TTI: 0-7077

Selection Criteria for Coarse Aggregate in Flexible Pavement Surfaces

Technical Report 0-7077-R1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
http://tti.tamu.edu/documents/0-7077-R1.pdf

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-21/0-7077-R1		

4. Title and Subtitle SELECTION CRITERIA FOR COARSE AGGREGATE IN FLEXIBLE PAVEMENT SURFACES	5. Report Date Published: November 2021
	6. Performing Organization Code
7. Author(s) Darlene C. Goehl, Charles Gurganus, Eun Sug Park	8. Performing Organization Report No. Report 0-7077-R1
9. Performing Organization Name and Address Texas A&M Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. Project 0-7077
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office 125 E. 11th Street Austin, Texas 78701-2483	13. Type of Report and Period Covered Technical Report: September 2020 to August 2021
	14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Synthesis: Evaluation Selection Criteria for TxDOT Form 2088, Surface Aggregate Selection Form
URL: http://tti.tamu.edu/documents/0-7077-R1.pdf

16. Abstract

The safety of the traveling public is a priority for the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). From the 1960s to current practice, FWHA's guidance has evolved along with TxDOT's policies and procedures to reduce wet-weather accidents. TxDOT's Form 2088 is part of the wet-surface crash reduction program. The research team performed a synthesis study and investigated current state-of-the-practice and emerging research for the criteria on TxDOT's Form 2088, along with criteria being used by other states and governing agencies that determine friction availability and demand. The factors that affect an agency's management of pavement surface friction to maintain highway safety while reducing wet-surface crashes were evaluated. A survey was performed with local and nationwide agencies to document the experience and performance of their management of pavement surface friction including the criteria used to establish pavement friction availability and demand.

17. Key Words	18. Distribution Statement
Coarse aggregate, wet surface crash reduction, pavement, and friction	No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia http://www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	66	

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SELECTION CRITERIA FOR COARSE AGGREGATE IN FLEXIBLE PAVEMENT SURFACES

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DISCLAIMER

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

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

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

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The authors would like to thank the TxDOT Research and Technology Implementation Division project director, Tom Schwerdt, and the members of the TxDOT Project Monitoring Committee, Ryan Barborak, Gisel Carrasco, Roberto Flores, Richard Izzo, Lacy Peters, and James Robbins. The authors would also like to thank the following survey respondents:

- TxDOT (Mike Arellano, Lacy Peters, James Robbins, Sergio Cantu, and Aldo Madrid).
- Rhode Island Department of Transportation (DOT) (Michael Byrne).
- Hawaii DOT (Kristi Grilho).
- Florida DOT (John Shoucair and Charles Holzchuher).
- New York State DOT (Tom Festa).
- Pennsylvania DOT (Lydia Peddicord and Patricia Baer).
- Michigan DOT (Nathan Maack).
- Idaho DOT.
- Alaska DOT.
- South Carolina DOT (Cliff Selkinghaus).
- Kentucky Transportation Cabinet (Amanda Dees).
- Missouri DOT (John Donahue).
- Tennessee DOT (Heather Hall).
- Ontario Ministry of Transportation.
- Anonymous survey respondents.

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CHAPTER 1. BACKGROUND

GENERAL

The safety of the traveling public is 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, which stated, "Every State shall have a program of design, construction and maintenance to improve highway safety." From the 1960s to current practice, FWHA's guidance evolved along with TxDOT's policies and procedures to reduce wet-weather accidents.

FHWA has issued programs and technical advisories related to pavement safety. Some of those programs and technical advisories are as follows:

- June 17, 2005, FHWA Technical Advisory T 5040.36 [1]: Both micro-texture and macro-texture 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 upon 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 presence of noise-sensitive receptors.
- June 17, 2010, FHWA Technical Advisory T 5040.38, Pavement Friction Management Technical Advisory [2]: This technical advisory 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.

T 5040.38 is the most recent guidance from FHWA covering topics such as use of test equipment for measuring pavement friction, identification and classification of roadway locations with elevated crash rates, prioritization of projects for improving pavement friction, appropriate frequency and extent of friction testing on a highway network, and determination of a pavement friction management program's effectiveness. The technical advisory has guidance for factors that should be considered when selecting pavement surface techniques or thresholds. These factors include the following:

- Splash and spray.
- Climate.
- Traffic volume and composition.
- Speed limit.
- Roadway geometry.
- Potential conflicting movements or maneuvers (frictional demand).

- Material quality and cost.
- Presence of noise-sensitive receptors.

T 5040.38 also discusses techniques that will provide surface texture for concrete and asphalt pavements and references Technical Advisory T 5040.36, Surface Texture for Asphalt and Concrete Pavements. TxDOT followed FHWA guidance along with TxDOT's research to improve its safety program. Since concrete pavement micro-texture is considered to be from the fine aggregate fraction, the fine aggregate should be wear and polish resistant, whereas in other pavements, the surface aggregate characteristics that should be considered are angularity, soundness, toughness, and polish resistance, which is from the coarse aggregate. TxDOT's Form 2088 was developed for pavement surfaces other than concrete pavement.

TXDOT FORM 2088

TxDOT's Form 2088, Surface Aggregate Selection, was developed and implemented in 1999 under the Wet Weather Accident Reduction Program (WWARP) [3]. The WWARP included three phases: wet-weather accident analysis, aggregate selection, and skid testing. Form 2088 was developed to assist with the flexible pavement aggregate selection phase of the program. The program described the frictional demand and availability of a roadway pavement surface. There are several factors described in the WWARP documentation; however, not all factors are included on Form 2088.

TxDOT does not have documentation for the development of Form 2088. The authors interviewed two former TxDOT employees, Caroline Heinen and Dale Rand, to try to determine how the form was developed, including the criteria and thresholds. Neither former TxDOT employee could provide information concerning how the original criteria in 1999 were developed. The authors surmise that the form was developed based on experience and past research efforts. The form was updated after the program name changed from WWARP to the Wet Surface Crash Reduction Program (WSCRP) [4] in August 2011. Figure 1 shows the current Form 2088, which was last revised in May 2012.

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 1. Form 2088 (Rev. 05/2012).

CHAPTER 2. SURVEY

SURVEY BACKGROUND

The authors prepared a fact-based survey questionnaire using the web-based software Qualtrics. The survey link was distributed through email to members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Materials and Pavements. The TxDOT Project Monitoring Committee handled the internal TxDOT distribution. The survey was developed to inquire about the state of the practice regarding the experience and practices for the criteria used to (a) determine friction demand for aggregate used on the surface of flexible pavements, (b) determine the friction available on the proposed pavement surface, and (c) select aggregate properties to meet the friction criteria for flexible pavements.

There were 22 survey responses; however, the Rhode Island and Hawaii Departments of Transportation (DOTs) emailed information (i.e., did not fill out the survey). The survey allowed the respondents to remain anonymous; however, several respondents provided contact information. Based on the survey responses, the state DOTs that responded were Texas, Rhode Island, Hawaii, Florida, New York, Pennsylvania, Michigan, Idaho, Alaska, South Carolina, Kentucky, Missouri, and Tennessee, along with the Ontario Ministry of Transportation.

The following items, as well as an option for other, were considered as potential factors affecting friction on pavements:

- Splash and spray (proposed pavement surface).
- Climate—precipitation.
- Climate—temperature.
- Traffic volume.
- Traffic composition (e.g., percent trucks).
- Speed limit.
- Roadway horizontal alignment.
- Roadway vertical alignment.
- Pavement cross-slope.
- Potential conflicting movements or maneuvers (intersections and driveways).
- Aggregate properties.
- Macro-texture of proposed pavement.
- Micro-texture of proposed pavement.
- Material cost.
- Material availability.
- Presence of noise-sensitive receptors.

SURVEY RESULTS

Friction Demand and Friction Availability

The results of this question indicate that the factor considered by most agencies is traffic volume. Five percent of those who responded do not have concerns with aggregate and therefore do not consider friction demand factors. None of the respondents considered the presence of noise-sensitive receptors. Figure 2 shows each factor along with the percentage of respondents who indicated their agency considers the factor for friction demand when selecting a pavement surface type.

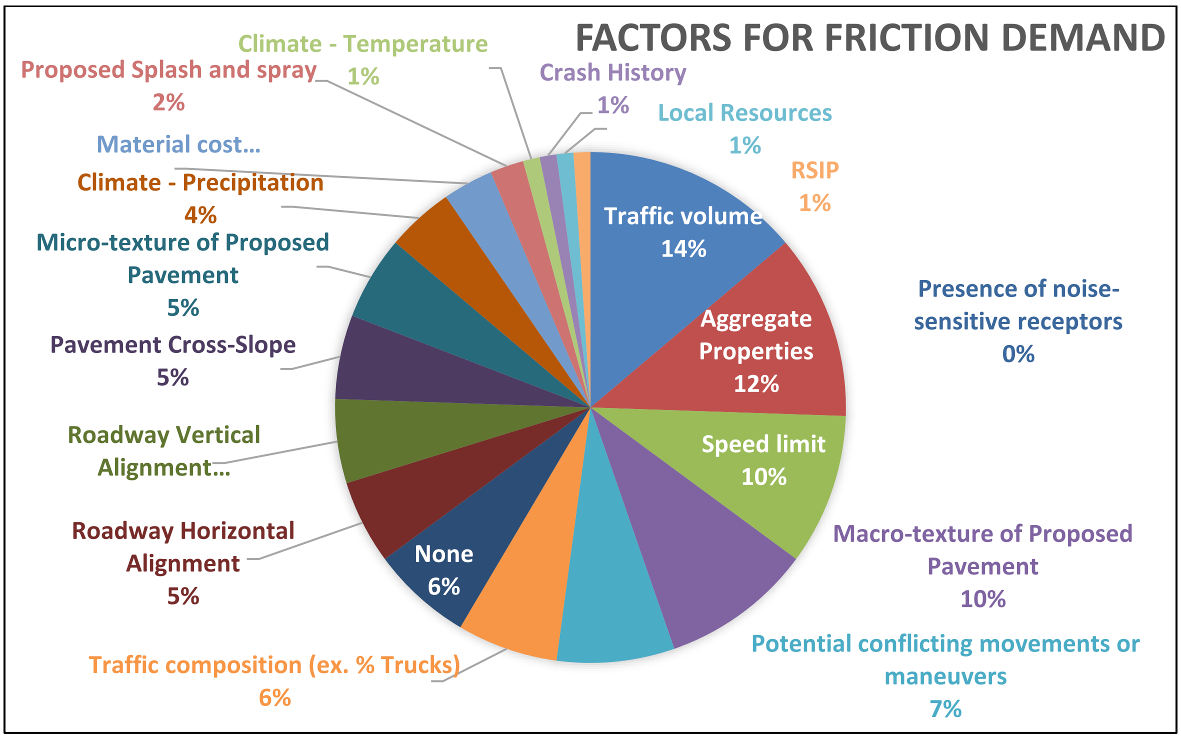

Figure 2. Factors for Friction Demand.

