJ: - -

Date:

Highway:

Limits:

County:

District:

Designer's Name:

Selection Guidelines for Bituminous Surface Aggregate Classification (SAC)

Demand for Friction	**Low (1)**	**Moderate (2)**	**High (3)**	**DESIGNER'S RATING 1**	**2**	**3**
Rain Fall (inches/year)	≤20	>20 ≤40	>40			
Traffic (ADT)	≤5000	>5000 ≤15,000	>15,000			
Speed (mph)	≤35	>35 ≤60	>60			
Trucks (%)	≤8	>8 ≤15	>15			
Vertical Grade (%)	≤2	>2 ≤5	>5			
Horizontal Curve (º)	≤3	>3 ≤7	>7			
Driveways (per mile)	≤5	>5 ≤10	>10			
Intersecting Roadways (ADT)	≤500	>500 ≤750	>750			
Wet Surface Crashes (%)	≤5	>5 <15	≥15			
Summary of Total Frictional Demand				0		
***Available Friction**	**Low (2)**	**Moderate (5)**	**High (8)**	**2**	**5**	**8**
Cross Slope (%)	<2	2 - 3	3 - 4			
Surface Design Life (years)	>10	>5 ≤10	≤5			
Macro Texture of proposed surface	Fine (Such as: HMAC Type 'D' and 'F')	Medium (Such as: HMAC Type 'C', CMHB, SuperPave, Microsurface)	Coarse (Such as: PFC, SMA, Seal Coat, NovaChip)			
Aggregate MicroTexture	SAC C	SAC B	SAC A			
Summary of Total Friction Available				0		
Does total available friction equal or exceed total frictional demand?				Yes	No	

*Parameters set by the designer that affect pavement friction.
Total friction available should always exceed total frictional demand.

Comments:

Contact/Help

Figure 2. Revised WSCRP SAC Form 2088.

Table 5. Frictional Demand Factors.

Factors from WWARP Stand-Alone Manual Notice	Form 2088 Friction Demand	Form 2088 Friction Available	Not on TxDOT Form	FHWA T5040.38
Precipitation	Inches/year		Wet days per year	Climate
Traffic volume	ADT		Vehicles per lane	Traffic volume
Speed	Speed limits		Operational speeds	Speed limit
Geometrics	Horizontal and vertical curves geometry		Super elevation, number of curves	Roadway geometry
Frequency of vehicle stops	Driveways per mile		Number of crossroads	Potential conflicting movements or maneuvers (frictional demand)
Amount of cross traffic	ADT			Potential conflicting movements or maneuvers (frictional demand)
Amount of truck traffic	Percent trucks		18–kip equivalent single axle load	Traffic composition
Surface texture		Macrotexture		
Drainage characteristics		Cross slope	Ponding, rutting	
Visibility restrictions			Sight distance	
Accident history	Wet surface crashes[1]			
Skid performance			Skid performance	
Material availability			Material availability	Materials quality and cost
Other (not on WWARP)				Splash and spray, presence of noise-sensitive receptors

[1] Not on the original WWARP Form 2088. The factor was added in 2012.

TxDOT SBD

TxDOT and the Texas A&M Transportation Institute developed scoring tools that can be used to evaluate the effects of geometric, traffic control, and roadside design elements on safety. The scoring tool uses changes in design parameters such as lane and shoulder width, rumble strips, horizontal and vertical curve geometry, and clearances to objects, allowing engineers to make appropriate design decisions. In addition, the tool uses a simple spreadsheet to determine safety scores, offering users a simple operating program. To increase user experience, the tool is set to offer a web version in the future.

The tool is used for all rural two- and multi-lane non-access-controlled projects, ranging from routine maintenance to complete reconstructions. It is required on pavement projects, including seal coats and overlays. Also, it applies to these scopes of work: Added Capacity/Mobility, Major Rehab/Widening, Super 2, Bridge Replacements (On System), Bridge Widening/Major Rehab, Seal Coats/Overlays, and Category 8 Widening Projects (all).

The tool is divided into three major categories: geometric, traffic, and roadside. There is a maximum of 100 points for the total score, with 40 points assigned to geometric elements, 20 points for traffic elements, and 40 points for roadside elements. A comparison of the safety in the proposed design relative to the standard is provided. An example is shown in Figure 3. The design elements are shown in **Table** 6 and **Table** 7.

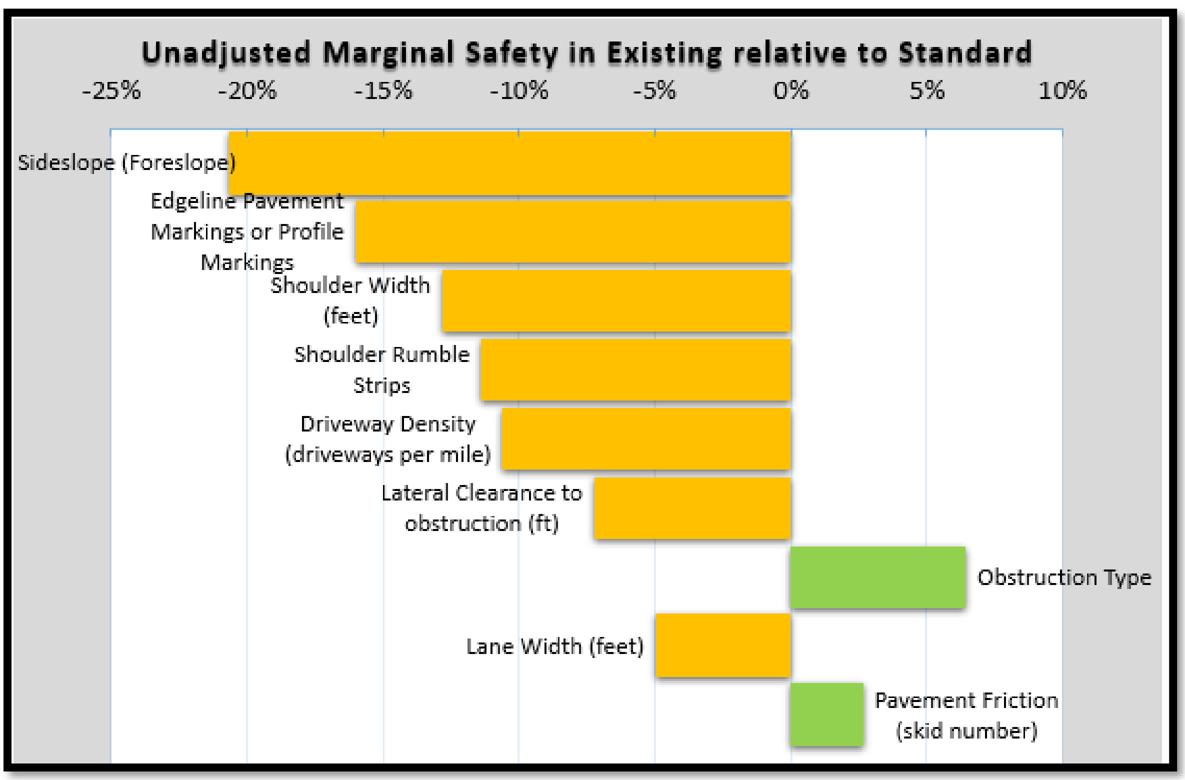

Figure 3. Safety Assessment Tool.

Table 6. Geometric Design Elements.

2-Lane	Multilane
Cross-slope or Superelevation (%)	Configuration of Multilane Roadway
Shoulder Width (feet)	Median Width (feet)
TWLTL (two-way left-turn lane)	Average Outside Shoulder Width (feet)
Passing or Climbing Lane in One Direction	Average Inside Shoulder Width (feet)
Lane Width (feet)	Number of Lanes per Direction of Travel
Horizontal Curve Present? Horizontal Curve Data for Controlling Element: Radius (feet) Length of Horizontal Curve (feet)	Horizontal Curve Present? Horizontal Curve Data for Controlling Element: Radius (feet) Length of Horizontal Curve (feet)
Vertical Curve Present? Vertical Curve Data for Controlling Element: Approach (Entry) Grade, G1 (%) Departure (Exit) Grade, G2 (%) Length (feet) Calculated Rate of Change, K (ft/ft) Calculated Sag or Crest?	Vertical Curve Present? Vertical Curve Data for Controlling Element: Approach (Entry) Grade, G1 (%) Departure (Exit) Grade, G2 (%) Length (feet) Calculated Rate of Change, K (ft/ft) Calculated Sag or Crest?
	Lane Width (feet)

Table 7. Traffic and Roadside Design Elements.

Traffic Design Elements	Roadside Design Elements
Advanced Static Curve Warning Signs	Side Slope (Foreslope)
Chevron Signs on Horizontal Curves	Backslope
Post-Mounted Delineators	Safety Edge
Edgeline Pavement Markings or Profile Markings	Lateral Clearance to Obstruction (ft)
Shoulder Rumble Strips	Obstruction Type
Centerline Rumble Strips	
Driveway Density (driveways per mile)	
Lighting	
Pavement Friction (skid number)	
Fixed Object Type (2-lane only)	

Regarding friction values, the TxDOT Maintenance Division recommends a guideline skid number of 38 for AC overlay and 52 for seal coat [10].

SBD and Form 2088

The SBD and Form 2088 contain several factors that should be considered when selecting a surfacing that provides adequate friction over the life of the pavement. Table 8 to Table 11 show the data needed for both procedures.

Table 8. Factors for Project, Climate, and Crash Data.

Project Information, Climate, Crash Data	SBD/SST Rural 2-Lane	SBD/SST Multilane	Form 2088
Design Speed (mph)	yes	yes	no
E max (%)	yes	yes	no
Dist. from Centerline to Left ROW (feet)	yes	yes	no
Dist. from Centerline to Right ROW (feet)	yes	yes	no
Location	yes	yes	yes
Posted Speed Limit (mph)	yes	yes	yes
Design Year AADT (vehicles per day)	yes	yes	yes
Truck (%)	no	no	yes
Rainfall (in/yr)	no	no	yes
Wet Surface Crashes (%)	no	no	yes

Table 9. Factors for Geometric Design Elements.

Geometric Design Elements	SBD/SST Rural 2-Lane	SBD/SST Multilane	Form 2088
Configuration of Multilane Roadway	no	yes	no
Median Width (feet)	no	yes	no
Lane Width (feet)	yes	yes	no
Average Outside Shoulder Width (feet)	no	yes	no
Average Inside Shoulder Width (feet)	no	yes	no
Number of Lanes per Direction of Travel	no	yes	no
Shoulder Width (feet)	yes	no	no
Vertical Curve Present?	yes	yes	no
Approach (Entry) Grade, G1 (%)	yes	yes	no
Departure (Exit) Grade, G2 (%)	yes	yes	no
Length (feet)	yes	yes	no
Calculated Rate of Change, K (ft/ft)	yes	yes	no
Calculated Sag or Crest?	yes	yes	no
TWLTL (two-way left-turn lane)	yes	no	no
Passing or Climbing Lane in One Direction	yes	no	no
Horizontal Curve Present?	yes	yes	yes

Horizontal Curve Data for Controlling Element:	yes	yes	yes
Length of Horizontal Curve (feet)	yes	yes	yes
Cross-slope or Superelevation (%)	yes	no	yes
Radius (feet)	yes	yes	yes
Vertical Curve Data for Controlling Element	yes	yes	yes

Table 10. Factors for Traffic Elements.

Traffic Elements	SBD/SST Rural 2-Lane	SBD/SST Multilane	Form 2088
Advanced Static Curve Warning Signs	yes	yes	no
Chevron Signs on Horizontal Curves	yes	yes	no
Post-Mounted Delineators	yes	yes	no
Edgeline Pavement Markings or Profile Markings	yes	yes	no
Shoulder Rumble Strips	yes	yes	no
Centerline Rumble Strips	yes	yes	no
Lighting	yes	yes	no
Pavement Friction (skid number)	yes	yes	no
Fixed Object Type	yes	no	no
Driveway Density (driveways per mile)	yes	yes	yes
Surface Design Life	no	no	yes
Macrotexture of Proposed Surface	no	no	yes
Microtexture—SAC	no	no	yes
Intersecting Roadways (ADT)	no	no	yes

Table 11. Factors for Roadside Elements.

Roadside Elements and Additional Sideslope Information	SBD/SST Rural 2-Lane	SBD/SST Multilane	Form 2088
Roadside Sideslope (Foreslope)	yes	yes	no
Roadside Backslope	yes	yes	no
Safety Edge	yes	yes	no
Roadside Lateral Clearance to Obstruction (ft)	yes	yes	no
Roadside Obstruction Type	yes	yes	no
Distance to Slope Toe from Shoulder (ft)	yes	yes	no
Minimum Foreslope Feasible within Current ROW	yes	yes	no
Additional R/W Needed on Left Side	yes	yes	no
Additional R/W Needed on Right Side	yes	yes	no

The SBD/SST safety score for pavement friction is part of the traffic elements, with each traffic element affecting the overall score by up to 20 points out of 100. The standard skid number (SN50S) is 47, and the optimal is 56. The effects of the SN50S to the 20 points is a maximum of

3 points. No lower limit is “flagged” as not acceptable. The range in score reduction by skid number is > 25, no reduction, > 12–24 is 1 point reduction, > 5–12 is a 2-point reduction, and ≤ 5 is a 3-point reduction.