Other factors that were included are crash history, local resources, and a roadway safety performance index, which is a system safety risk index that uses multiple roadway, traffic, and pavement variables. While there were many factors indicated as affecting friction, several of those had general criteria and only a few had measurable criteria. Table 1 depicts the items with measurable criteria. Even though these items had measurable criteria, how the measure was used to select the aggregate was not indicated in all cases.

Table 1. Friction Criteria.

Factor	Criteria
Climate—Precipitation	Our rural areas typically have higher rainfall—lends itself to perform seal coats.
	Rainfall per year.
Climate—Temperature	District Surface Asphalt Temps Exceeds 200 F.
Traffic Volume	Premium mixes are considered in higher volume roadways; starting at >5 million ESALs.
	>10,000 ADT.
	AADT <2500 – Superpave 12.5.
	Table 5.4 of Pub. 242: http://www.dot.state.pa.us/public/PubsForms/Publications/PUB%20242.pdf Refer to Figure 3 (SRL is skid resistance level) [5].
	ADT.
Traffic Composition (ex. % Trucks)	Use PG76-22 binders on highways with high %trucks. No threshold value is looked at, we typically review the PMIS data for rutting and compare that information with the traffic data.
	1 Million < Annual ESAL < 3 Million – Superpave 12.5 FC2.
	Type of mix dictates aggregate type.
	% Trucks.
Speed Limit (may include design or posted speed, please describe)	<45 mph for seal coats is recommended.
	40 mph.
	For High Friction Surface Treatments (HFST) posted speed 35 MPH or greater.
	Posted speed limit.
Roadway Horizontal Alignment	HFST—curves with sight distance obstructions before a stop sign or signal.
	% horizontal curves.
	Very Sharp Curves.
	Degree of Curvature.
Roadway Vertical Alignment	HFST—curves with sight distance issues for an intersection or upcoming horizontal curve or steep down grade leading into a signal or stop sign.
	% vertical curves.
	Very Steep Slopes.
	%Grade.
Pavement Cross-Slope	For flat cross slopes <2% - macrotexture is important.
	HFST where super elevation is deficient.
	% cross slope.
	Ranges 2–5, design value.
Potential Conflicting Movements or Maneuvers	Minimize the use on Seal Coat in areas with high turning movements.
	HFST where sight distance is an issue or a steep down grade on the approach.
	Toll Plazas approaches.
	ADT of Intersecting Roads.

Factor	Criteria
Aggregate Properties	SAC B always recommended by District.
	They're listed in TxDOT's variety flexible pavement specs.
	Mix type dictates aggregate type.
	HFST—uses Bauxite.
	Wear and Freeze-Thaw Soundness.
	Dynamic Friction Value > 40.
	Hardness.
	Surface aggregates are approved based on a variety of criteria and are divided into 4 types that are used on projects according to ADT values.
Macro-Texture of Proposed Pavement	For flat cross slopes <2% - macrotexture is important.
	High friction mixture type (seal coat, TOM, SMA, or PFC); no dense graded or SP.
	Mix type dictates aggregate type.
	Skid Resistance Test (Lock Wheel) > 35.
	Fine Medium Coarse.
Micro-Texture of Proposed Pavement	DFV >40.
	SAC—Surface Aggregate Classification.
Material Cost	Premium Mixes are used on higher ADT highways.
	Placement rate.
Other, please describe	Review Police Reports on Crash History. A history of wet surface crashes will lead to placing SMA mixes and/or Thin Bonded Wearing Course to improve the skid resistance.
	RSPI > 6 and Speed > 40 - SAC A.
	Studded tire wear governs the choice of surface course and aggregate type/hardness in many projects.
	Surface Design Life.

TABLE 5.4
SRL CRITERIA

INITIAL OR CURRENT ONE-WAY ADT	INITIAL OR CURRENT TWO-WAY ADT	SRL DESIGNATION
Above 10,000	Above 20,000	E
2,501 - 10,000	5,001 - 20,000	H; Blend of E and M; Blend of E and G
1,501 - 2,500	3,001 - 5,000	G; Blend of H and M; Blend of E and L
501 - 1,500	1,001 - 3,000	M; Blend of H and L; Blend of G and L; Blend of E and L
0 - 500	0 - 1,000	L

*E = Excellent, H = High, G = Good, M = Medium, L = Low

Figure 3. Pennsylvania Department of Transportation Criteria [5].

Figure 4 shows the percent of respondents that indicated the factors had measurable criteria.

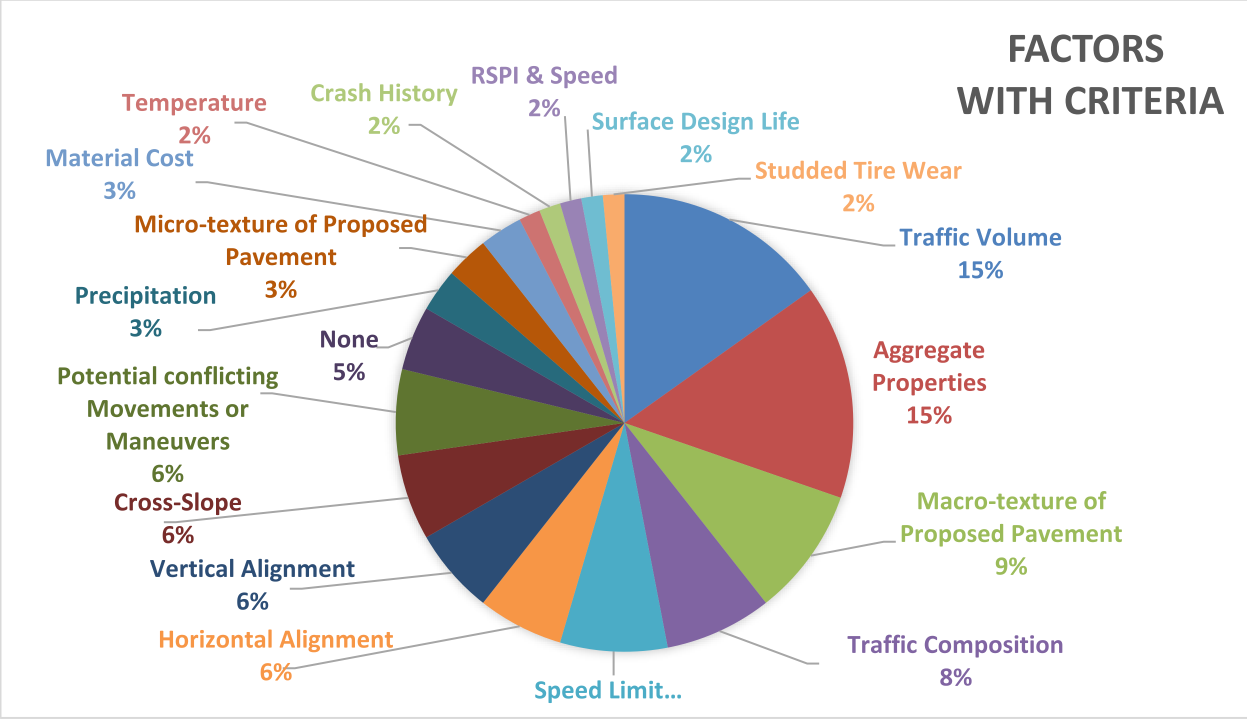

Figure 4. Factors with Measurable Criteria.

Figure 5 shows each factor compared to the influence categories of friction demand, proposed friction, economics, and other.