TXDOT RESEARCH PROJECTS SUMMARY

TxDOT Research Project 6713-1, Quantitative Relationship between Crash Risks and Pavement Skid Resistance, analyzed crash rates’ relationship with skid numbers (SNs). The analysis indicates that the wet and dry surface crashes are the same when the SN is greater than or equal to 39. Refer to Table 12 for skid number recommendations from research 6713-1 [11].

Table 12. Skid Number Thresholds 6713-1.

Skid Resistance Level	All Weather Crashes (SN)	Wet Weather Crashes (SN)	Recommendation
SN1	14	17	Minimum.
SN2	28	29	Project level testing is recommended between SN1 and SN2. Vigilant between SN2 and SN3.
SN3	74	74	Desirable: An increase in SN results in a little reduction in crash rate when SN > SN3.

TxDOT Research Project 6714-1, Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves, incorporated pavement surface type, friction, and aggregate properties to develop an estimate of changes in crash rates. Table 13 shows the data needed for the crash prediction model calculations. An example of the inputs and crash prediction model calculations is shown in Figure 4.

Table 13. Crash Prediction Model Input Data.

Input Description	SBD/SST	Form 2088
Average daily traffic volume (veh/d)	Yes (range)	Yes (range)
Curve radius (ft)	Yes	Yes (range)
Deflection angle (degrees)	n/a	n/a
85th-percentile tangent speed (mph) (optional)	n/a	n/a
Regulatory speed limit (mph)	Yes	n/a
Advisory speed (mph)	n/a	n/a
Average lane width (ft)	Yes	n/a
Average shoulder width (ft)	Yes	n/a
Grade (%)	Yes	Yes (range)
Analysis period (yr)	n/a	Yes (range)
Reported crash count in analysis period	n/a	Yes (range)

Superelevation rate (%)	Yes	Yes (range)
Skid number at test speed (before and after)	Yes (after)	n/a
Annual Precipitation rate (in)	n/a	Yes (range)

Texas Curve Margin of Safety Worksheet

General Information					
District		Control section		Date	April 17, 2023
Highway		Beginning milepoint		Analyst	
Curve ID number		Ending milepoint		Curve deflection	Right

Site Characteristics Input Data			
Average daily traffic volume (ADT, veh/d)			1800
Truck percentage			12
ADT growth rate (%)			3
Roadway configuration			2U
Curve radius (ft)			1145
Deflection angle (degrees)			90
85th % tangent speed (mph)			
Regulatory speed limit (mph)			70
Advisory speed (mph)			55
Average lane width (ft)			11
Average shoulder width (ft)			3
Grade (%)		PC	2
(Deflection to Right)		MC	0
		PT	-2
Annual precipitation rate (inches)			35
Superelevation rate (%)		Before	After
Deflection to Left	PC		
	MC	6	6
	PT		
Deflection to Right	PC		
	MC	6	6
	PT	0	0

Pavement Treatment Input Data	
Skid number for existing surface	15
Proposed treatment type	Seal Coat (Gr. 3, 4, 5)
Aggregate type 1	Limestone
% contribution to coarse aggregate	100
Aggregate type 2 (optional)	Dolomite
% contribution to coarse aggregate	0
Economic discount rate	3.0%
Treatment cost	$50,000

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

Skid Number Calculations			
Skid number	Before	After	Terminal
at advisory speed	14.2	44.3	24.6
at skid test speed	15.0	46.9	26.1

Crash Prediction Model Calculations		
Predicted Crash Counts in Analysis Period		
	Before	After
All	2.209	1.675
Wet-weather	0.543	0.165
Run-off-road (ROR)	2.106	1.548
Wet-weather ROR	0.506	0.153
Predicted Change in Crash Count		
All		-25.0%
Wet-weather		-70.3%
Run-off-road (ROR)		-27.3%
Wet-weather ROR		-70.3%
Overall Crash Modification Factors (CMFs)		
Curve radius	1.988	
Annual precip.	1.632	
Skid number	1.252	0.940
Skid x Precip.	2.044	1.534
Wet-Weather CMFs		
Curve radius	1.000	
Annual precip.	2.959	
Skid number	2.586	0.769
Skid x Precip.	7.652	2.275
Run-off-Road CMFs		
Curve radius	2.315	
Annual precip.	1.632	
Skid number	1.284	0.933
Skid x Precip.	2.096	1.523
Wet-Weather Run-off-Road CMFs		
Curve radius	1.000	
Annual precip.	3.065	
Skid number	2.586	0.769
Skid x Precip.	7.925	2.356

Benefit-Cost Analysis Calculations	
Average crash cost	$668,082
Analysis period (yr)	7
SK at end of analysis period	39.6
Benefit-cost ratio	5.87
Net benefit	$243,725
Period of improved *SK* (yr)	21
SK at end of improved period	26.1
Benefit-cost ratio	11.18
Net benefit	$509,200

Page 1

Figure 4. Output from Texas Curve Margin of Safety Worksheet [12].

TxDOT Research Project 6932-1, Pavement Safety-Based Guidelines for Horizontal Curve Safety, developed guidelines for the crash modification factors (CMF) used in the Texas Curve Margin of Safety Worksheet. The CMF is used in the SBD method.

TxDOT Research Project 7077-1, Synthesis: Evaluation Selection Criteria for TxDOT Form 2088, Surface Aggregate Selection Form, developed recommendations for changes to Form 2088, including merging with the safety scoring tool. The factors that would need to be added so that the SBD/SST incorporated inputs from Form 2088 and the wet weather crash prediction model are shown in Table 14 [13]. TxDOT Research Project 0-4618, Conversion of Two-Lane Rural Roadways to Four-Lane Roadways, found in the intersection analysis that major-road ADT and cross-road ADT were statistically significant [14]. This project did not include the cross-road ADT in its crash prediction models.

Table 14. Additional SBD/SST Inputs.

Input Description	Crash Model	Form 2088
Deflection angle (degrees)	Yes	n/a
85th-percentile tangent speed (mph) (optional)	Yes	n/a
Regulatory speed limit (mph)	Yes	n/a
Advisory speed (mph)	Yes	n/a
Analysis period (yr)/surface design life	Yes	Yes
Reported crash count in analysis period	Yes	Yes
Annual precipitation rate (in)	Yes	Yes
Truck (%)	n/a	Yes
Skid number at test speed (before and after)	Yes	n/a
Macrotexture of proposed surface and microtexture—SAC	n/a	Yes
Intersecting roadway traffic volume (ADT)	n/a	Yes

LITERATURE REVIEW SUMMARY

Over 22 references were reviewed. The research team conducted a literature review of pavement friction requirements for all 50 state departments of transportation and found specific criteria in Louisiana, Michigan, Pennsylvania, Maryland, Florida, Tennessee, Utah, West Virginia, and Wyoming.

Nationally, there is no standardized procedure for designing pavement surfaces to minimize wet weather accidents. The selection of aggregates differs from one state to another, and some aggregate evaluation methods, such as acid insoluble testing, are questionable concerning their effectiveness.

In Texas, the tools, Form 2088 and SBD, are intended to assist designers to manage risks of crashes especially in wet conditions and need to be combined to offer a standardized method for all TxDOT districts. Additionally previous research used to correlate wet weather crash rates and pavement friction should be used to establish improved criteria that will help designers minimize the risk of wet weather crashes.

Integrating the methods developed in this project is intended to bridge the gap between the approaches in the two current tools, the SBD and Form 2088. Integration of the SBD and Form 2088 will provide the following benefits:

- Streamline the data inputs already required for the SBD.
- Avoid duplication of efforts by having one tool instead of two.
- Risk evaluation criteria that improve the assessment of pavement friction and its effect on safety.

CHAPTER 3. RISK ASSESSMENT PROCEDURE

RISK ASSESSMENT PROCEDURE BACKGROUND

A risk assessment procedure was developed based on analyzing the factors affecting pavement surface friction demand and availability. The aggregate microtexture and macrotexture influences were evaluated. An analysis of the pavement surface type related to friction criteria and the expected life of the pavement surface was evaluated and incorporated into the procedure.

The following factors affecting friction demand and availability were analyzed:

- Crash records data, such as:
  - Pavement surface condition (ice, snow, wet, or dry).
  - Time of day (dark, light, twilight).
  - Geometry (in a curve or intersection).
- Pavement analyst data, such as SN.
- The factors on TxDOT Form 2088.
- The factors in TxDOT SBD.

The friction demand, availability, and influence of the aggregate texture are the factors used to select aggregate properties to meet the friction criteria for the life of the pavement surface. For the pavement surface type selection, the following were analyzed and evaluated:

- Relationship to crashes.
- Criteria, including thresholds.
- Areas needing additional research.
- Areas needing validation of criteria thresholds.
- Identification of potential sources of data.

TxDOT's current risk assessment procedure relies on Form 2088 to determine the appropriate surface aggregate classification needed. The SBD has safety factors associated with horizontal curves and estimates the changes in safety based on the proposed project details.

RISK ASSESSMENT CRITERIA

Improved safety is the key outcome of the risk assessment procedure. The proposed pavement needs adequate friction to reduce the risk of wet weather crashes. The performance of pavement friction is monitored in the pavement management data through the collection of skid data. The key points from previous research that will be considered for incorporation into the risk assessment procedure include the climate and crash data analysis.

Precipitation in Texas can be quantified in several ways. U.S. Climate Normal data were obtained from the National Oceanic and Atmospheric Administration (NOAA) website. The most commonly used precipitation data are rainfall normalized to an annual total inch. However, when quantifying risk, the frequency of rainfall is also an important factor. Figure 5 shows the total annual rainfall and number of rain days. As seen visually, the frequency of rain days for < 20 inch total and > 40 inch total match up well. However, there appears to be a break in the 20–40 inch range that needs to be further investigated based on how often it rains.

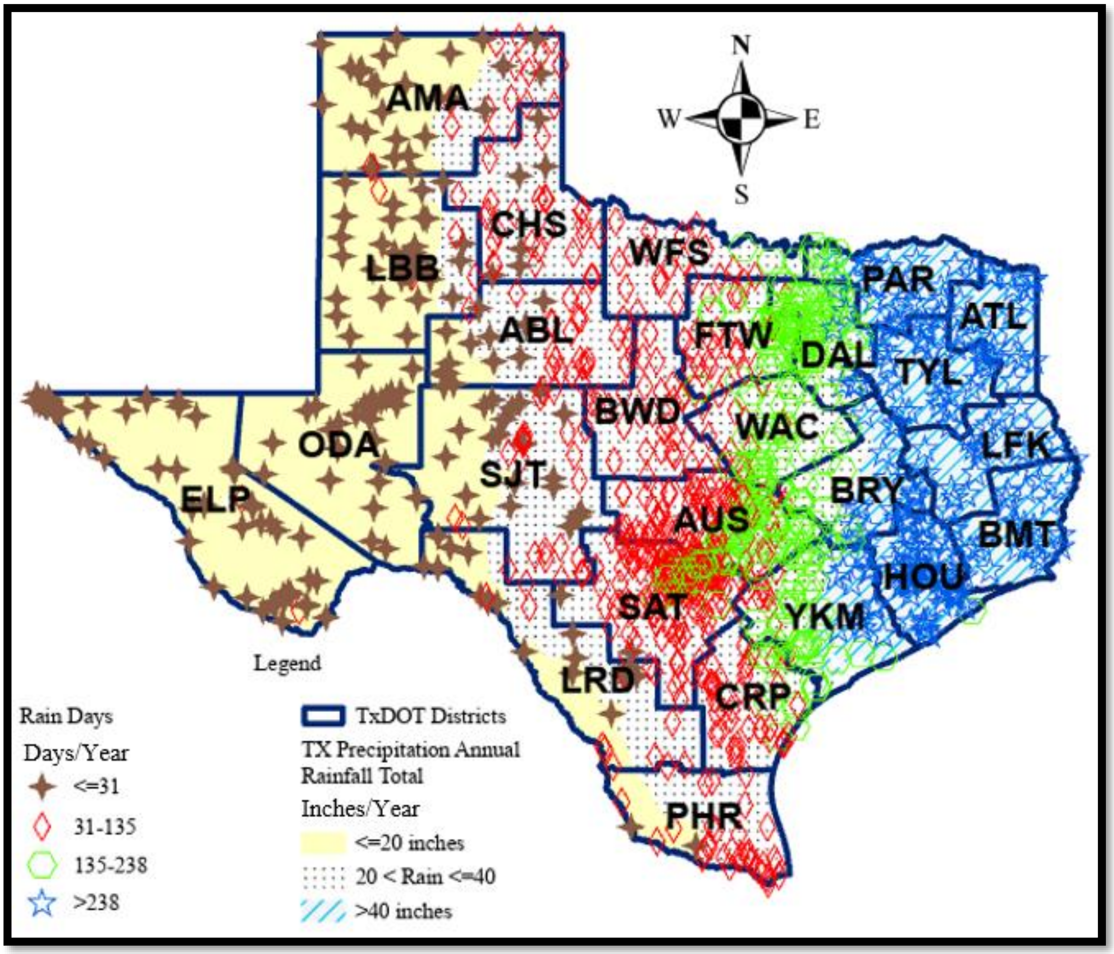

Figure 5. Annual Precipitation Totals and Frequency.

CRASH DATA ANALYSIS

Multiple data sets are being merged based on geospatial location. These data sets include the following:

- TxDOT RHINO data, 2021.
- Pavement Analyst data for skid number for the years 2018, 2019, 2020, 2021, and 2022.
- Crash records information system records for the years 2018, 2019, 2020, 2021, and 2022.
- NOAA climate data for annual precipitation and number of rain days recorded by Texas climate stations.

- 30-year normal.
- Years 2018, 2019, 2020, 2021, and 2022.

Several previous research reports contain analysis of skid data and crash data. Crashes from multiple years were analyzed in order to remove biases from unusual climate conditions that may skew the prediction of normal rates. It is unclear from previous studies whether the skid testing was performed at 40 mph with ribbed tire or at 50 mph with smooth tire. Since the previous studies mention skid test values from more than one testing method, a data analysis was performed in this study, and the results are discussed in the next section. The data analysis used TxDOT data based on the 50 mph smooth tire testing (SN50S).

Crash Data and Skid Number Analysis

The research team analyzed statistical data to evaluate the relationship between crashes and skid numbers. Although Wet crashes are the main target crashes of this study, the research team analyzed the Total and Dry crashes as well. The Dry crashes are simply the difference between the Total and Wet crashes.

Initially, the statistical dataset contained 167,495 segments corresponding to 72,978.2 miles, with crashes occurring for 5 years (2018–2022). Other recorded data in those five years are:

- Skid numbers (minimum skid [minskid], maximum skid [maxskid], average skid [avgskid]).
- Roadway characteristic variables (segment length, annual average daily traffic [AADT], surface type, etc.).
- Annual precipitation data (total annual precipitation, number of days with precipitation greater than or equal to 0.1 at each segment).

Upon initial evaluation of the data from each segment, the research team determined that skid numbers were missing for 4,106 segments (2.5 percent of the data), and thus 4,106 segments (corresponding to 554.6 miles) were removed from further analysis. Consequently, only 163,389 segments (corresponding to 72,423.6 miles) were retained in the analysis dataset. Appendix A contains the distributions and summary statistics of variables.

Appendix A also contains the correlation analysis among variables before the main safety analysis. While high correlations between the dependent variables (crashes) and independent variables (skid numbers, roadway characteristic variables, etc.) are desirable, including highly correlated independent variables simultaneously in the regression model leads to a significant estimation problem (the problem of collinearity) and should be avoided. From the correlation analysis, minskid was chosen as the primary study variable to assess the relationship between skid numbers and crashes. As already mentioned, it should be avoided to include all three skid numbers (that are highly correlated) in the model due to the issue of collinearity. The variable daily vehicle miles of travel (dvmt) was chosen to account for the effect of traffic and segment length instead of individually including AADT and segment length.

Negative binomial (NB) regression models were applied to each of the Total, Wet, and Dry crashes using crash frequency as a dependent variable and minskid and other roadway characteristic variables as independent variables. The general form of the expected number of crashes in a NB regression model can be given as shown in Equation 1.

$$\boldsymbol{\mu_i = exp(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki})} \qquad \textbf{Equation 1}$$

Where:

μ_i is the expected number of crashes at segment i,
$X_{1i}, \ldots, X_{ki}$ are independent variables corresponding to roadway characteristics of segment i, and
$\beta_0, \beta_1, \beta_2, \ldots, \beta_k$ are the regression coefficients.

The GENMOD procedure in statistical analysis software was used for the NB regression analyses.

After exploring various NB regression model forms with different independent variables, the model including log(dvmt) and surface type (srf_type_regrouped in Appendix A) as independent variables seemed to be most appropriate for these data. Models with a precipitation variable (total annual precipitation for five years or number of days with precipitation greater than or equal to 0.1 inches), along with other independent variables, were also explored. Because over 15 percent of segments have missing precipitation data (25,874 segments have missing total annual precipitation, and 25,563 segments have missing number of days with precipitation greater than or equal to 0.1), the NB models without a precipitation variable were first fitted.

Table 15 through Table 17 present the estimated model coefficients for each Total, Wet, and Dry crash. The effect of skid numbers is statistically significant at $\alpha = 0.05$. The estimated coefficients for minskid for Total, Wet, and Dry crashes are −0.0103, −0.0147, and −0.0092, respectively, which correspond to the percent crash reduction of 1.0 percent (= $[1\text{-}e^{-0.0103}] \times 100$), 1.5 percent (= $[1\text{-}e^{-0.0147}] \times 100$), and 0.9 percent (= $[1\text{-}e^{-0.0092}] \times 100$) as the minimum skid number increases by 1 (unit). If minskid increases by 10, the percent reduction in Total, Wet, and Dry crashes associated with minimum skid numbers are 9.8 percent (= $[1\text{-}e^{-0.103}] \times 100$), 13.7 percent (= $[1\text{-}e^{-0.147}] \times 100$) and 8.8 percent (= $[1\text{-}e^{-0.092}] \times 100$), respectively. The effect of minskid is somewhat stronger for Wet crashes than Dry crashes.

Table 15. Estimates of Regression Coefficients of NB Regression Model Applied to Total Crash Data from 163,389 Segments.

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits	Wald 95% Confidence Limits	Wald Chi-Square	Pr > ChiSq
Intercept		1	−2.6585	0.0197	−2.6972	−2.6198	18119.5	< .0001
Log_dvmt		1	0.6131	0.0022	0.6088	0.6174	78967.3	< .0001
srf_type_regrouped	**10_11_13**	1	−0.3725	0.0099	−0.3919	−0.3530	1412.02	< .0001
srf_type_regrouped	**123**	1	0.0216	0.0155	−0.0087	0.0519	1.96	0.1619
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
minskid		1	−0.0103	0.0003	−0.0109	−0.0096	958.70	< .0001
Dispersion		1	2.1149	0.0114	2.0927	2.1373	—	—

Table 16. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 163,389 Segments.

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits	Wald 95% Confidence Limits	Wald Chi-Square	Pr > ChiSq
Intercept		1	−4.9824	0.0315	−5.0442	−4.9205	24951.1	< .0001
Log_dvmt		1	0.6827	0.0034	0.6760	0.6893	40443.3	< .0001
srf_type_regrouped	**10_11_13**	1	−0.2620	0.0139	−0.2893	−0.2347	353.64	< .0001
srf_type_regrouped	**123**	1	−0.1394	0.0182	−0.1751	−0.1037	58.67	< .0001
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
minskid		1	−0.0147	0.0005	−0.0156	−0.0138	989.74	< .0001
Dispersion		1	1.8227	0.0184	1.7871	1.8591	—	—

Table 17. Estimates of Regression Coefficients of NB Regression Model Applied to Dry Crash Data from 163,389 Segments

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept		1	−2.8363	0.0206	−2.8767	−2.7958	18916.3	< .0001
Log_dvmt		1	0.6117	0.0023	0.6072	0.6162	72101.4	< .0001
srf_type_regrouped	**10_11_13**	1	−0.3776	0.0103	−0.3978	−0.3574	1346.94	< .0001
srf_type_regrouped	**123**	1	0.0277	0.0160	−0.0036	0.0589	3.01	0.0827
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
minskid		1	−0.0092	0.0003	−0.0099	−0.0085	707.79	< .0001
Dispersion		1	2.2212	0.0123	2.1972	2.2454	—	—

Next, the models including a precipitation variable (total annual precipitation for five years or number of days with precipitation greater than or equal to 0.1) were fitted. Table 18 and Table 19 present the estimated coefficients of fitting models, including the number of days with precipitation greater than or equal to 0.1 (denoted by 2018–2022 days ≥ 0.1) for each of the Total, Wet, and Dry crashes. The results of fitting the models including total annual precipitation for five years were not materially different from those of Table 15 through Table 17 and are not shown here.

It can be seen in Table 18 through Table 20 that the effect of skid numbers is again statistically significant at $\alpha = 0.05$, although the values of coefficient estimates changed slightly due to incorporating a precipitation variable in the model. The estimated coefficients for minskid for Total, Wet, and Dry crashes are −0.0114, −0.0185, and −0.0099, respectively, which correspond to the percent crash reduction of 1.1 percent (= $[1\text{-}e^{-0.0114}] \times 100$), 1.8 percent (= $[1\text{-}e^{-0.0185}] \times 100$), and 1.0 percent (= $[1\text{-}e^{-0.0099}] \times 100$) as the minimum skid number increases by 1 (unit). If minskid increases by 10, the percent reduction in Total, Wet, and Dry crashes associated with minimum skid numbers are 10.8 percent (= $[1\text{-}e^{-0.114}] \times 100$), 16.9 percent (= $[1\text{-}e^{-0.185}] \times 100$), and 9.4 percent (= $[1\text{-}e^{-0.099}] \times 100$), respectively. Again, the effect of minskid is stronger for wet crashes compared to dry crashes, as expected.

Table 18. Estimates of Regression Coefficients of NB Regression Model Applied to Total Crash Data from 137,826 Segments Having Precipitation Data.

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−2.8693	0.0248	−2.9179	−2.8207	13394.4	< .0001
Log_dvmt		1	0.6075	0.0024	0.6029	0.6121	66272.8	< .0001
srf_type_regrouped	**10_11_13**	1	−0.3682	0.0109	−0.3895	−0.3469	1146.41	< .0001
srf_type_regrouped	**123**	1	−0.0228	0.0169	−0.0559	0.0104	1.81	0.1789
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0012	0.0001	0.0011	0.0013	385.00	< .0001
minskid		1	−0.0114	0.0004	−0.0121	−0.0107	948.41	< .0001
Dispersion		1	2.1114	0.0123	2.0874	2.1357	—	—

Table 19. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 137,826 Segments Having Precipitation Data.

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−5.6061	0.0387	−5.6819	−5.5302	21000.5	< .0001
Log_dvmt		1	0.6838	0.0037	0.6766	0.6910	34637.6	< .0001
srf_type_regrouped	**10_11_13**	1	−0.2131	0.0152	−0.2429	−0.1832	195.86	< .0001
srf_type_regrouped	**123**	1	−0.2230	0.0197	−0.2616	−0.1844	128.50	< .0001

srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0030	0.0001	0.0028	0.0031	1290.50	< .0001
minskid		1	−0.0185	0.0005	−0.0195	−0.0174	1262.77	< .0001
Dispersion		1	1.7640	0.0194	1.7264	1.8025	—	—

Table 20. Estimates of Regression Coefficients of NB Regression Model Applied to Dry Crash Data from 137,826 Segments Having Precipitation Data.

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−2.9753	0.0258	−3.0257	−2.9248	13339.1	< .0001
Log_dvmt		1	0.6054	0.0025	0.6006	0.6103	60340.8	< .0001
srf_type_regrouped	**10_11_13**	1	−0.3791	0.0113	−0.4012	−0.3570	1126.25	< .0001
srf_type_regrouped	**123**	1	−0.0036	0.0175	−0.0379	0.0306	0.04	0.8353
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0009	0.0001	0.0008	0.0010	189.03	< .0001
minskid		1	−0.0099	0.0004	−0.0106	−0.0091	653.96	< .0001
Dispersion		1	2.2226	0.0134	2.1965	2.2490	—	—

Previous research indicated that at a skid number of 40 or greater, there was no difference between wet weather and dry weather crashes [15]. To investigate whether the current data also support this claim (i.e., the difference in the effect of skid number for Wet crashes and Dry crashes becomes negligible for segments with skid numbers that are greater than or equal to 40), the dataset was divided into two subsets, one with minskid ≥ 40 and the other with minskid < 40. The model with minskid, log(dvmt), surface type, and precipitation (2018–2022 days ≥ 0.1) was applied to Wet crashes and Dry crashes based on each dataset.

Table 21 and Table 22 contain the results for the segments with minskid < 40. The estimated coefficients for minskid for Wet and Dry crashes are −0.0202 and −0.0079, respectively, which correspond to the percent crash reduction of 2.0 percent (= $[1-e^{-0.0202}] \times 100$) and 0.8 percent (= $[1-e^{-0.0079}] \times 100$) as the minimum skid number increases by 1 (unit). If minskid increases by 10, the percent reduction in Wet and Dry crashes associated with minimum skid numbers are 18.3 percent (= $[1-e^{-0.202}] \times 100$) and 7.6 percent (= $[1-e^{-0.079}] \times 100$), respectively. For segments with minskid < 40, the safety benefit of minskid is much more noticeable for Wet crashes than for Dry crashes (11 percent more crash reduction for Wet crashes as minskid increases by 10).

Table 21. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 103,207 Segments Having Minskid < 40.

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−5.5585	0.0424	−5.6417	−5.4753	17147.7	< .0001
Log_dvmt		1	0.6841	0.0039	0.6764	0.6918	30524.6	< .0001
srf_type_regrouped	**10_11_13**	1	−0.2061	0.0170	−0.2395	−0.1727	146.30	< .0001
srf_type_regrouped	**123**	1	−0.2342	0.0204	−0.2741	−0.1942	132.00	< .0001
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0029	0.0001	0.0028	0.0031	1067.87	< .0001
minskid		1	−0.0202	0.0008	−0.0217	−0.0186	655.34	< .0001
Dispersion		1	1.7535	0.0202	1.7143	1.7937	—	—

Table 22. Estimates of Regression Coefficients of NB Regression Model Applied to Dry Crash Data from 103,207 Segments Having Minskid < 40.