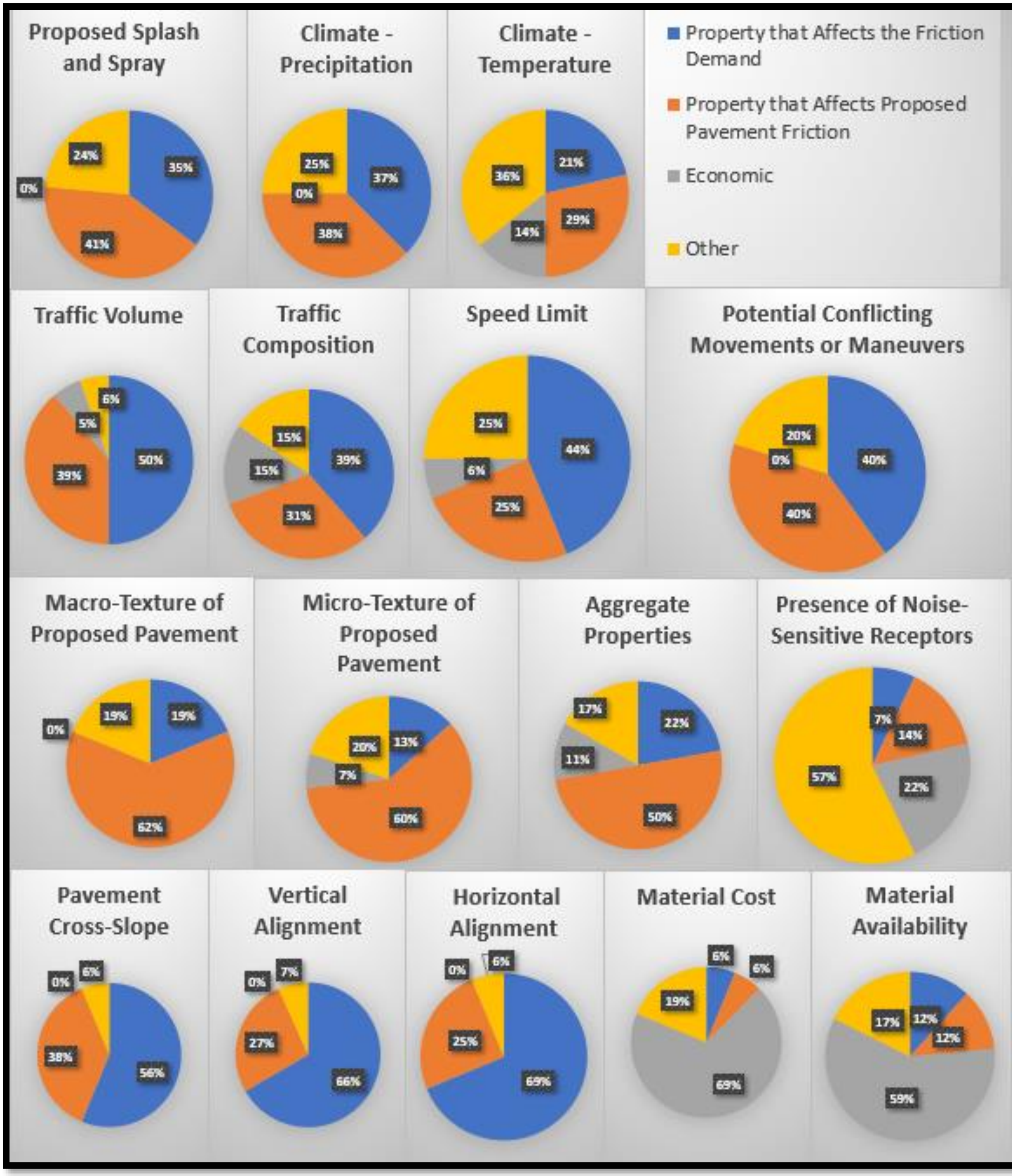

Figure 5. Influences for Each Factor.

Figure 6 depicts the importance of the factors for selecting the surface aggregate, with the aggregate properties considered to be the most important on a scale of 1 to 100 and with 100 being the most important.

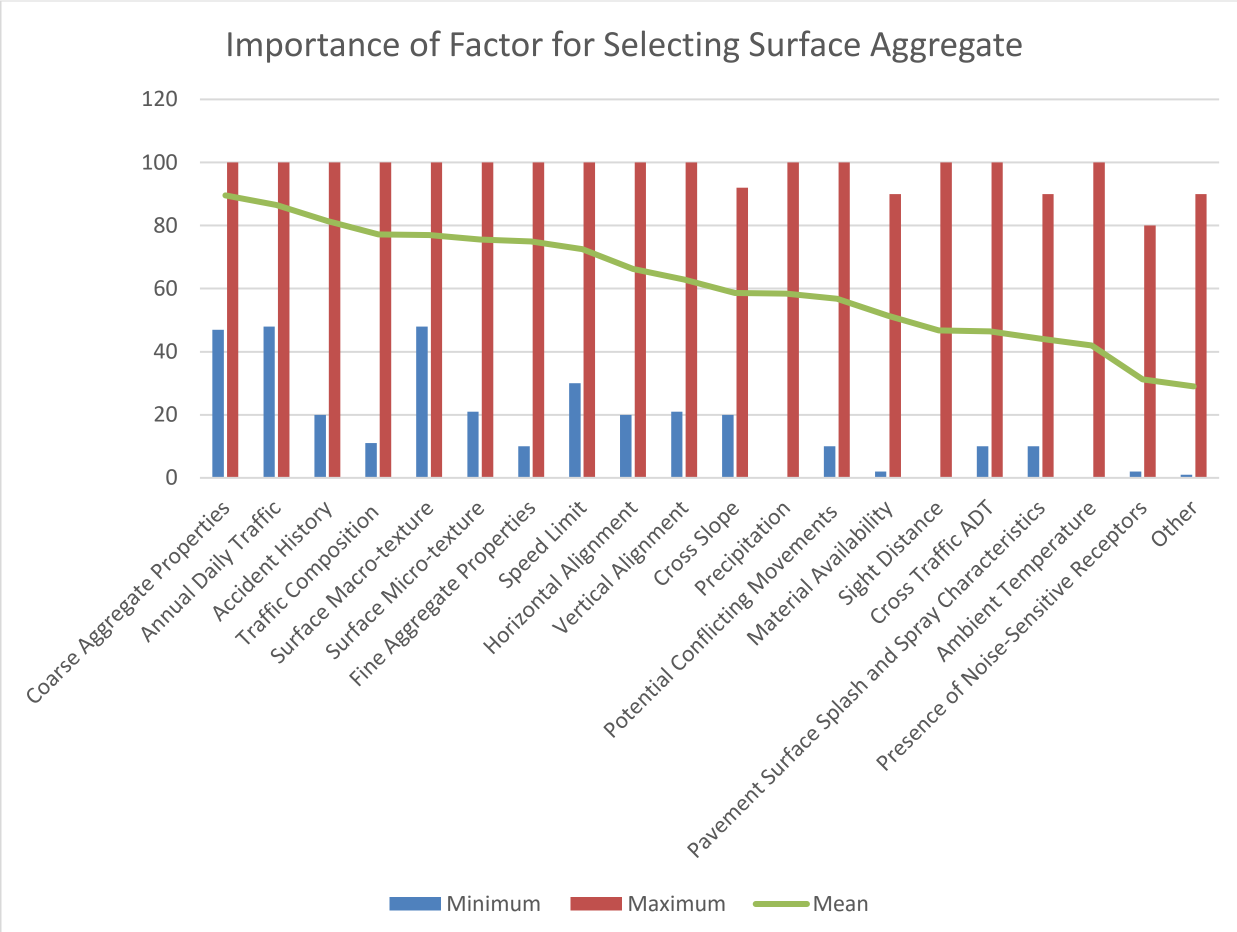

Figure 6. Importance of Factors for Selecting Surface Aggregate.

Aggregate Properties

The following items, as well as an option for other, were considered as potential aggregate characteristics for pavement friction:

- Angularity.
- Soundness.
- Toughness.
- Polish resistance.
- Wear resistance.
- Texture.

The other coarse aggregate characteristics identified were abrasion resistance, carbonate versus non-carbonate content of gravels, and acid insoluble residue (AIR) for carbonates.

Figure 7 shows the importance of the aggregate properties, with all properties considered important when evaluated on a scale of 1 to 100 and with 100 being the most important.

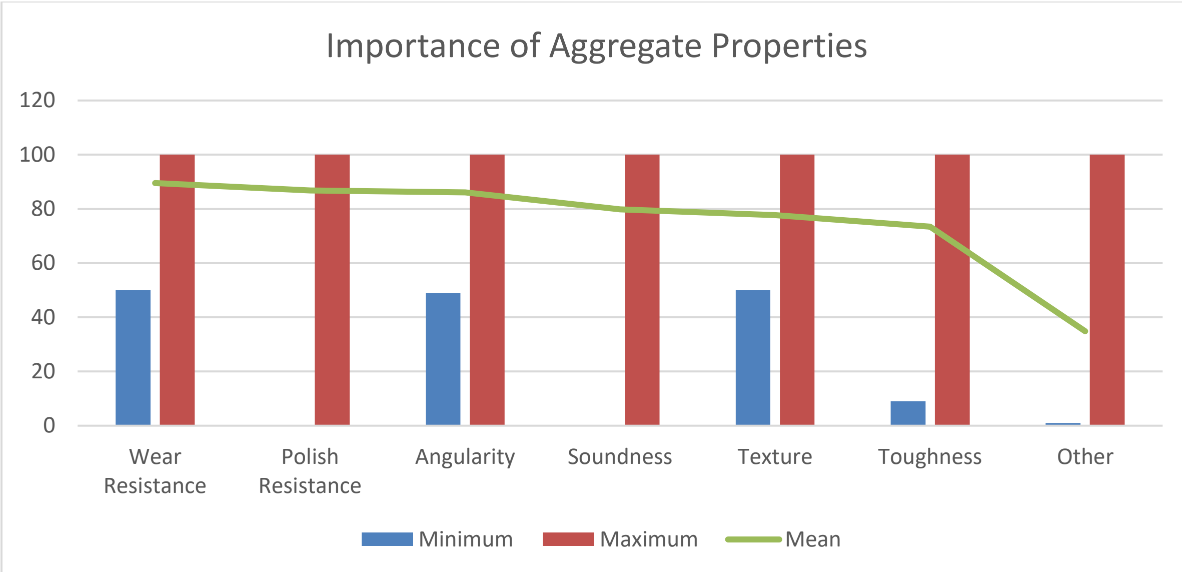

Figure 7. Importance of Aggregate Properties.

The survey asked which of the aggregate tests listed, including other, are used to aid in the determination of the aggregate properties required to meet the friction demand. Table 2 shows the aggregate tests and the percent of respondents who used the test. Some of the respondents used the tests but not necessarily for friction demand concerns. The table includes the coarse aggregate tests with measurable criteria (shown below is the test when provided in the response comments). All respondent comments in the table and report text are verbatim.

Table 2. Aggregate Tests.

Aggregate Test	Use
Soundness Using Sodium Sulfate • Less than 15%	8.14%
Soundness Using Magnesium Sulfate • Less than 20%	9.30%
Other test that measures aggregate resistance to disintegration, please describe • Aggregate Abrasion Value • Similar to AASHTO T 103	3.49%
Polish Test for Coarse Aggregate • Aggregates are tested for Polish Value utilizing AASHTO T279 (British Wheel) • DFT and DFT 40	9.30%
Other test that provides an estimate of the polish and relative wear of coarse aggregate, please describe • DFT • Polish Stone Value • Iterative three-wheel polishing and dynamic friction testing of bound aggregate samples • For aggregate from sand and gravel sources we determine the geologic make-up of the aggregate and run that through a calculation to assign it an “Aggregate Wear Index” value • Every aggregate is assigned an “Aggregate Wear Index” number and then the • blend of those must meet a minimum value based on ADT.	5.81%
Acid Insoluble Residue • Min 20% AIR for friction • Tiered approval Minimum of 15% for 1st level	10.47%
Crushed Faces test	15.12%
Angularity test	8.14%
LA Abrasion	12.79%
MicroDeval	9.30%
Other tests, please describe. • x-ray for MGCO3 • Idaho IT-15, Idaho Degradation Test. This test covers the procedure for testing a graded aggregate for resistance to the production of fines by abrasion in the presence of water when tested in the Idaho Degradation Machine. • Dynamic Friction Test • Nordic Abrasion, ATM 312 (Alaska Test Method) • Silica content, calcium carbonate content • Petrographic • Surface Aggregate Classification per Tex-499-A • Divide our approved surface aggregates into 4 types and each type has a threshol of where they can be used according to ADT. • Aggregates are assigned a Friction Rating value ranging from 1-4. • Petrographic	8.14%

Idaho DOT supplied information about its aggregate test method, which states, "This test method is intended as a quantitative measure of the resistance of a graded aggregate to production of fines by abrasion in the presence of water. The test provides a means by which it is possible to evaluate how the aggregate may perform in the road" [6]. The Idaho Standard Method of Test for Idaho Degradation, Idaho IT-15-95, can be found at https://apps.itd.idaho.gov/apps/manuals/QA/Archive/Files/QA_2015/QAHome.pdf.

Figure 8 shows the importance of the aggregate tests from most to least important based on the average importance value on a scale of 1 to 100, with 100 being the most important.

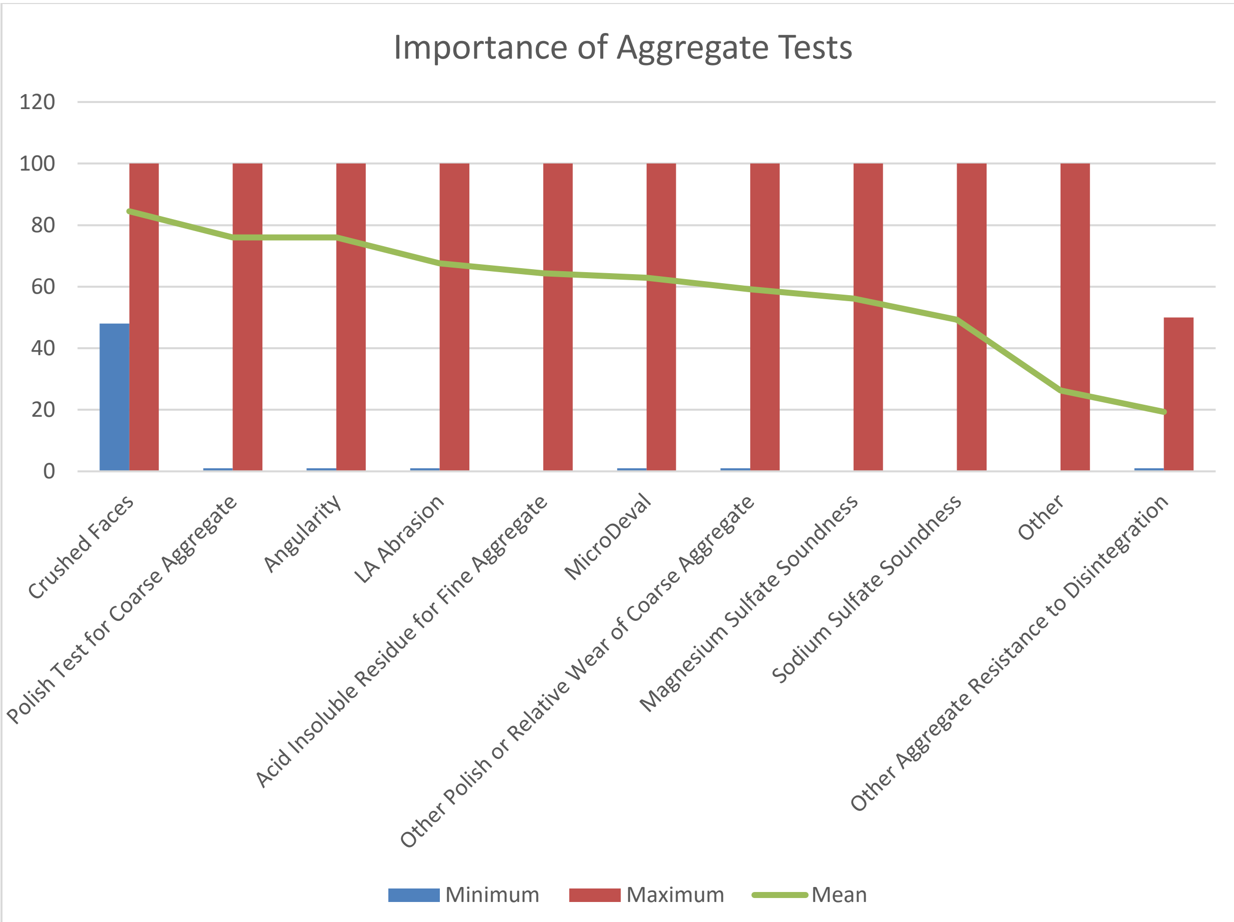

Figure 8. Importance of Aggregate Tests.

Some agencies have criteria for the fine aggregate used in flexible pavement to aid in the determination of the aggregate characteristics required to meet the friction demand. The requirements include the following:

- Petrographic test.
- AIR greater than 25 percent (only for Portland cement concrete pavements).
- Fine aggregate from approved parent material.

- Angularity for determining the aggregate wear index value for fine aggregates.
- Combined gradation meeting 75 percent minimum of surface-approved aggregates.

The following (anonymous) comments were provided to help determine aggregate criteria and thresholds related to friction demand:

- We use mixtures with gradation that produce good macrotexture. So the primary aggregate criteria is soundness to assure the aggregate is hard enough to sustain the macrotexture.
- Premium surface coarse aggregate for high friction requirements (high volume highways) must be approved through a multi-step process: 1) geological assessment of quarry, 2) laboratory testing of aggregate, including PSV >50 and AAV <6%, 3) A two year monitoring period of a 500 meter paved test section, including brake force trailer friction testing each year.
- NYS has 3 levels of friction demand. For asphalt pavement, the key parameter is aggregate hardness (petrology) and durability. We have petrographic limits on the percent carbonate of gravels and the %AIR of carbonate rocks. We are just beginning to evaluate TWPD/DFT polishing and testing to determine rates of polish of various aggregates.
- Dynamic Friction Testing.
- Please refer to SOP 2-1 (https://www.tn.gov/content/dam/tn/tdot/hq-materials-tests/standard-operating-procedures/2-1_Aggregate_Approval_Process.pdf) for aggregate approval and specification section 903.11 (https://www.tn.gov/content/dam/tn/tdot/construction/old_web_page/TDOT_2015_Spec_Book_FINAL_pdf.pdf) and 903.25 (https://www.tn.gov/content/dam/tn/tdot/construction/supplemental-specifications/Const_2015_900SS.pdf) for more information.

The Tennessee DOT uses the following aggregate tests for riding surfaces and provided the following additional reference information:

- SOP 2-1 [7]:
    - 1.3.2 Aggregates for use in riding surfaces (Surface Aggregates) must meet additional requirements:
        - Silica Dioxide Content, ASTM C25.
        - Calcium Carbonate Content, ASTM C25.
        - Acid Insoluble Residue, ASTM D3042.
        - Accelerated British Pendulum Numbers (BPN), ASTM D3319/AASHTO T279.

Other Requirements

Five agencies described requirements for new pavement surface friction, which are as follows:

- Skid > 40 (two agencies).
- Skid number (SN) (two agencies).
- Design field view > 40 and skid resistance > 35.

Forty-seven percent of the agencies measured pavement friction with a ribbed tire skid test at 40 mph. Thirty-two percent of the agencies measured pavement friction with a smooth tire skid test at 50 mph. Twenty-one percent of the agencies used other methods described as follows:

- Skid test with ribbed tire at travelling speed (typically 80 to 100 km/h) according to ASTM E274 and E501.
- Locked-wheel friction testers to measure pavement friction. Almost all of our testing is done with a smooth tire at speeds between 25-50 mph which are then calculated to 40 mph. A few times per year we receive special testing requests for the ribbed tire.
- Skid Test with Smooth tire at 40km.
- Dynamic Friction Tester.

The Florida Department of Transportation has an extensive approval process for new sources used for open-graded friction courses, which can be found at the following website: https://www.flrules.org/gateway/RuleNo.asp?title=CONSTRUCTION AGGREGATES&ID=14-103.005.