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−2.9013	0.0301	−2.9603	−2.8423	9288.98	< .0001
Log_dvmt		1	0.5961	0.0027	0.5908	0.6014	48335.8	< .0001
srf_type_regrouped	**10_11_13**	1	−0.3945	0.0132	−0.4204	−0.3686	888.54	< .0001
srf_type_regrouped	**123**	1	−0.0224	0.0185	−0.0586	0.0139	1.46	0.2270
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0007	0.0001	0.0006	0.0008	92.84	< .0001
minskid		1	−0.0079	0.0007	−0.0092	−0.0066	143.30	< .0001
Dispersion		1	2.2901	0.0150	2.2609	2.3196	—	—

Table 23 and Table 24 contain the results for the segments with minskid ≥ 40. The estimated coefficients for minskid for Wet and Dry crashes are −0.0082 and −0.0031, respectively, which correspond to the percent crash reduction of 0.8 percent (= $[1\text{-}e^{-0.0082}] \times 100$) and 0.3 percent (= $[1\text{-}e^{-0.0031}] \times 100$) as the minimum skid number increases by 1 (unit). If minskid increases by 10, the percent reduction in Wet and Dry crashes associated with minimum skid numbers are 7.9 percent (= $[1\text{-}e^{-0.082}] \times 100$) and 3.1 percent (= $[1\text{-}e^{-0.031}] \times 100$), respectively. Once minskid exceeds 40, the effect of minskid seems to be attenuated. Also, there appears to be a much smaller difference between Wet and Dry crashes in the effect of minskid for the segments with minskid ≥ 40, compared to those with minskid < 40.

Table 23. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 34,619 Segments Having Minskid ≥ 40.

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−6.1998	0.1489	−6.4916	−5.9079	1733.65	< .0001
Log_dvmt		1	0.6845	0.0107	0.6636	0.7054	4118.25	< .0001
srf_type_regrouped	**10_11_13**	1	−0.2508	0.0348	−0.3191	−0.1826	51.91	< .0001
srf_type_regrouped	**123**	1	0.0444	0.0786	−0.1096	0.1984	0.32	0.5718
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0033	0.0002	0.0029	0.0038	230.91	< .0001
minskid		1	−0.0082	0.0022	−0.0124	−0.0039	14.08	0.0002
Dispersion		1	1.8460	0.0667	1.7198	1.9814	—	—

Table 24. Estimates of Regression Coefficients of NB Regression Model Applied to Dry Crash Data from 34,619 Segments Having Minskid ≥ 40.

Parameter	Group	DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−3.8482	0.0853	−4.0154	−3.6810	2035.15	< .0001
Log_dvmt		1	0.6536	0.0060	0.6419	0.6654	11854.3	< .0001
srf_type_regrouped	**10_11_13**	1	−0.2927	0.0214	−0.3347	−0.2506	186.17	< .0001
srf_type_regrouped	**123**	1	0.2582	0.0601	0.1404	0.3760	18.47	< .0001
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0015	0.0001	0.0012	0.0018	123.30	< .0001
minskid		1	−0.0031	0.0013	−0.0056	−0.0006	5.96	0.0146
Dispersion		1	1.8446	0.0291	1.7884	1.9027	—	—

PROPOSED RISK ASSESSMENT PROCEDURE

For this procedure, the "risk" is the likelihood of a wet weather crash occurring under the conditions evaluated. The crash model and the SBD/SST were combined to provide a risk level based on the skid number. Then the risk level was used in the overall safety assessment in the SBD/SST.

Risk levels are shown in Table 25 and were determined based on TxDOT Research Project 0-6713-1 and the crash analysis performed in this project. It is proposed that the risk level or CMF be displayed instead of the SN50S in the reporting. The CMF is used in the SBD tool to estimate the crash risk, which will be discussed further in the next chapter. Additionally, the pavement friction input area will have an additional input area to add the pavement elements so the skid number can be predicted based on the proposed surface materials.

Table 25. Risk Levels.

Risk	SN50S Lower Limit	SN50S Upper Limit	Comments
Minimal	> 39		Wet Weather and Dry Weather crash rates are similar when SN > 39, CMF = 1
Low	> 32	≤ 39	CMF calculated for SBD
Moderate	> 24	≤ 32	CMF calculated for SBD
High	> 17	≤ 24	CMF calculated for SBD
Very High Risk		< 17	Message that this is "Not acceptable," change pavement type or aggregate properties.

CHAPTER 4. SBD MODIFICATIONS

BACKGROUND SBD MODIFICATIONS

The SBD uses a CMF based on whether the roadway is rural or urban, two-lane, multi-lane undivided, or multi-lane divided, and whether the crash was property damage only (PDO) or a combination of fatalities and injury (FI) accidents.

SAFETY ANALYSIS OF SKID NUMBERS ON WET CRASHES

The objective of this analysis was to evaluate the relationship between wet crashes and skid numbers and develop CMFs for wet crashes by roadway category. Three types of wet crashes (all wet, FI wet, and PDO wet) were considered. Table 26 shows the six roadway categories considered (represented by the variable 'RU_Lanes').

Table 26. RU_Lane Codes.

Code	Description
1	Urban—two lanes
2	Urban—multi lanes undivided
3	Urban—multi lanes divided
4	Rural—two lanes
5	Rural—multi lanes undivided
6	Rural—multi lanes divided

The original dataset contained 167,495 segments (corresponding to 72,978.2 miles) with crashes for five years (2018–2022), skid numbers by segment (minimum skid [minskid], maximum skid [maxskid], average skid [avgskid]), roadway characteristic variables (segment length, AADT, surface type, etc.), and annual precipitation data (total annual precipitation, number of days with precipitation greater than or equal to 0.1 inch at each segment). However, the measurements of skid numbers were missing for 4,106 segments (2.5 percent of the data), and those 4,106 segments (corresponding to 554.6 miles) were removed from further analysis. For wet crashes, it is important to account for precipitation.

Recall that the number of days with precipitation greater than or equal to 0.1 was missing for 25,563 segments, which leaves 137,826 segments in the dataset developing CMFs for wet crashes. Appendix B contains the distributions and summary statistics of the variables for the analysis of the 137,826 segments (corresponding to 60,356.2 miles) retained in the dataset. As in the previous analyses, minskid is used as the main study variable to assess the relationship between skid numbers and wet crashes.

NB regression models were applied to each of Wet, FI_Wet, and PDO_Wet crashes using crash frequency as a dependent variable and minskid and other roadway characteristic variables as independent variables for each of the six roadway categories given above. (The frequency table for RU_Lanes in Appendix B shows how many road segments belong to each category.) The general form of the expected number of crashes in a NB regression model is shown in Equation 1. More details on NB regression models can be found in Spiegelman et al. (2010).

In addition to the main study variable minskid (X_{1i}), the variables for daily vehicle miles of travel (log of dvmt), surface type (srf_type_regrouped), and the number of days with precipitation greater than or equal to 0.1 inch (2018–2022 days ≥ 0.1) are also included in the model to account for the effects of traffic and segment length, the effect of surface type, and the effect of precipitation, respectively. A negative estimate for β_1 in Equation 1 indicates a positive safety effect of higher skid numbers (i.e., a decrease in crashes). The CMF (θ) of skid numbers can then be estimated by Equation 2.

$$\hat{\theta} = \exp\left(\hat{\beta}_1\right)$$ **Equation 2**

Where:

$\hat{\beta}_1$ and $\hat{\theta}$ denote the estimates of β_1 and θ, respectively.

Table 27 through Table 44 present the estimated coefficients of NB models for Wet, FI_Wet, and PDO_Wet crashes for each of the six roadway categories. It can be seen that the effects of skid numbers are statistically significant at α = 0.05 for all three wet crash types and six roadway categories.

Table 27. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 26,654 Urban 2-Lane Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−4.5023	0.0727	−4.6448	−4.3599	3836.75	<.0001
Log_dvmt		1	0.5802	0.0069	0.5667	0.5938	7011.27	<.0001
srf_type_regrouped	**10_11_13**	1	−0.1744	0.0384	−0.2496	−0.0991	20.64	<.0001
srf_type_regrouped	**123**	1	−0.3918	0.0331	−0.4567	−0.3270	140.37	<.0001
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0028	0.0002	0.0025	0.0031	284.22	<.0001
minskid		1	−0.0148	0.0011	−0.0170	−0.0126	170.27	<.0001
Dispersion		1	2.1140	0.0397	2.0377	2.1932	—	—

Table 28. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 26,654 Urban 2-Lane Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−5.9166	0.1001	−6.1127	−5.7205	3496.25	<.0001
Log_dvmt		1	0.6303	0.0096	0.6115	0.6490	4347.67	<.0001
srf_type_regrouped	**10_11_13**	1	−0.1689	0.0511	−0.2690	−0.0688	10.94	0.0009
srf_type_regrouped	**123**	1	−0.4297	0.0406	−0.5093	−0.3500	111.84	<.0001
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0021	0.0002	0.0017	0.0025	102.88	<.0001
minskid		1	−0.0136	0.0015	−0.0165	−0.0108	88.28	<.0001
Dispersion		1	1.8894	0.0583	1.7785	2.0073	—	—

Table 29. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 26,654 Urban 2-Lane Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−4.9575	0.0797	−5.1136	−4.8013	3870.41	<.0001
Log_dvmt		1	0.5836	0.0076	0.5686	0.5985	5880.11	<.0001
srf_type_regrouped	**10_11_13**	1	−0.1661	0.0414	−0.2472	−0.0851	16.13	<.0001
srf_type_regrouped	**123**	1	−0.4008	0.0351	−0.4696	−0.3321	130.54	<.0001

srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0031	0.0002	0.0027	0.0034	300.59	<.0001
minskid		1	−0.0151	0.0012	−0.0175	−0.0127	153.00	<.0001
Dispersion		1	2.0907	0.0451	2.0041	2.1811	—	—

Table 30. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 8,420 Urban Multi-Lane Undivided Segments.

Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits (lower)**	**Wald 95% Confidence Limits (upper)**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	−5.1264	0.1267	−5.3747	−4.8782	1637.72	<.0001
Log_dvmt		1	0.6554	0.0128	0.6304	0.6805	2628.07	<.0001
srf_type_regrouped	**10_11_13**	1	−0.0944	0.0641	−0.2200	0.0313	2.17	0.1409
srf_type_regrouped	**123**	1	0.0002	0.0792	−0.1550	0.1553	0.00	0.9985
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0031	0.0003	0.0026	0.0037	141.11	<.0001
minskid		1	−0.0124	0.0017	−0.0157	−0.0090	52.13	<.0001
Dispersion		1	1.5056	0.0553	1.4011	1.6179	—	—

Table 31. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 8,420 Urban Multi-Lane Undivided Segments.

Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits (lower)**	**Wald 95% Confidence Limits (upper)**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	−6.8521	0.1819	−7.2086	−6.4956	1418.98	<.0001
Log_dvmt		1	0.7374	0.0185	0.7011	0.7736	1588.91	<.0001
srf_type_regrouped	**10_11_13**	1	−0.3033	0.0891	−0.4779	−0.1287	11.59	0.0007
srf_type_regrouped	**123**	1	−0.0080	0.1008	−0.2055	0.1896	0.01	0.9369
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0027	0.0003	0.0020	0.0033	58.19	<.0001
minskid		1	−0.0095	0.0023	−0.0140	−0.0049	16.51	<.0001
Dispersion		1	1.3219	0.0859	1.1638	1.5015	—	—

Table 32. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 8,420 Urban Multi-Lane Undivided Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−5.4463	0.1394	−5.7195	−5.1731	1526.70	<.0001
Log_dvmt		1	0.6525	0.0141	0.6249	0.6800	2149.12	<.0001
srf_type_regrouped	**10_11_13**	1	−0.0513	0.0685	−0.1856	0.0831	0.56	0.4544
srf_type_regrouped	**123**	1	−0.0044	0.0844	−0.1697	0.1610	0.00	0.9585
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0032	0.0003	0.0027	0.0038	129.92	<.0001
minskid		1	−0.0144	0.0019	−0.0180	−0.0108	60.31	<.0001
Dispersion		1	1.4722	0.0628	1.3541	1.6006	—	—

Table 33. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 10,220 Urban Multi-Lane Divided Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−5.8153	0.1260	−6.0623	−5.5684	2130.22	<.0001
Log_dvmt		1	0.7080	0.0111	0.6863	0.7297	4089.46	<.0001
srf_type_regrouped	**10_11_13**	1	0.3116	0.1171	0.0822	0.5411	7.09	0.0078
srf_type_regrouped	**123**	1	−0.1594	0.0393	−0.2365	−0.0823	16.41	<.0001
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0014	0.0003	0.0009	0.0020	30.86	<.0001
minskid		1	−0.0091	0.0020	−0.0131	−0.0052	20.41	<.0001
Dispersion		1	2.0804	0.0529	1.9793	2.1867	—	—

Table 34. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 10,220 Urban Multi-Lane Divided Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−7.2412	0.1671	−7.5686	−6.9137	1878.86	<.0001
Log_dvmt		1	0.7292	0.0146	0.7006	0.7578	2491.14	<.0001
srf_type_regrouped	**10_11_13**	1	0.1776	0.1382	−0.0933	0.4486	1.65	0.1989

srf_type_regrouped	**123**	1	−0.1380	0.0465	−0.2291	−0.0469	8.81	0.0030
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0012	0.0003	0.0006	0.0018	14.06	0.0002
minskid		1	−0.0085	0.0025	−0.0134	−0.0037	11.90	0.0006
Dispersion		1	1.7874	0.0722	1.6514	1.9346	—	—

Table 35. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 10,220 Urban Multi-Lane Divided Segments.

Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits (lower)**	**Wald 95% Confidence Limits (upper)**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	−6.1959	0.1346	−6.4596	−5.9322	2120.33	<.0001
Log_dvmt		1	0.7168	0.0119	0.6935	0.7401	3628.04	<.0001
srf_type_regrouped	**10_11_13**	1	0.3160	0.1195	0.0818	0.5501	7.00	0.0082
srf_type_regrouped	**123**	1	−0.1520	0.0409	−0.2321	−0.0719	13.84	0.0002
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0015	0.0003	0.0009	0.0020	29.61	<.0001
minskid		1	−0.0107	0.0021	−0.0148	−0.0066	25.75	<.0001
Dispersion		1	2.0254	0.0566	1.9175	2.1394	—	—

Table 36. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 75,185 Rural 2-Lane Segments.

Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits (lower)**	**Wald 95% Confidence Limits (upper)**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	−6.5057	0.0518	−6.6073	−6.4042	15755.2	<.0001
Log_dvmt		1	0.7601	0.0052	0.7499	0.7703	21492.6	<.0001
srf_type_regrouped	**10_11_13**	1	0.0610	0.0147	0.0322	0.0898	17.25	<.0001
srf_type_regrouped	**123**	1	−0.3022	0.1175	−0.5324	−0.0721	6.62	0.0101
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0031	0.0001	0.0029	0.0033	1041.02	<.0001
minskid		1	−0.0189	0.0006	−0.0200	−0.0177	1065.83	<.0001
Dispersion		0	1.0000	0.0000	1.0000	1.0000	—	—

Note: For this dataset, the coefficient estimates were obtained by fitting a Poisson regression model because the NB regression model could not be fitted due to error in estimation routine.

Table 37. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 75,185 Rural 2-Lane Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−7.9748	0.1057	−8.1820	−7.7676	5691.29	<.0001
Log_dvmt		1	0.7730	0.0108	0.7519	0.7941	5153.00	<.0001
srf_type_regrouped	**10_11_13**	1	0.1046	0.0301	0.0455	0.1636	12.06	0.0005
srf_type_regrouped	**123**	1	−0.3724	0.2553	−0.8728	0.1280	2.13	0.1446
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0035	0.0002	0.0031	0.0039	301.64	<.0001
minskid		1	−0.0169	0.0011	−0.0192	−0.0147	217.29	<.0001
Dispersion		1	1.0087	0.0626	0.8932	1.1391	—	—

Table 38. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 75,185 Rural 2-Lane Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−6.6291	0.0739	−6.7739	−6.4842	8044.06	<.0001
Log_dvmt		1	0.7267	0.0077	0.7117	0.7417	8979.04	<.0001
srf_type_regrouped	10_11_13	1	0.0170	0.0222	−0.0266	0.0605	0.58	0.4451
srf_type_regrouped	123	1	−0.2626	0.1699	−0.5956	0.0704	2.39	0.1222
srf_type_regrouped	45679	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0031	0.0001	0.0029	0.0034	444.88	<.0001
minskid		1	−0.0187	0.0008	−0.0204	−0.0171	504.66	<.0001
Dispersion		1	1.1812	0.0394	1.1064	1.2610	—	—

Table 39. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 4,133 Rural Multi-Lane Undivided Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−6.5296	0.2343	−6.9888	−6.0705	776.91	<.0001
Log_dvmt		1	0.7910	0.0255	0.7410	0.8411	959.59	<.0001
srf_type_regrouped	10_11_13	1	0.0012	0.1017	−0.1981	0.2005	0.00	0.9904
srf_type_regrouped	123	1	−0.3411	0.1816	−0.6970	0.0148	3.53	0.0603

srf_type_regrouped	45679	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0020	0.0004	0.0012	0.0029	20.97	<.0001
minskid		1	−0.0180	0.0029	−0.0237	−0.0122	37.51	<.0001
Dispersion		1	1.1038	0.0971	0.9290	1.3114	—	—

Table 40. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 4,133 Rural Multi-Lane Undivided Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−8.5009	0.3865	−9.2584	−7.7433	483.72	<.0001
Log_dvmt		1	0.8792	0.0413	0.7983	0.9601	453.45	<.0001
srf_type_regrouped	10_11_13	1	−0.1567	0.1686	−0.4872	0.1738	0.86	0.3528
srf_type_regrouped	123	1	−0.3894	0.2721	−0.9226	0.1438	2.05	0.1524
srf_type_regrouped	45679	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0024	0.0007	0.0011	0.0037	12.63	0.0004
minskid		1	−0.0201	0.0046	−0.0292	−0.0110	18.86	<.0001
Dispersion		1	1.0703	0.1913	0.7540	1.5192	—	—

Table 41. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 84,133 Rural Multi-Lane Undivided Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−6.7104	0.2581	−7.2162	−6.2046	676.12	<.0001
Log_dvmt		1	0.7763	0.0280	0.7214	0.8312	768.43	<.0001
srf_type_regrouped	**10_11_13**	1	0.0447	0.1110	−0.1730	0.2623	0.16	0.6876
srf_type_regrouped	**123**	1	−0.3339	0.1965	−0.7191	0.0512	2.89	0.0893
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0018	0.0005	0.0009	0.0028	14.18	0.0002
minskid		1	−0.0174	0.0032	−0.0238	−0.0111	29.06	<.0001
Dispersion		1	1.0674	0.1116	0.8697	1.3101	—	—

Table 42. Estimates of Regression Coefficients of NB Regression Model Applied to Wet Crash Data from 13,214 Rural Multi-Lane Divided Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−6.7318	0.1113	−6.9500	−6.5136	3656.90	<.0001
Log_dvmt		1	0.7996	0.0102	0.7796	0.8196	6151.86	<.0001
srf_type_regrouped	**10_11_13**	1	−0.1373	0.0662	−0.2671	−0.0075	4.30	0.0382
srf_type_regrouped	**123**	1	−0.2510	0.0461	−0.3414	−0.1606	29.63	<.0001
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0032	0.0002	0.0027	0.0036	210.89	<.0001
minskid		1	−0.0263	0.0015	−0.0293	−0.0233	296.30	<.0001
Dispersion		1	1.0623	0.0345	0.9968	1.1322	—	—

Table 43. Estimates of Regression Coefficients of NB Regression Model Applied to FI_Wet Crash Data from 13,214 Rural Multi-Lane Divided Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−7.7397	0.1664	−8.0658	−7.4136	2163.59	< .0001
Log_dvmt		1	0.7561	0.0149	0.7268	0.7853	2564.75	< .0001
srf_type_regrouped	**10_11_13**	1	−0.1102	0.0967	−0.2997	0.0793	1.30	0.2545
srf_type_regrouped	**123**	1	−0.4619	0.0685	−0.5961	−0.3278	45.53	< .0001
srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	—	—
2018–2022 days ≥ 0.1		1	0.0030	0.0003	0.0024	0.0036	95.26	< .0001
minskid		1	−0.0226	0.0022	−0.0270	−0.0182	101.11	< .0001
Dispersion		1	1.0547	0.0650	0.9347	1.1902	—	—

Table 44. Estimates of Regression Coefficients of NB Regression Model Applied to PDO_Wet Crash Data from 13,214 Rural Multi-Lane Divided Segments.

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits (lower)	Wald 95% Confidence Limits (upper)	Wald Chi-Square	Pr > ChiSq
Intercept		1	−7.1309	0.1227	−7.3713	−6.8904	3379.57	< .0001
Log_dvmt		1	0.8161	0.0112	0.7941	0.8380	5311.50	< .0001
srf_type_regrouped	**10_11_13**	1	−0.1559	0.0733	−0.2995	−0.0124	4.53	0.0333
srf_type_regrouped	**123**	1	−0.1852	0.0490	−0.2812	−0.0892	14.29	0.0002

srf_type_regrouped	**45679**	0	0.0000	0.0000	0.0000	0.0000	.	.
2018–2022 days ≥ 0.1		1	0.0031	0.0002	0.0026	0.0036	171.75	< .0001
minskid		1	−0.0275	0.0017	−0.0308	−0.0242	267.74	< .0001
Dispersion		1	1.0814	0.0391	1.0074	1.1608		

Table 45 contains the CMF estimates obtained by Equation 2 as well as the regression coefficients for minskid for Wet, FI_Wet, and PDO_Wet crashes for each of the six roadway categories.

Table 45. Skid Number Regression Coefficients and CMF Estimates.

Categories	**All Wet Crashes**	**All Wet Crashes**	**FI Wet Crashes**	**FI Wet Crashes**	**PDO Wet Crashes**	**PDO Wet Crashes**
	$\hat{\beta}_1$	$\hat{\theta}$	$\hat{\beta}_1$	$\hat{\theta}$	$\hat{\beta}_1$	$\hat{\theta}$
Urban—2-lanes	−0.0148	0.99	−0.0136	0.99	−0.0151	0.99
Urban—multi-lanes undivided	−0.0124	0.99	−0.0095	0.99	−0.0144	0.99
Urban—multi-lanes divided	−0.0091	0.99	−0.0085	0.99	−0.0107	0.99
Rural—2-lanes	−0.0189	0.98	−0.0169	0.98	−0.0187	0.98
Rural—multi-lanes undivided	−0.0180	0.98	−0.0201	0.98	−0.0174	0.98
Rural—multi-lanes divided	−0.0263	0.97	−0.0226	0.98	−0.0275	0.97

Notes: 1. $\hat{\beta}_1$ is the estimated regression coefficient for minskid; 2. $\hat{\theta}$ is the CMF estimate, obtained by Equation 2.

Table 46 and Table 47 contains the CMF estimates obtained by Equation 2 for Wet, FI_Wet, and PDO_Wet crashes for each of the six roadway categories.

Table 46. Skid Number CMF Estimates by Urban Roadway Categories.

Condition	2-lanes	Multi-lane Undivided	Multi-lane Divided
All Wet Crashes	0.99	0.99	0.99
FI Wet Crashes	0.99	0.99	0.99
PDO Wet Crashes	0.99	0.99	0.99

Table 47. Skid Number CMF Estimates by Rural Roadway Categories.

Condition	2-lanes	Multi-lane Undivided	Multi-lane Divided
All Wet Crashes	0.98	0.98	0.97
FI Wet Crashes	0.98	0.98	0.98
PDO Wet Crashes	0.98	0.98	0.97

SBD

TxDOT has been utilizing SBD to assess the safety level of different design alternatives. Analyzing the safety score of design configurations makes it possible to estimate the safety score and improve safety at the earliest stage, thereby reducing crashes and injuries. The SBD tool includes various roadway features, including geometric, traffic, roadside, pedestrian, and bicyclist elements. The evaluation of the safety score follows the methodology documented in the American Association of State Highway and Transportation Officials (AASHTO) *Highway Safety Manual (HSM)* (AASHTO 2011). It is primarily based on the safety performance functions and CMFs. The CMFs for pavement skid number developed in this project can be incorporated into the SBD tool. The research team developed a web-based tool to calculate the CMF for skid number for different roadway types to achieve this objective.

The skid number value is required to calculate the CMF. However, since skid number data may not always be readily available to analysts, it becomes necessary to estimate this parameter. The research team also developed a skid number estimation tool to address this issue.

Although the project team has estimated the skid number CMFs for wet weather crashes for different severity levels, the SBD tool considers total crashes when calculating the safety score of a project. Therefore, it becomes necessary to determine the ratio of wet weather crashes to total crashes on different roadway types. The research team used the safety data to develop the ratios and base conditions of skid number for each facility type. The results are shown in Table 48. The base condition is calculated as the average skid number on each facility type's segments. It is used as the base condition of skid number (i.e., when CMF = 1.0).

Table 48. Ratio of Wet, FI_Wet, and PDO_Wet Crashes and Base Skid Number for Different Roadway Categories.

Roadway Type	Wet Ratio	FI Wet Ratio	PDO Wet Ratio	Base Skid Number
Rural—2-lanes	0.169	0.0513	0.1177	34.48
Rural—multi-lanes undivided	0.1727	0.0519	0.1207	29.37
Rural—multi-lanes divided	0.2552	0.0583	0.197	25.85
Urban—2-lanes	0.1458	0.0435	0.1022	27.68
Urban—multi-lanes undivided	0.1165	0.038	0.0785	28.42
Urban—multi-lanes divided	0.166	0.0481	0.1179	24.45

Notes: (1) ratio is defined as target wet-weather crash number divided by total crash number; (2) base skid number is calculated as the average min skid number of segments.