SURVEY SUMMARY

The states that specifically indicated that they do not have specific requirements based on friction demand were Idaho, Hawaii, and Rhode Island. Alaska uses criteria for studded tire wear.

Seven respondents (32 percent) used a skid value of the as-built surface. Thirteen (59 percent) respondents used the polish test or a similar test to estimate polish and relative wear of the coarse aggregate. Some respondents indicated that they may use both, but that information is not clear from the survey. However, the majority of the respondents used some type of skid or polish value (PV) requirement. TxDOT uses a surface aggregate classification (SAC) system.

Pennsylvania, Tennessee, Idaho, Alaska, and Florida provided additional information about their procedures.

CHAPTER 3. SPECIFICATIONS

A review of all 50 U.S. states, Puerto Rico, New Zealand, and Australia (Access Canberra Territory, New South Wales Roads and Maritime Services, Northern Territory, Queensland, Tasmania, Victoria, and Western Australia) specifications was performed.

New Zealand and Australia use a PV requirement. In general, there is a minimum value for hot mix; however, the Australian Northern Territory has a PV for seal coat based on average daily traffic (ADT). The ADT ranges are less than 300, 300 to 6,000, and more than 6,000.

For the United States and Puerto Rico, 13 of the 51 (25 percent) specification books reviewed contained specific requirements for pavement friction.

ALABAMA DEPARTMENT OF TRANSPORTATION

The requirements shown in Table 3 are located in the Alabama DOT’s standard specifications for highway construction [8].

Table 3. Alabama Department of Transportation Section 401, 403, 409, 423, 424, and 490.

Section	**Requirements**	
General Requirement in Section 401, 403, and 409	The use of carbonate stone such as limestone, dolomite, or aggregate tending to polish under traffic shall be restricted as follows, based on the average daily traffic count in both directions.	
Section	**ADT Range**	**Requirements**
SECTION 401 BITUMINOUS SURFACE TREATMENTS	500 vehicles or less per day	No restrictions apply.
	More than 500 but less than or equal to 1,000 vehicles per day	Carbonate stone shall not be used in the final application. Aggregates for the final application (wearing layer) shall be limited to siliceous aggregates such as granite, quartzite, blast furnace slag, or lightweight aggregates (expanded clays or shales produced by the Rotary Kiln Method).
	Over 1,000 vehicles per day	Carbonate stone shall not be used in any application.
SECTION 403 MICRO-SURFACING SEAL COAT	500 vehicles per day or less	No restrictions apply.
	501 to 5,000 vehicles per day	Carbonate stone shall be limited to a maximum of 30% of the blended gradation.
	Over 5,000 vehicles per day	Carbonate stone shall not be used in any application.
SECTION 409 TRIPLE	← 500 vehicles per day	No restrictions apply.

<table>
<tr><th>Section</th><th colspan="2">Requirements</th></tr>
<tr><td rowspan="2">LAYER BITUMINOUS SURFACE TREATMENT</td><td>500 but ← 1,000 vehicles per day</td><td>Carbonate stone shall not be used in the final application. Aggregates for the final application (wearing layer) shall be limited to siliceous aggregates such as granite, quartzite, blast furnace slag, or lightweight aggregates (expanded clays or shales produced by the Rotary Kiln Method).</td></tr>
<tr><td>>1,000 vehicles per day</td><td>Carbonate stone shall not be used in any application.</td></tr>
<tr><td rowspan="10">SECTION 423 STONE MATRIX ASPHALT (SMA) (FIBER STABILIZED ASPHALT CONCRETE)

SECTION 424 SUPERPAVE BITUMINOUS CONCRETE BASE, BINDER, AND WEARING SURFACE LAYERS</td><td colspan="2">Aggregates that tend to polish under traffic, such as limestone, dolomite, or marble, shall be permitted only in widening as defined by Article 410.01, shoulder paving, underlying layers, and layers that are to be covered by polymer-modified open-graded friction course (Section 420) mix in this contract, except as noted below.</td></tr>
<tr><td colspan="2">Allowable Carbonate Stone Criteria for SMA or Superpave</td></tr>
<tr><td>BPN 9 Value of Aggregate Source*</td><td>Maximum Allowable Percentage of Carbonate Stone</td></tr>
<tr><td>≤ 25</td><td>30</td></tr>
<tr><td>26 through 28</td><td>35</td></tr>
<tr><td>29 through 31</td><td>40</td></tr>
<tr><td>32 through 34</td><td>45</td></tr>
<tr><td>≥ 35</td><td>50</td></tr>
<tr><td colspan="2">*This value, BPN 9, is made using the British Pendulum Tester on aggregate source specimen polished for 9 hours on an accelerated polishing machine known as the British Wheel as per ASTM D 3319, ASTM E 303, and BMTP-382.</td></tr>
<tr><td colspan="2">In no case shall the total amount of virgin carbonate stone in the combined mixture used as actual wearing surface layers exceed the percentage shown above. When parts of the carbonate stone used in the mix are from differing strata of material or coming from multiple sources that are represented by different BPN 9 values, the lowest BPN 9 value will be used.</td></tr>
<tr><td>SECTION 490 BRIDGE DECK THIN POLYMER OVERLAY</td><td colspan="2">Polish Stone Value 38 min. AASHTO T 279</td></tr>
</table>

ALASKA DEPARTMENT OF TRANSPORTATION AND PUBLIC FACILITIES

The Alaska Department of Transportation and Public Facilities specifications [9] refer to a studded tire wear requirement based on the Nordic abrasion test, ATM 312 [10].

FLORIDA DEPARTMENT OF TRANSPORTATION

In order to be on the approved product list, Florida Department of Transportation’s specifications must meet the following requirements in Section 523 Patterned Pavement [11], which are summarized in Table 4. In Section 901 Coarse Aggregate, for limestone, dolomite, and sandstone used as a friction coarse, the crushed limestone shall have a minimum acid insoluble content of 12 percent using FM5-510 and others must meet the requirements by Rule14-103.005(1), Florida Administrative Code, which is located at https://www.flrules.org/gateway/RuleNo.asp?title=CONSTRUCTION%20AGGREGATES&ID=14%E2%80%90103.005.

In summary, Rule 14-103.005(1) [12] requires a test section be constructed and tested meeting the following roadway criteria:

- Minimum 50 mph speed limit.
- Minimum 14,000 ADT.
- No intersection, ramps, driveways, or curves.
- Minimum of four lanes.
- Minimum length of 1,000 ft.

If the friction number falls below 30 or the test section is otherwise determined to be a threat to public safety within the first two years of construction completion, the evaluation will be terminated. At the end of the two years, the section will be compared to a control section and previously approved FC-5 aggregates with the results being equivalent or better. Friction tests will be conducted at 40 mph in accordance with ASTM E274-97, using both E501 (Rib) and the E524 (Blank) test tires by the State Materials Office on the test section:

- Immediately after construction.
- Then monthly for two months and thereafter at intervals of two months until the accumulated traffic reaches 6 million (vehicles) coverage, or the friction number stabilizes.

Table 4. Florida Department of Transportation Section 523.

Description	Comments	
Manufacturer's Recommendations	Applicability of use • on concrete or asphalt surfaces • in vehicular or non-vehicular travel	
For Use in Vehicular Traffic Areas	ASTM E-274, Skid Resistance of Paved Surfaces	Using a standard ribbed full scale tire at a speed of 40 mph (FN40R), and has a minimum FN40R value of 35, or
	ASTM E-1911, Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester (DFT)	At a speed of 40 mph (DFT40), and has a minimum DFT40 value of 40
For Use in Non-Vehicular Traffic Areas	ASTM E-303 using the British Pendulum Tester and has a British Pendulum Number (BPN) of at least 40	

INDIANA DEPARTMENT OF TRANSPORTATION

The requirements shown in Table 5 are located in Indiana Department of Transportation's standard specifications for highway construction [13].

Table 5. Indiana Department of Transportation Specifications.

Section	Requirement
SECTION 411—WARRANTED MICRO-SURFACING	Skid Resistance—friction number as measured by ASTM E 274 and E 524. Friction Number no less than 30, average 3.5.* Individual friction tests will be performed in each lane every 1/2 mi for the length of the project.
SECTION 904—AGGREGATES	Polish resistant aggregates are defined as those aggregates in accordance with ITM 214 [14]. Aggregates meeting these requirements will be maintained on the Department's list of approved Polish Resistant Aggregates.
	ITM 214 requirements [14] for acceptance criteria: After two years exposure to traffic, if the coarse aggregate HMA friction values are equal to or greater than the approved dolomite or polish resistant aggregate HMA friction values, the material will be approved as a Polish Resistant Aggregate. -or After three years exposure to traffic, if the coarse aggregate HMA friction values are equal to or greater than an average of 35.0, with no individual location value less than 30.0, the material will be approved as a Polish Resistant Aggregate. The approved list includes two categories as follows: • Coarse aggregates that are approved for use in HMA surface mixtures for contracts with traffic ESAL's equal to or greater than 3,000,000 and less than 10,000,000. • 9.2.2 Coarse aggregates that are approved for use when blended with air-cooled blast furnace slag, steel furnace slag, or sandstone in HMA surface mixtures for contracts with traffic ESAL's equal to or greater than 10,000,000.

LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

The Louisiana Department of Transportation and Development specifications [15] refer to a friction rating (FR), which is assigned to the coarse aggregate during source approval. Coarse gravel is only evaluated if the percent double face crushed is at least 75 percent; otherwise, it is assigned a rating of III. Table 6 presents the FR and allowable use.

Table 6. Louisiana Department of Transportation and Development Section 1003, 501, and 507.

Section 1003 Aggregates		Section 502 Asphalt Concrete Mixtures	Section 507 Asphalt Surface Treatment (AST)
FR	Polish Value	Allowable Usage	AST Type
I	>37	All Mixtures	A, B, C, D, E
II	35 to 37	All Mixtures	A, B, C, D, E
III	30 to 34	All Mixtures, except mainline wearing courses with plan ADT greater than 7000[1]	B, C, D, E
IV	<30	All Mixtures, except mainline wearing courses[2]	D, E

[1] When current ADT is greater than 7,000, blending of FR III aggregates and FR I and/or II aggregates will be allowed for travel lane wearing courses at these percentages: at least 30 percent by weight (mass) of the total aggregates with FR I, or at least 50 percent by weight (mass) of the total aggregate with FR II. The frictional aggregates used to obtain the required percentages shall not have more than 10 percent passing the No. 8 (2.36 mm) sieve.

[2] When the ADT is less than 2,500, blending of FR IV aggregates with FR I and/or II aggregates will be allowed for travel lane wearing courses at these percentages: at least 50 percent by weight (mass) of the total aggregate in the mixture with FR I or II. The frictional aggregates used to obtain the required percentages shall not have more than 10 percent passing the No. 8 (2.36 mm) sieve.

MICHIGAN DEPARTMENT OF TRANSPORTATION

The Michigan Department of Transportation specifications [16] refer to an aggregate wear index. The test method for the aggregate wear index is Michigan Test Methods 111 and Michigan Test Methods 112 [17].

PENNSYLVANIA DEPARTMENT OF TRANSPORTATION

The Pennsylvania Department of Transportation specifications [18] refer to a skid resistance level (SRL). The SRL is defined in the Bulletin 14 supporting information document [19]. The specification SRL requirements are as designated on the plans and shown in Table 7. The SRLs are aggregate friction guidelines for bituminous wearing surfaces. The SRL is for both coarse and fine aggregate. For FJ-1 wearing surfaces, the SRL is based on the current ADT for resurfacing and anticipated initial daily traffic on new facilities (refer to Table 8).

Table 7. Pennsylvania Department of Transportation Specifications Section 489.

Section	Requirement		
SECTION 489—ULTRA-THIN BONDED WEARING COURSE	ADT		
	<5,000	5,000 to <20,000	>20,000
	G or higher	H or higher	E

Table 8. Pennsylvania Department of Transportation Skid Resistance Level.

ADT	SRL
20,000 and above	E
5,000 to 20,000	E, H, Blend of E & M, or Blend of E & G
3,000 to 5,000	E, H, G, Blend of H & M, or Blend of E & L
1,000 to 3,000	E, H, M, G, Blend of H & L, or Blend of G & L or Blend of E & L
1,000 and below	Any
SRL	**Aggregate Type**
E	Sandstones; siltstones; Loyalhanna Limestone sources (calcareous sandstones) which consistently contain more than 30% + #200 acid insoluble residue; gneisses and igneous rocks which contain high amounts of micas; several quartzite sources which have been sheared so that they have softer, sheared microcrystalline quartz surrounding the remaining intact quartz grains; and gravels which contain either a) < 25% carbonates, < 10% chert, and high percentages of dirty sandstones and siltstones; or b) < 10% carbonates, < 15% chert, and high percentages of dirty sandstone and siltstones.
H	Argillites; diabases, gneisses, granites and granodiorites, basalts, and gabbros which do not contain large amounts of micas; open hearth slag; blast furnace slag; metamorphic quartzites (no difference in hardness between quartz cement and quartz grains); sandy limestones; a few coarsely crystalline dolomites (e.g., the Ledger dolomite); and gravels which contain either: a) > 25% and < 34% total carbonates, and <10% chert; or b) > 15% chert and < 25% chert, and < 10% carbonates; or c) large amounts of quartzite.
G	Siliceous limestone and dolomite; limestones and dolomites with consistent wide textural variation (i.e., they always contain finely to moderately or coarsely crystalline dolomite or limestone); gravels which contain more than 34% carbonates and more than 10% chert; and serpentinites.
M	Many dolomites and some limestones that are not consistently finely textured all the time.
L	Most limestones and some dolomites that are very finely textured, and contain very little, if any, acid insoluble residue retained on the #200 sieve.

TENNESSEE DEPARTMENT OF TRANSPORTATION

The Tennessee Department of Transportation specifications [20] require a polish-resistant aggregate (refer to Figure 9).

903.24 Aggregates for Riding Surfaces (Polish-Resistant Aggregates)

Provide coarse aggregate consisting of crushed gravel, crushed granite, crushed slag, crushed quartzite, crushed gneiss, or crushed sandstone. Other crushed aggregate may be used provided it has the chemical, physical, and performance characteristics specified in Table 903.24-1.

Table 903.24-1: Quality Requirements for Type I, II, III, and IV Aggregate

Aggregate Property	Test Method	Type I (all roads)	Type II (all roads)	Type III (15,000 ADT max, excluding Interstates)	Type IV (5,000 ADT max)
Silica Dioxide Content, % min	ASTM C25	40%	30%	20%	10%
Calcium Carbonate Content, % max		32%	--	--	--
Acid Insoluble Residue, % min	ASTM D3042	50%	35%	25%	--
British Pendulum Number,[(1)] min	AASHTO T 278 AASHTO T 279	30	30	25	22

(1) After 9 hours of accelerated polishing using the British Wheel in accordance with AASHTO T 279

In addition to the requirements specified in Table 903.24-1, Type II, III, and IV aggregates shall have met the preapproval process of the Division of Materials and Tests. All aggregate types must also maintain a satisfactory level of field performance to remain an approved source.

Process and stockpile the material as an independent and separate operation. The Engineer will sample and test each stockpile for approval prior to use.

927

Figure 9. Tennessee Department of Transportation Aggregate Requirements [20].

TEXAS DEPARTMENT OF TRANSPORTATION

TxDOT refers to the SAC system for seal coat and hot-mix surface courses.

UTAH DEPARTMENT OF TRANSPORTATION

The Utah Department of Transportation specifications [21] have references to skid value; otherwise, they note a skid resistant texture (refer to Table 9).

Table 9. Utah Department of Transportation Specifications.

<table>
<tr><th>Section</th><th>Requirement</th></tr>
<tr><td>SECTION 03372, THIN BONDED POLYMER OVERLAY</td><td>A warranty guarantees the polymer overlay system against material and installation defects incurred under traffic for a period of 5 years. Skid requirement of Loss of skid resistance: Skid resistance less than 40 as measured according to ASTM E 274.</td></tr>
<tr><td>SECTION 03375, BRIDGE DECK METHACRYLATE RESIN TREATMENT</td><td><table>
<tr><th colspan="2">Skid Resistance Test Results</th></tr>
<tr><th>Before Application</th><th>After Application</th></tr>
<tr><td>< 40</td><td>≥ Before Application</td></tr>
<tr><td>≥ 40</td><td>≥ 40</td></tr>
</table></td></tr>
</table>

WEST VIRGINIA DEPARTMENT OF TRANSPORTATION

The West Virginia Department of Transportation specifications [22], Section 402 Asphalt Skid Resistant Pavement, are summarized in Table 10.

Table 10. West Virginia Department of Transportation Specifications.

Description	Notes
Gravel	Considered polish resistant aggregate.
Slag	Considered polish resistant aggregate.
Dolomite	May be used alone or as a part of a coarse aggregate blend on roadways with a projected ESAL value of less than 3,000,000. On roadways with a projected ESAL value of 3,000,000 or greater, acceptable dolomite may be used only as a part of the coarse aggregate blend and shall not exceed 50% of that blend.
Limestone	Shall contain a minimum of 10% quartz retained on the #200 (75µm) sieve.
Dolomite Limestone	Shall contain a minimum of 10% elemental magnesium
Shale, Coal, and Other Lightweight Deleterious Material and Friable Particles	Shall not exceed 3%.

WYOMING DEPARTMENT OF TRANSPORTATION

The Wyoming Department of Transportation specifications [23] for micro-surface and chip seal reference a polish-resistant aggregate with PV requirements, as summarized in Figure 10.

803.6.2 Polish Resistant Aggregate

[1] Provide aggregate that is in accordance with one of the test methods in Table 803.6.2-1, Polish Resistant Aggregate Requirements.

Table 803.6.2-1
Polish Resistant Aggregate Requirements

Test Method	Description	Specification
AASHTO T 279	9 hour (Polish Value), min.	32
AASHTO T 242	Skid Number, min.(1)	40

(1) Base the skid number on historical skid numbers accumulated for a period of at least five years for a pavement that has carried traffic exceeding 3,500,000 accumulated 18-kip equivalent single axle loads.

Figure 10. Wyoming Department of Transportation Polish-Resistant Aggregate [23].

PUERTO RICO DEPARTMENT OF TRANSPORTATION AND PUBLIC WORKS

The Puerto Rico Department of Transportation and Public Works Specification 703—Aggregates [24] has a polishing value of 48 percent as determined by ASTM D 3319, Standard Practice for the Accelerated Polishing of Aggregates Using the British Wheel, for aggregates in surface courses of hot mix and seal coat.

CHAPTER 4. LITERATURE REVIEW

TXDOT-RELATED RESEARCH

The researchers requested historical files for the development of Form 2088; however, there is no documentation. Two reports were found that reviewed the skid program in Texas. The first was in 1992 and the second in 2008.

It appears that many of the friction demand criteria thresholds are found in the 1992 research performed by Ivey et al. [25]. The research indicated that available friction was defined by rainfall, pavement surface friction, and drainage, while friction demand was a function of traffic volume and roadway geometry. An examination of the ratio of wet-surface accidents to dry-surface accidents was recommended to identify when a pavement is overrepresented by wet-surface accidents.

Development of a regression equation to predict wet-surface accidents was discussed; however, the conclusion was that "regression equations are unlikely to ever be developed with sufficient predictive validity to accurately foretell where future wet-surface accidents will occur, or how many accidents will be sustained at a particular location" [25]. Due to this, an alternate method was recommended that compares pavements in the same geographic area because they should have the same ratio of wet-surface to dry-surface accidents.