Using Table 45 to Table 48, safety analysts can calculate the adjusted skid number CMF for given area type (rural or urban), lane number category (2-lane or multi-lane), and median configuration (divided or undivided). Taking rural 2-lane as an example, the adjusted skid number CMF is calculated as:

$$CMF = 1 - ratio + ratio \times \ CMF^{(sn-base)} = 1 - 0.169 + 0.169 \times 0.98^{(sn-34.48)}$$ **Equation 3**

Where:

sn is the value of the design skid number.

PAVEMENT SKID NUMBER UTILITY TOOL DEVELOPMENT

Skid Number CMF Calculator

Based on the requirements for calculating skid number CMFs, the project team developed the user interface, shown in Figure 6, with the following inputs and options:

- Area Type:
  - Rural.
  - Urban.
- Number of Lanes:
  - 2-Lane.
  - Multi-Lane (more than 2).
- Geometric Median Configuration:
  - No Median.
  - Two-Way Left-Turn Lane (TWLTL).
  - Divided.

- Skid Number:
    - A number between 10 and 80.

The geometric median configuration corresponds to the undivided (No Median and TWLTL), which are divided in the CMF tables. The three options are consistent with the SBD tool geometric median configuration options.

Figure 6. User Interface of Skid Number CMF Calculator.

After users fill the form on the page, the adjusted skid number CMF shows below the form. As users change the inputs, the CMF value updates instantly.

The user interface also includes input value validation. For example, if the skid number is beyond the reasonable range, a warning message shows up to indicate users that the skid number must not exceed the range, as shown in Figure 7. If the users select a facility type for which the CMF is not available, a warning message also displays on the user interface. Figure 8 illustrates an example of a rural two-lane divided roadway, which is rare, and the skid number CMF for this type of roadway is not available.

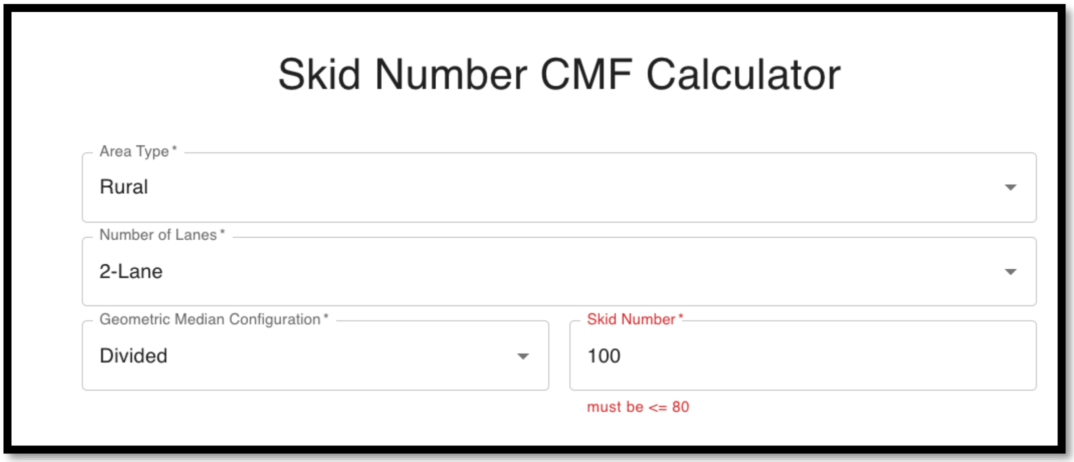

Figure 7. Data Validation of Skid Number CMF Calculator.

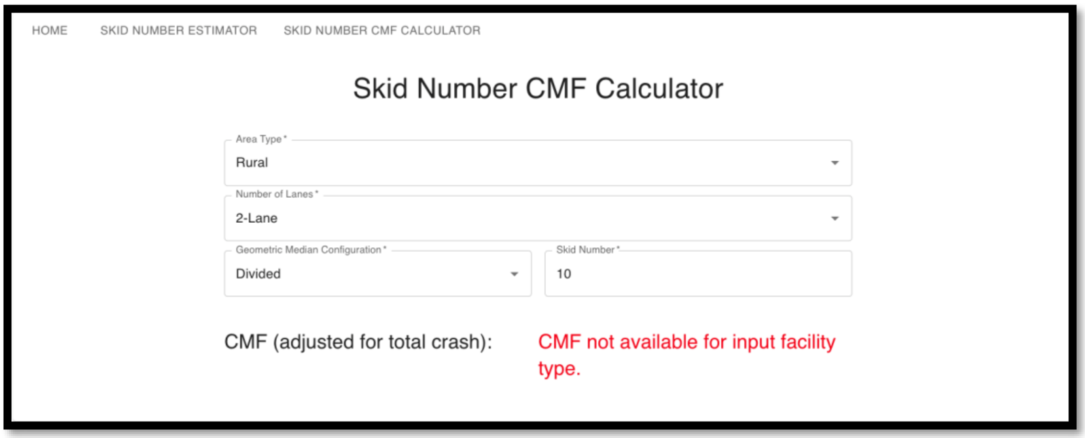

Figure 8. Warning Message of Skid Number CMF Calculator.

Skid Number Estimator

As previously mentioned, pavement skid numbers are not always available to analysts. It is necessary to estimate skid number values. In this task, the research team developed a skid number estimator tool. The user interface is shown in Figure 5. The current version of the estimator tool includes a few inputs for illustration purposes since the method for estimating skid number is still under development. Like the skid number CMF calculator tool, after users fill out the form, the estimated skid number displays below the form (Figure 9).

Once the skid number estimation method is developed and documented, this tool can be updated with the actual model inputs and calculation parameters.

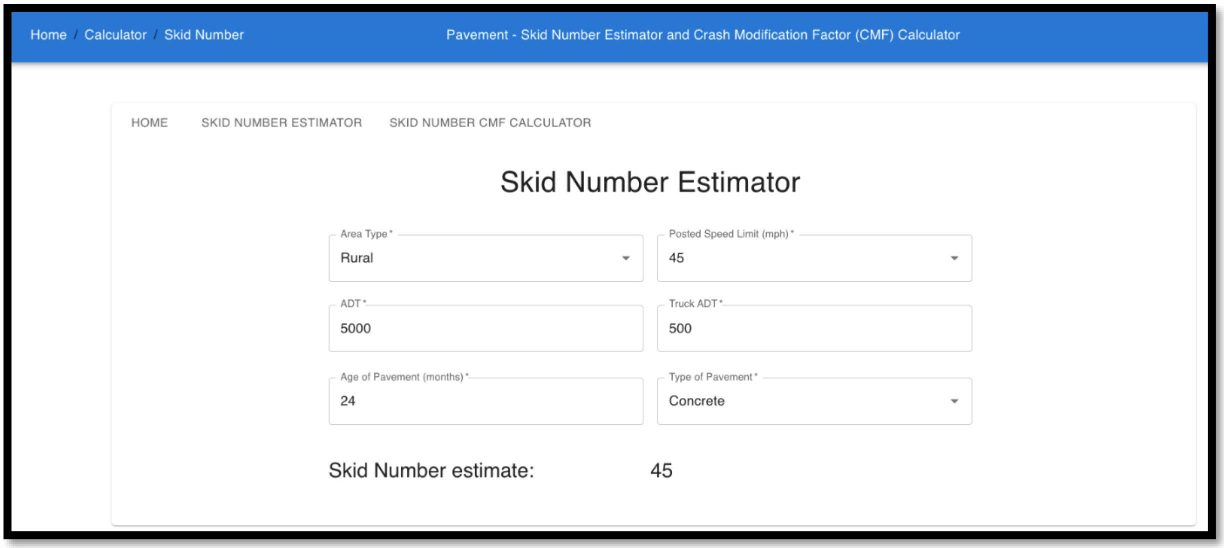

Figure 9. User Interface of Skid Number Estimator.

Integration with SBD Tool

The two pavement skid number utility tools discussed in this report are developed using programming language Python and JavaScript. The specific libraries include Flask and React, which are fully compatible with the TxDOT SBD tool technical stack. While developing the skid number utility tools, the research team designed the variables and their options to be consistent with the SBD tool as much as possible. Thus, the pavement number tools can be relatively easily integrated with the SBD tool. In addition, for the common variables (e.g., geometric median configuration, ADT), the utility tools can retrieve their values from the SBD tool, thus users do not have to repeatedly fill the same entries. The process makes the whole tool more user friendly and seamless.

SUMMARY SBD MODIFICATIONS

The research team calculated ratios of wet weather crashes over total crashes and established base skid numbers for different roadway types. Using these ratios and base skid numbers, safety analysts can compute adjusted skid number CMFs for total crashes.

Based on the method for adjusted skid number CMFs, the research team developed a skid number CMF calculator tool. The user interface and data validation procedures were documented. Additionally, a framework for the skid number estimator tool was developed. Once the method becomes available, the estimator tool can be updated accordingly. Both tools are compatible with the TxDOT SBD tool and can be seamlessly integrated into it.

CHAPTER 5. CASE STUDIES

Case studies in the Atlanta (ATL), Fort Worth (FTW), and Bryan (BRY) Districts were developed. The existing data for the SST and Form 2088 were reviewed along with the skid testing data for each roadway. The report does not show the complete data summaries since they contain skid numbers. Table 49 is a summary of the projects provided by the ATL, FTW, and BRY Districts. The approximate locations are shown in Figure 10 and Figure 11.

A workshop was held with representatives from each district and the project monitoring committee. In general, the districts designated the appropriate SAC for the roadway conditions. It was found that improvements to the SBD tool will improve the design data for all projects.

Table 49. Case Study Summary.

District	Highway	County	Control—Section—Job	DFO	DFO	~ Paving Year	Surface	AADT	Posted Speed
FTW	IH 20	Parker	0314-07-075	406	414.3	2022	SP-C SAC A	64,546	70
FTW	SH 6	Erath	0258-01-029;0258-02-059	229.16	245.74	2021	SP-C SAC A	2,175	70
FTW	FM 455	Wise	1352-04-015, 0444-02-023	25.847	31.255	2023	TY-PB GR-3 SAC-B	619	55
FTW	FM 1855	Parker	0649-02-036, 0444-02-023	5.933	15.468	2023	TY-PB GR-3 SAC-A	2,504	55
BRY	SH 30	Grimes	021204048, 0049-09-089	14.933	15.985	2023	SP-C SAC A	8,204	65
BRY	SH 14	Robertson	0049-15-014, 0049-15-014	55.804	60.018	2022	TY-PL GR-4 SAC A	3,473	75
ATL	US 80	Harrison	0096-09-080	144.42	152.56	2022	SP-C SAC A	6,193	75
ATL	US 59	Cass	0218-04-119	37.128	39.428	2022	SP-C SAC A	10,000	75
ATL	IH 369	Bowie	0218-02-055	0	3.52	2024	PFC SAC A	33,218	65
ATL	FM 1735	Titus	1226-02-016	0	2.1	2023	SP-D SAC A	1,459	60

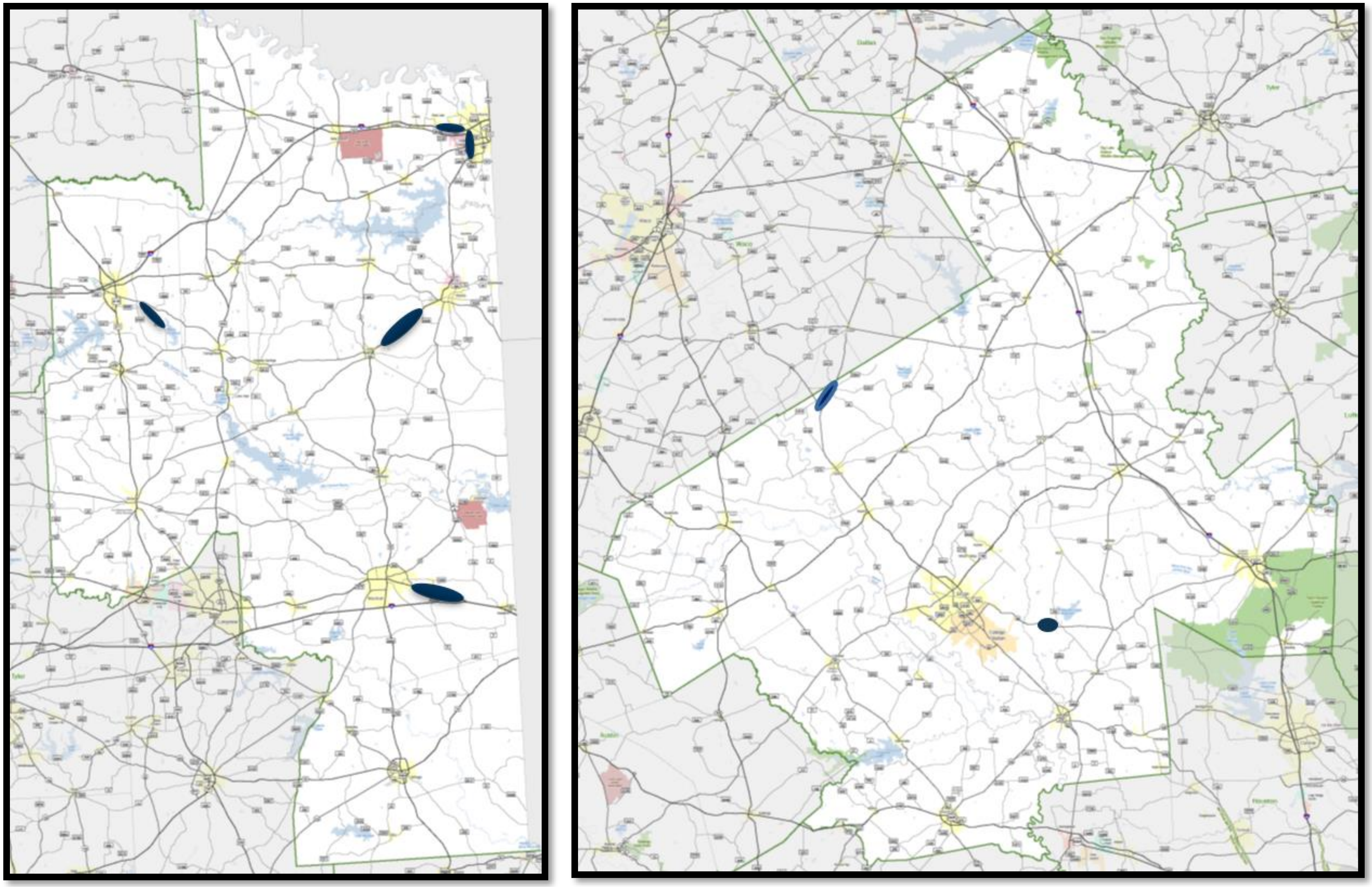

Figure 10. ATL (left) and BRY (right) Project Locations.

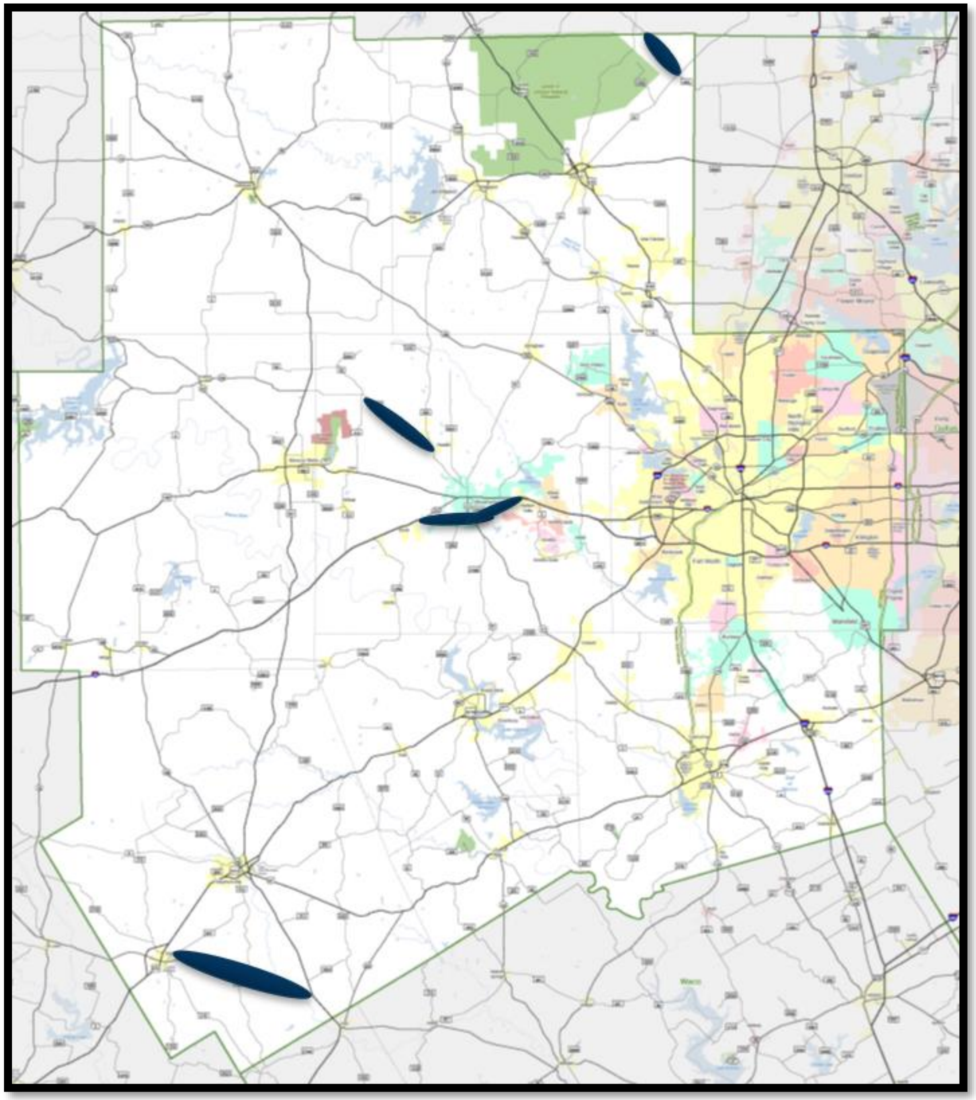

Figure 11. FTW Project Locations.

CHAPTER 6. RECOMMENDATIONS

RISK ASSESSMENT PROCEDURE

The key outcome of the risk assessment procedure is intended to improve safety. This report discusses the WSCRP and SBD safety analysis methods. The proposed pavement needs adequate friction to reduce the risk of wet weather crashes. The performance of pavement friction is monitored in the pavement management data through the collection of skid data.

Form 2088 is an equally weighted assessment tool that evaluates the friction demand and the potential friction available based on the pavement surface type and cross slope. The SBD uses a CMF to quantify the safety effects of the geometry, traffic elements, and roadside elements to evaluate the safety potential of the proposed work. This research developed a CMF for the skid number. Combining these methods will ensure that the input process will be streamlined to avoid duplication of efforts by having one tool instead of two. The new process will improve the assessment of pavement friction and its effect on safety.

A framework was developed to incorporate the pavement friction CMF into the SBD; however, it cannot be used until the method to estimate the skid number from the pavement type and aggregate properties is completed. No changes to the surface aggregate classification system are recommended until the associated research is completed.

The following is the proposed risk assessment procedure:

1. Determine the skid number (SN50S) for the proposed pavement surface.
2. Review the SN50S based on the risk levels shown in Table 25.
3. When the risk level is not acceptable, change the surface aggregate, surface type, or a combination of the surface aggregate and surface type.
4. Repeat steps 1 through 3 until the proposed pavement is at an acceptable risk level for the project.
5. Use Table 48 and Equation 3 to determine the CMF.
6. Use the CMF in the SBD.
7. Evaluate the overall project and pavement friction safety condition.
8. When the overall safety conditions are not acceptable, consider changing other aspects of the project including the pavement friction.
9. Repeat steps 1 through 7 until an acceptable safety condition is achieved.

FUTURE WORK

Estimate of Skid Number

TxDOT Research Project 0-7151, Develop Recommendations for Evaluating Surface Types and Aggregate Properties to Minimize Wet Weather Crashes, is developing a laboratory-based system to select the pavement surface type and coarse aggregate types that will provide adequate skid resistance over the life of the pavement. The research team recommends continuing Project 0-7151 and using the method developed in that project to estimate the skid number used for the SBD CMF calculation estimate.

If that method is adopted by TxDOT, consider replacing the surface aggregate classification system with this method along with the results for the updated SBD and the risk levels shown in Table 25.

Update SBD

Use the framework setup in this project along with the information from 0-7151 to improve the safety prediction of the SBD for pavement friction. Since skid data are not open to public records, a method needs to be developed to estimate the skid number from the pavement type and aggregate sources to generate a CMF that can be used along with the other criteria in the SBD. This can be done in the background so that a skid number is not reported; however, a TxDOT designer or engineer can review the estimated skid number.

CHAPTER 7. VALUE OF RESEARCH

It is important to perform research that provides value to the citizens of Texas. The value can be both quantitative and qualitative. TxDOT uses an SII calculator for the benefit cost analysis associated with safety projects. The SII calculator can be found at https://www.txdot.gov/about/programs/highway-safety-engineering.html. The current value it designates for FI accidents is $4,000,000 and $330,000 for non-incapacitating injury (NI) accidents. During this research, it was found that on average the wet weather accidents with associated skid data from 2018 to 2022 were approximately 7,721 FI accidents and 18,015 NI accidents and other crashes per year on 72,978 centerline miles. TxDOT's project tracker data indicate for resurfacing and rehabilitation type projects that 2,313 miles or 3.2 percent of the sections evaluated is under construction at this time [16]. Therefore using the same percentage, the estimate of savings will be based on 245 FI and 180 NI accidents. The median traffic volume was 3,618 vehicles per day, and assuming a 3 percent growth rate, the traffic volume would increase to 4,594 in 10 years.

To determine the value of this research, the concepts in the *Highway Safety Improvement Program (HSIP) Guidelines* were used. The annual savings is calculated using Equation 4, and the annual change in savings is calculated using Equation 5.

$$\boldsymbol{S = R \times \frac{(C_f \times F + C_i \times I)}{Y} - M} \qquad \textbf{Equation 4}$$

Where:

S is annual savings in preventable crash costs,
R is crash reduction factor (see following subsection for explanation),
F is number of preventable fatal and incapacitating injury crashes,
C_f is cost of a fatal or incapacitating injury crash, $4,000,000,
I is number of preventable non-incapacitating injury crashes,
C_i is cost of a non-incapacitating injury crash, $330,000,
Y is number of years of crash data, and
M is change in annual maintenance costs for the proposed project relative to the existing situation [17].

$$\boldsymbol{Q = \left(\frac{\left(\frac{A_a - A_b}{A_b} \right)}{L} \right) \times S} \qquad \textbf{Equation 5}$$

Where:

Q is the annual change in crash cost savings, as determined by the above formula,
A_a is projected average annual Average Daily Traffic (ADT) at the end of the project service life,
A_b is average annual ADT during the year before the project is implemented, and
L is project service life (see following subheading for explanation) [17].

Variables R, F, I, and L are found in the HSIP Work Codes Table and are shown here in Table 50.

Table 50. HSIP Work Codes for 303 Resurfacing Projects.

Definition:	**Provide a new roadway surface to increase pavement skid numbers on all the lanes.**
Reduction Factor (%):	30%
Service Life (Years):	10
Maintenance Cost:	0

Using Equation 4, $S = 0.3 \times \frac{(4{,}000{,}000 \times 245 + 330000 \times 571)}{10} - 0$ results in an annual savings of \$35,016,450. Using Equation 5, $Q = \left(\frac{\left(\frac{4594-3618}{3618}\right)}{10}\right) \times 35{,}016{,}450$ results in an annual savings change of \$944,611.80. Then using the TxDOT value of research (VOR) spreadsheet, it is found that the cost to benefit ratio is 1,825. The research benefit areas are shown in Table 50, and the value of research is shown in Figure 12.

Table 51. Research Benefit Areas.

Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both	Definition in context to the Project Statement
Level of Knowledge	X			X			This project will significantly increase the understanding and knowledge of the factors that affect surface aggregate selection and risk of wet weather crashes associated with friction. Improving knowledge will help designers make more informed decisions, resulting in lowering the risk of wet weather accidents.
Management and Policy	X			X			With a positive outcome of the research, knowledge, tools, and methods can be used as policy by management for minimizing the risk of wet weather accidents.
Quality of Life	X			X			Reducing the risk of wet weather accidents will benefit all users.
Customer Satisfaction	X			X			Reducing the risk of wet weather accidents will improve drivers' experience.
Reduced User Cost		X			X		Reducing the risk of wet weather accidents will result in less accidents, which will reduce user costs.
Materials and Pavements		X			X		The characteristics and factors that affect selection of surface aggregate will help improve the current system, resulting in selecting a low risk material.
Infrastructure Condition		X				X	Selecting the appropriate surface aggregate will improve infrastructure network condition.
Engineering Design Improvement			X			X	Understanding the factors and thresholds of the aggregate and roadway design characteristics that affect the friction will help improve engineering design accuracy.
Safety			X			X	Reduce the risk of wet weather accidents for the traveling public by selection of a low risk pavement friction.