Development of a friction demand index was discussed as a way to classify a section of roadway and use it to compare to a friction level (based on the SN). Table 11 is a summary of the criteria used in the friction demand index. Precipitation was broken into the ranges of the annual rainfall of 8 to 19 inches, 20 to 39 inches, and 40 to 60 inches (West Texas = 0.25 in/hr, Central Texas = 0.5 in/hr, and East Texas = 0.65 in/hr). These levels were used to define the pavement surface drainage condition of good, average, or poor. Criteria considered with drainage were macro-texture, cross-slope, and drainage path. The drainage path was a function of horizontal curves (D <=1°), cross-slope, vertical curves (sag), pavement distresses (rutting, unevenness, shoulder buildup), curbs, or inadequate or clogged drains.

Table 11. Friction Demand Index versus Conditions.

FDI	Mean Speed	Roadway Geometry[1]	Sight Distance | Grade Intersections	Horizontal Curves (Degree of Curve, D)
1	<45	or rural road with straight tangents and or long radius curves with	few visibility problems | Unlimited visibility and MUTCD advance signing	Mean speed (MS) < curve Design Speed (cDS) or D<=2°
2	<55	or low access on straight tangents and or long radius curves with	few visibility problems | Good visibility and MUTCD advance signing	MS<cDS or 2° < D <=5°
3	<65	or medium access and long radius curves	No extreme visibility problems | limited visibility and MUTCD + signing and marking	MS<cDS or D >5°
4	<65	and low access levels long radius curves	No extreme visibility restrictions | Good visibility and MUTCD advance signing	MS> cDS (advisory speed >10mph below posted)
5	<65	or medium or high access levels or medium or sharp curves	significant visibility restrictions | limited visibility and MUTCD + signing and marking	MS> cDS (advisory speed >20mph below posted)

Jayawickrama and Madhira [26] performed a study in which they reviewed the aggregate classification system used by TxDOT. Specifically, they looked at the laboratory procedures for testing aggregates with respect to frictional behavior. Based on the methods evaluated, the researchers concluded that the PV test and the AIR test specifically address skid resistance properties of the pavement aggregates. Methods that may relate to skid resistance are the micro-Deval and magnesium sulfate soundness (MSS). There was a concern with the repeatability of the AIR test.

Field skid data clearly showed that the synthetic aggregates, sandstones, and igneous materials consistently provided very good to excellent skid resistance [26]. Gravel was good overall but less consistent because some sources had significant amounts of carbonate material that may have contributed to the variable performance. Limestones and dolomite-limestones had the greatest variability, with some performing poorly and others very well.

Based on the lab-to-field correlations using a terminal SN > 35 to be considered as very good to excellent performance, the following criteria stood out:

- AIR < 80%, micro-Deval loss < 8%, and MSS loss <= 5%.
- PV at high range correlated better than PV at low range.
- No one test alone was a good indicator, but a combination of PV and MSS may be a good indicator for classifying sources.

The TxDOT *Roadway Design Manual* [27] covers many of the design factors. Information from the manual is summarized in the following paragraphs.

Speed

Low speed is less than or equal to 45 mph. High speed is greater than or equal to 50 mph.

Intersection Sight Distance and Driveways

The factors recommended to be considered when designing an intersection include sight distance along both highway approaches and across corners and grades to be as flat as possible on both highways. Driveways should also be designed with sufficient sight distance.

Horizontal Curves

Superelevation rate maximums for design are 6 to 8 percent. The minimum horizontal curve radius is based on the design speed and maximum superelevation rate. The side friction factors are defined in the manual based on design speed.

Cross-Slope

Two percent is the recommended pavement cross-slope for usual conditions. One percent is the minimum. Three percent is the maximum unless in superelevation.

Vertical Grade

The maximum grades are based on design speed, functional classification, urban and suburban versus rural, and type of terrain. The following are the ranges based on the functional class, with the urban and suburban listed first and then the rural:

- Local: Less than 15 percent | 5 percent to 12 percent.
- Collector: 6 percent to 12 percent | 5 percent to 10 percent.
- Arterial: 5 percent to 9 percent | 3 percent to 6 percent.
- Freeway: 3 percent to 5 percent | 3 percent to 5 percent.

Sag vertical curves are designed based on headlight sight distance, passenger comfort, drainage control, and general appearance. The sight distance and drainage control are important criteria for wet-weather accident reduction. Minimum vertical grades required for pavement drainage are as follows:

- Uncurbed pavements with an adequate crown to drain the surface water laterally: Flat or level grades are satisfactory.
- Side ditches: The roadway grade should seldom be less than 0.5 percent for unpaved ditches and 0.25 percent for lined channels.
- Curbed pavements: Desirable minimum grades of 0.35 percent should be provided to facilitate surface drainage.

Safety Analysis

The safety analysis is based on a three-to-five-year crash data analysis to calculate a crash rate. A crash modification factor can be used to estimate the potential impacts of an improvement. The Design Division is developing a safety tool. This tool is based on the research performed in project 0-6932, Pavement Safety-Based Guidelines for Horizontal Curve Safety [28].

Pratt et al. [28] developed a safety score spreadsheet to evaluate safety-related project criteria compared to the existing roadway safety rating. TxDOT has related documents on its website [29, 30]. This tool is required to be used on rural PM, 2R, 3R, and 4R projects. The tool is required on pavement projects, including seal coats and overlays. The tool 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 has three categories for roadway elements: 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. Table 12 is a comparison of factors on the safety score spreadsheet and Form 2088.

Table 12. Form 2088 and Safety Score Factors.

Form 2088	Safety Score Spreadsheet
Rainfall (inches/year)	—
Trucks (%)	—
Intersecting Roadways (ADT)	—
Wet Surface Crashes (%)	—
Surface Design Life (years)	Category (4R, 3R)—Future Enhancement
Speed (mph)	Design Speed (mph)
	Posted Speed (mph)
Cross Slope (%)	E max (%)
Traffic (ADT)	Design Year AADT (vehicles per day)
Cross Slope (%)	Cross-Slope or Superelevation (%)
Horizontal Curve	Horizontal Curve Present?
	Horizontal Curve Data for Controlling Element:
	Radius (feet)
	Length of Horizontal Curve (feet)
Driveways (per mile)	Driveway Density (driveways per mile)
Vertical Grade	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?
Macro-Texture	Pavement Friction (skid number)
Aggregate Micro-Texture	
Other Factors on Safety Score Spreadsheet That Are Not on Form 2088	
Dist. from Centerline to Left ROW (feet)	Edgeline Pavement Markings or Profile Markings
Dist. from Centerline to Right ROW (feet)	Shoulder Rumble Strips
Lane Width (feet)	Centerline Rumble Strips
Shoulder Width (feet)	Lighting
TWLTL (two-way left-turn lane)	Fixed Object Type
Passing or Climbing Lane in One Direction	Sideslope (Foreslope)
Advance Static Curve Warning Signs	Backslope
Chevron Signs on Horizontal Curves	SafetyEdge
Post-Mounted Delineators	Lateral Clearance to obstruction (ft)
	Obstruction Type

Note: — means not applicable.

TxDOT's Maintenance Division recommends, as a guideline for proposed skid values, using an SN of 38 for asphalt concrete overlay and an SN of 52 for seal coats[30]. The existing SN can be found in the PMIS database, through the Pavement Analyst software. Figure 11 shows the CMFs for intersection sight distance for three different ADT levels. The ADT ranges are less than 5,000, 5,000 to 15,000, and greater than 15,000.

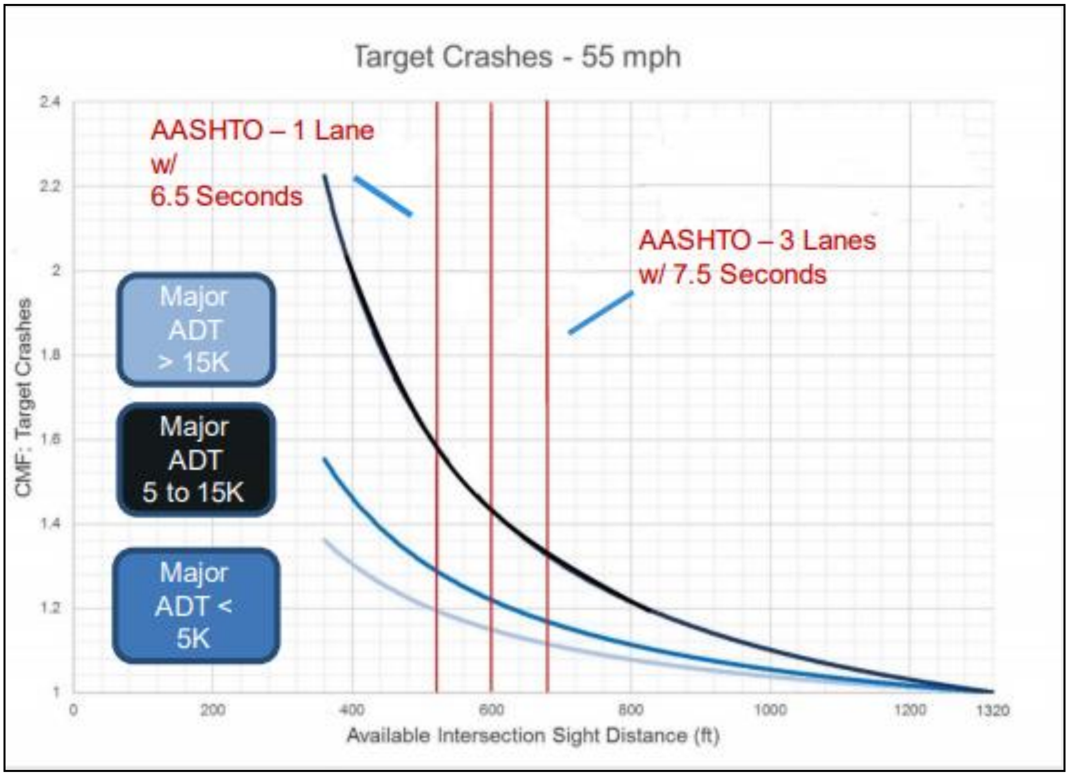

Figure 11. CMT for Intersection Sight Distance [31].