Project #	0-7142		
Project Name:	Develop Safety Scoring Tool for the Wet Surface Crash Reduction Program		
Agency:	TTI	Project Budget	$ 200,002
Project Duration (Yrs)	2.0	Exp. Value (per Yr)	$ 35,016,450
Expected Value Duration (Yrs)	10	Discount Rate	3%
Economic Value			
Total Savings:	$ 401,918,147	Net Present Value (NPV):	$ 364,921,661
Payback Period (Yrs):	0.005712	Cost Benefit Ratio (CBR, $1 : $___):	$ 1,825

Years	Expected Value
0	$34,816,448
1	$35,961,062
2	$36,905,674
3	$37,850,285
4	$38,794,897
5	$39,739,509
6	$40,684,121
7	$41,628,733
8	$42,573,344
9	$43,517,956
10	$44,462,568
11	$0
12	$0
13	$0
14	$0

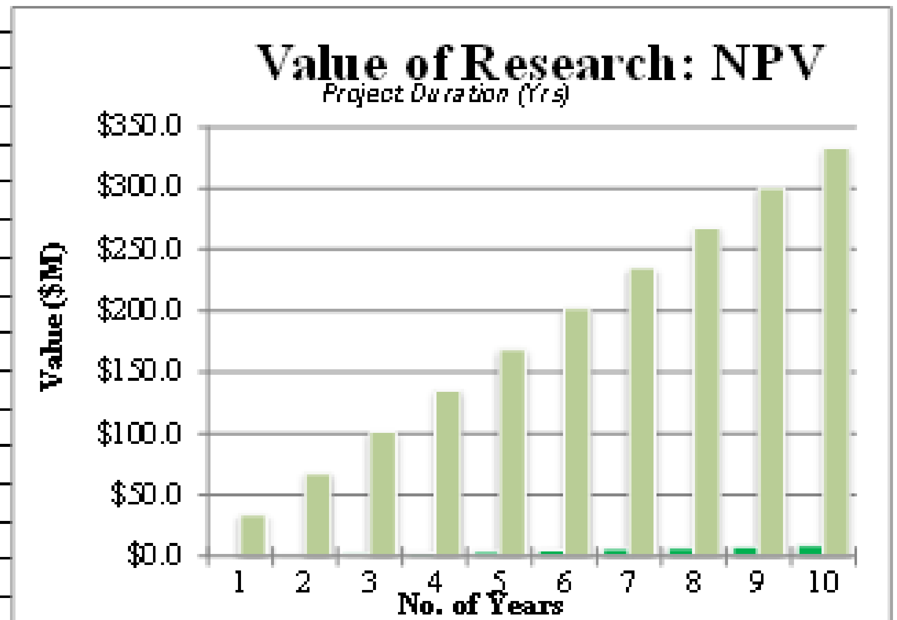

Figure 12. VOR Summary.

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APPENDIX A: DATA ANALYSIS SUMMARY STATISTICS

DISTRIBUTION OF VARIABLES IN THE DATASET OF SEGMENTS WITH NONMISSING SKID NUMBERS

Table 52 through Table 61 are the variable distributions and summary statistics for the dataset.

Table 52. Quantiles for Crash Types.

Quantiles	Comment	Total Crashes	Fatal	Incapacitating Injury	Non-Incapacitating Injury	Minor Injury	Other
100.00%	maximum	1022	9	25	97	176	771
99.50%		110	2	4	13	22	74
97.50%		40	1	2	5	7	27
90.00%		11	0	1	2	2	7
75.00%	quartile	3	0	0	0	0	2
50.00%	median	0	0	0	0	0	0
25.00%	quartile	0	0	0	0	0	0
10.00%		0	0	0	0	0	0
2.50%		0	0	0	0	0	0
0.50%		0	0	0	0	0	0
0.00%	minimum	0	0	0	0	0	0

Table 53. Summary Statistics for Crash Types.

Description	Total Crashes	Fatal	Incapacitating Injury	Non-Incapacitating Injury	Minor Injury	Other
Mean	4.9565638	0.0597409	0.1714008	0.5749469	0.831384	3.3190912
Std Dev	17.787933	0.2921965	0.624194	2.1171493	3.6076731	12.264836
Std Err Mean	0.0440062	0.0007229	0.0015442	0.0052377	0.0089252	0.0303424
Upper 95% Mean	5.042815	0.0611577	0.1744274	0.5852127	0.8488771	3.3785618
Lower 95% Mean	4.8703125	0.058324	0.1683741	0.5646811	0.8138909	3.2596207
N	163389	163389	163389	163389	163389	163389

Table 54. Quantiles for Pavement Condition and Climate.

Quantiles	Comment	Day	Night	Wet	Dry	Total Annual Precipitation—5 Years	2018–2022 Days ≥ 0.1 Inches Rain
100.00%	maximum	745	287	190	938	382.28	435
99.50%		85	26	17	95	348.57	422
97.50%		31	10	7	34	312.16	383
90.00%		8	3	2	9	267.59	334
75.00%	quartile	2	1	0	2	235.09	300
50.00%	median	0	0	0	0	172.72	234
25.00%	quartile	0	0	0	0	123.79	179
10.00%		0	0	0	0	83.99	141
2.50%		0	0	0	0	56.39	100
0.50%		0	0	0	0	40.91	74
0.00%	minimum	0	0	0	0	35.24	34

Table 55. Summary Statistics for Pavement Condition and Climate.

Description	Day	Night	Wet	Dry	Total Annual Precipitation–5 Years	2018–2022 Days ≥ 0.1 Inches Rain
Mean	3.6867721	1.2697917	0.7708781	4.1856857	178.87063	237.01671
Std Dev	13.616055	4.7101238	3.050718	15.368672	70.053655	76.247398
Std Err Mean	0.0336853	0.0116525	0.0075473	0.0380211	0.1889104	0.2053806
Upper 95% Mean	3.7527944	1.2926305	0.7856706	4.2602063	179.24089	237.41925
Lower 95% Mean	3.6207497	1.246953	0.7560856	4.1111651	178.50037	236.61417
N	163389	163389	163389	163389	137515	137826

Table 56. Quantiles for Pavement Friction.

Quantiles	Comment	minskid	maxskid	avgskid	minskid	stdskid
100.00%	maximum	99	99	99	99	58.5484
99.50%		72.5	87.8	74.9593	72.5	31.4344
97.50%		61.6	69.625	63.7	61.6	22.6221
90.00%		51.6	59.7	54.4	51.6	14.9907
75.00%	quartile	40	49.8	44.1	40	9.49331
50.00%	median	29.1	38.1	33.7125	29.1	5.35752
25.00%	quartile	20.3	28.5	25.3	20.3	2.75772
10.00%		14.3	20.8	18.8	14.3	1.27279
2.50%		9	14	13	9	0.35355
0.50%		5.1	8.7	8.3	5.1	0.07071
0.00%	minimum	1	1	1	1	0

Table 57. Summary Statistics for Pavement Friction.

	minskid	maxskid	avgskid	minskid	stdskid
Mean	31.083004	39.496844	35.292889	31.083004	6.9943885
Std Dev	14.209609	15.12326	13.602221	14.209609	5.9779121
Std Err Mean	0.0351537	0.037414	0.033651	0.0351537	0.0187624
Upper 95% Mean	31.151905	39.570174	35.358844	31.151905	7.0311626
Lower 95% Mean	31.014104	39.423513	35.226934	31.014104	6.9576144
N	163389	163389	163389	163389	101513

Table 58. Quantiles for Traffic Data.

Quantiles	Comment	aadt_car	aadt_Truck	adt_current	dvmt	trk_aadt_%
100.00%	maximum	301026	40950	319455	388430	99.9
99.50%		174727	20353	192578	76131.2	60.5
97.50%		90689	13826	101145	26416.3	45.5
90.00%		25244	3146	28428	6515.25	31.4
75.00%	quartile	9799	1100	11167	1869.25	20.4
50.00%	median	2961	436	3618	429.696	12.5
25.00%	quartile	803	128	981	74.0345	7.3
10.00%		246	44	304	12.408	4.3
2.50%		68	15	93	1.89	2.6
0.50%		27	5	36	0.384	1.6
0.00%	minimum	0	0	4	0.008	0

Table 59. Summary Statistics for Traffic Data.

Description	aadt_car	aadt_Truck	adt_current	dvmt	trk_aadt_%
Mean	11117.319	1494.7175	12612.036	3253.4403	15.545997
Std Dev	25376.206	3376.5547	28011.498	11738.64	11.432821
Std Err Mean	62.779129	8.3533827	69.298675	29.040652	0.0282841
Upper 95% Mean	11240.365	1511.09	12747.86	3310.3594	15.601433
Lower 95% Mean	10994.273	1478.3451	12476.213	3196.5213	15.490561
N	163389	163389	163389	163389	163389

Table 60. Quantiles for Traffic Data.

Quantiles	Comment	len_sec	ln_miles	dtrkvmt	Speed_max
100.00%	maximum	23.717	52.04	84781.7	85
99.50%		5.1972	12.3602	13773.5	75
97.50%		2.921	6.784	3940.35	75
90.00%		1.215	3.072	774.182	75
75.00%	quartile	0.443	1.196	215.202	70
50.00%	median	0.134	0.368	49.84	60
25.00%	quartile	0.028	0.074	8.76	55
10.00%		0.006	0.015	1.5	45
2.50%		0.001	0.004	0.255	30
0.50%		0.001	0.002	0.055	30
0.00%	minimum	0.001	0.002	0	5

Table 61. Summary Statistics for Traffic Data.

Description	len_sec	ln_miles	dtrkvmt	Speed_max
Mean	0.4432585	1.1122691	481.30576	58.972422
Std Dev	0.860958	2.0526274	2164.039	11.842482
Std Err Mean	0.00213	0.0050781	5.3536955	0.0292976
Upper 95% Mean	0.4474332	1.122222	491.79888	59.029844
Lower 95% Mean	0.4390838	1.1023162	470.81263	58.914999
N	163389	163389	163389	163389

CORRELATION ANALYSIS

Table 62 and Table 63 are the correlations for the dataset.

Table 62. Multivariate Correlations among Roadway Characteristic Variables.

Description	**dvmt**	**dtrkvmt**	**adt_cur**	**aadt_truck**	**trk_aadt_p**	**len_sec**	**ln_miles**	**spd_max**
dvmt	1.0000	0.7708	0.4953	0.4625	-0.0183	0.2065	0.4624	0.0977
dtrkvmt	0.7708	1.0000	0.2825	0.4573	0.1783	0.2594	0.4859	0.1639
adt_cur	0.4953	0.2825	1.0000	0.8040	-0.1455	-0.0969	0.0336	0.0443
aadt_truck	0.4625	0.4573	0.8040	1.0000	0.1524	-0.0623	0.0702	0.1811
trk_aadt_p	−0.0183	0.1783	−0.1455	0.1524	1.0000	0.1423	0.1311	0.3788
len_sec	0.2065	0.2594	−0.0969	−0.0623	0.1423	1.0000	0.9290	0.1940
ln_miles	0.4624	0.4859	0.0336	0.0702	0.1311	0.9290	1.0000	0.1999
spd_max	0.0977	0.1639	0.0443	0.1811	0.3788	0.1940	0.1999	1.0000

Table 63. Multivariate Correlations among Crashes, Skid Numbers, and Roadway Characteristic Variables.

Description	**Total**	**Wet**	**Dry**	**minskid**	**maxskid**	**avgskid**	**dvmt**	**trk_aadt_p**	**spd_max**
Total	1.0000	0.8248	0.9937	−0.1235	−0.0879	−0.1147	0.5549	−0.1098	−0.0695
Wwet	0.8248	1.0000	0.7562	−0.1331	−0.0810	−0.1176	0.5574	−0.0595	−0.0009
Dry	0.9937	0.7562	1.0000	−0.1165	−0.0856	−0.1094	0.5316	−0.1153	−0.0803
minskid	−0.1235	−0.1331	−0.1165	1.0000	0.7080	0.9152	−0.1413	0.0262	−0.0024
maxskid	−0.0879	−0.0810	−0.0856	0.7080	1.0000	0.9225	−0.0584	0.0877	0.0875
avgskid	−0.1147	−0.1176	−0.1094	0.9152	0.9225	1.0000	−0.1078	0.0639	0.0485
dvmt	0.5549	0.5574	0.5316	−0.1413	−0.0584	−0.1078	1.0000	−0.0183	0.0977
trk_aadt_p	−0.1098	−0.0595	−0.1153	0.0262	0.0877	0.0639	−0.0183	1.0000	0.3788
spd_max	−0.0695	−0.0009	−0.0803	−0.0024	0.0875	0.0485	0.0977	0.3788	1.0000

APPENDIX B. WET CRASH MODELING FOR CMF

Table 64 through Table 65 are the variable distributions and summary statistics for the wet crash dataset.

Table 64. Quantiles for Crashes.

Quantiles	Comment	wet	FI_wet	PDO_wet	Dvmt	Log_dvmt	2018–2022_days ≥ 0.1	minskid
100.00%	maximum	190	55	143	388430	12.8699	435	99
99.50%		18	6	13	75276.8	11.2289	422	72.5
97.50%		7	2	5	26547.4	10.1867	383	61.6
90.00%		2	1	1	6579.5	8.79171	334	51.6
75.00%	quartile	0	0	0	1876.68	7.53726	300	40
50.00%	median	0	0	0	432.376	6.0693	234	29.1
25.00%	quartile	0	0	0	75.0105	4.31763	179	20.3
10.00%		0	0	0	12.552	2.52988	141	14.2
2.50%		0	0	0	1.91	0.6471	100	8.9
0.50%		0	0	0	0.38214	-0.962	74	5.1
0.00%	minimum	0	0	0	0.008	-4.8283	34	1

Table 65. Summary Statistics for Crashes.

Description	wet	FI_wet	PDO_wet	Dvmt	Log_dvmt	2018–2022_days ≥ 0.1	minskid
Mean	0.7823342	0.2290569	0.5532773	3252.5051	5.8492567	237.01671	31.083422
Std Dev	3.1073706	0.9869553	2.2908414	11694.654	2.4233552	76.247398	14.229165
Std Err Mean	0.00837	0.0026585	0.0061706	31.500817	0.0065276	0.2053806	0.0383278
Upper 95% Mean	0.7987394	0.2342675	0.5653716	3314.2461	5.8620506	237.41925	31.158544
Lower 95% Mean	0.7659291	0.2238464	0.541183	3190.7641	5.8364628	236.61417	31.0083
N	137826	137826	137826	137826	137826	137826	137826