ADT ranges in the safety assessment tool are shown in Table 13.

Table 13. Average Daily Traffic Ranges in the Safety Assessment Tool.

Rural Two-Lane ADT Ranges (Vehicles per Day)	Rural Multi-Lane (Vehicles per Day)
<400	<2,000
400 to 2,000	2,001 to 40,000
2,000 to 8,000	>40,001
>8,000	

FORM 2088 FACTORS AND CRITERIA

Rainfall

The rainfall criterion is measured in inches per year (in/yr) with the following ranges:

- Low: Less than or equal to 20 in/yr.
- Moderate: Greater than 20 in/yr but less than or equal to 40 in/yr.
- High: Greater than 40 in/yr.

These ranges are in line with the recommendations from Ivey et al. [25]. The FHWA-related factor similar to Form 2088's rainfall factor is splash and spray (proposed pavement surface), precipitation, and temperature.

Technical Advisory T 5040.36 Surface Texture for Asphalt and Concrete Pavements [32] states, "An increased probability of wet-weather conditions would justify a higher level of texture or higher threshold value for a friction-related parameter. Research in Sweden concluded that, for worn pavements, crash rates increase on days with rainfall of 10 mm (0.39 inches) or greater."

Jackson et al. [33] evaluated the rainfall impacts on traffic safety—specifically fatal crashes in Texas related to rain. A review of the fatal crashes compared to the rain-related fatal crashes from 1982 to 2011 resulted in 8.1 percent for the United States, with Texas having a lower rate during this period of 7.1 percent. The following are conclusions from this study:

- "The results indicate a very strong decreasing rain-related fatal crash rate trend (after normalization by total fatal crashes). However, neither the Texas annual rainfall nor the numbers of rain-related fatal crashes show any decreasing or increasing trends. This shows that neither total fatal crashes nor rain-related fatal crashes are impacted by the population growth in Texas.
- "Total fatal crashes are very slightly correlated with rainfall in Texas (correlation coefficient of .02), while rain-related fatal crashes are strongly correlated with rainfall (0.77) and moderately with total crashes (0.52). However, the normalized rain-related fatal crashes have a higher correlation (0.90). This indicates that the relationship between rainfall and fatal crashes is very complex. Although the spatial statistical analysis confirms the relationship, the small temporal correlation indicates that other factors might also influence the relationship.
- "Those factors may include congestions during rainfall events due to reduced speeds and the number of rain days compared to non-rain days and rainfall intermittency impacts" [34].

Flintsch et al. [34] found that the reduction in potential crashes based on the friction between the tire and pavement was the critical contributing factor. The document provides guidelines for state DOTs and highway agencies to effectively use tire pavement friction data to support asset management decisions.

When water on the roadway is too thick to be broken up by the tire, hydroplaning can occur. The thick film of water builds up in front of the tire, spreads out underneath, and lifts the tire off the surface, resulting in a significant loss of friction. The friction, macro-texture, cross-slope, longitudinal grade, and radius of curvature all affect the pavement surface drainage and potential for hydroplaning. Precipitation is a critical factor; however, temperature is not.

Pratt et al. [28] found that an analysis of the 1981–2010 National Oceanic and Atmospheric Administration climate normal dataset yielded trends similar to those shown on Form 2088. Figure 12 is a graph of the annual precipitation rate versus the crash modification factor to show the influence of rain on crashes.

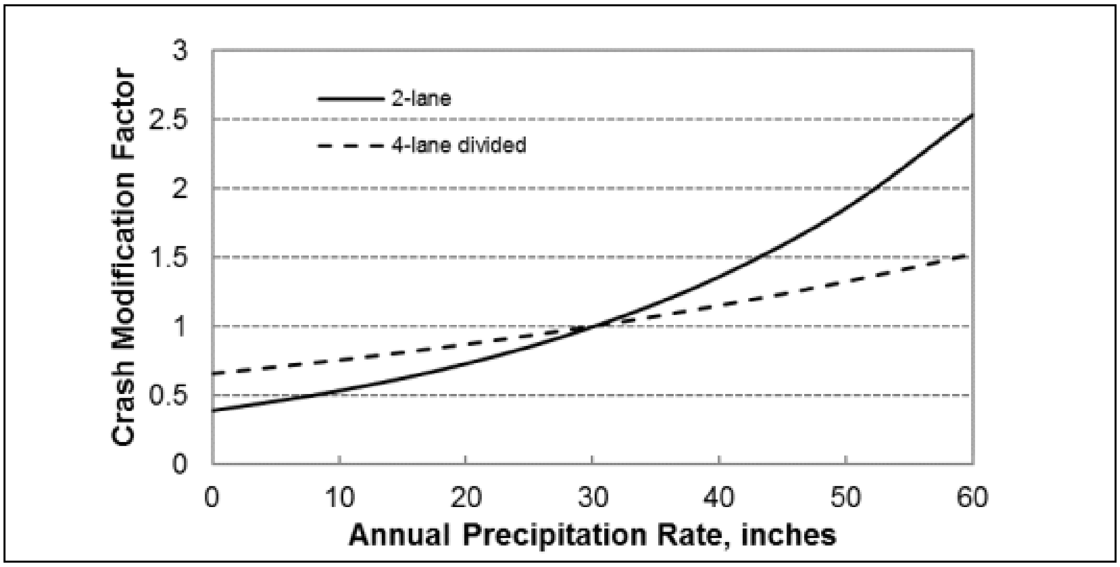

Figure 12. Rainfall versus Crash Modification Factor [28].

Traffic

The traffic criterion is measured in ADT with the following ranges:

- Low: Less than or equal to 5,000.
- Moderate: Greater than 5,000 but less than or equal to 15,000.
- High: Greater than 15,000.

The FHWA-related factor similar to Form 2088's traffic factor is traffic volume. Historical TxDOT design criteria used a PV requirement based on ADT, as shown in Table 14.

Table 14. TxDOT Polish Value Requirement (Pre-WWARP) [35].

Present ADT	Polish Value (minimum)
<750	—
750 to 2,000	28
2,000 to 5,000	30
>5,000	32

Note: — means not applicable.

Speed

The speed criterion is measured in miles per hour with the following ranges:

- Low: Less than or equal to 35 mph.
- Moderate: Greater than 35 mph but less than or equal to 60 mph.
- High: Greater than 60 mph.

The FHWA-related factor similar to Form 2088's speed factor is speed limit.

Technical Advisory T 5040.36 Surface Texture for Asphalt and Concrete Pavements [32] states that "50 mph and higher are high-speed facilities. Higher speed facilities may justify a higher level of texture or higher threshold value for a friction-related parameter. Friction test results will decrease with increasing speed, reaching a minimum at approximately 60 mph. Friction on surfaces with low texture falls more rapidly with speed than on high textured surfaces."

Flintsch et al. [34] found water film thickness has a noticeable effect on friction when the speed is higher than 40 mph.

A Policy on Geometric Design of Highways and Streets [36] indicates that speed affects the severity of a crash, but it is not well understood how it contributes to a crash. Due to this phenomenon, the roadway design elements should account for the appropriate speed.

Trucks

The truck criterion is measured in percentage with the following ranges:

- Low: Less than or equal to 8 percent.
- Moderate: Greater than 8 percent but less than or equal to 15 percent.
- High: Greater than 15 percent.

The FHWA-related factor similar to Form 2088's truck factor is traffic composition.

Vertical Grade

The vertical grade criterion is measured in percentage with the following ranges:

- Low: Less than or equal to 2 percent.
- Moderate: Greater than 2 percent but less than or equal to 5 percent.
- High: Greater than 5 percent.

The FHWA-related factor similar to Form 2088's vertical grade factor is roadway vertical alignment.

A Policy on Geometric Design of Highways and Streets [36] indicates that grade affects the stopping sight distance. Stopping distance is shorter on upgrades and longer on downgrades compared to a level roadway. Pavement friction is not a direct part of the equations used for determining stopping sight distance. The policy states, "Implicit in the choice of this deceleration threshold is the assessment that most vehicle braking systems and the tire-pavement friction levels of most roadways are capable of providing a deceleration rate of at least 11. ft/s^2. The friction available on most wet pavement surfaces and the capabilities of most vehicle braking systems can provide braking friction that exceeds this deceleration rate" [36].

Horizontal Curve

The horizontal curve criterion is measured in degree of curve with the following ranges:

- Low: Less than or equal to 3 degrees.
- Moderate: Greater than 3 degrees but less than or equal to 7 degrees.
- High: Greater than 7 degrees.

The FHWA-related factor similar to Form 2088's horizontal curve factor is roadway horizontal alignment.

Technical Advisory T 5040.36 Surface Texture for Asphalt and Concrete Pavements [32] indicates that curves with a radius of curvature of less than 500 m (1,640 ft) have significantly higher crash rates.

A Policy on Geometric Design of Highways and Streets [36] contains a basic equation for vehicle operation on a curve that includes the following variables:

- Superelevation.
- Side friction demand factor.
- Speed.
- Gravitational constant of 32.2 ft/s^2.
- Radius of curve.

The side friction is the lateral acceleration that acts on a vehicle. Side friction levels for pavement that does not have adequate skid-resistant properties (not caused by wet weather) should not control design since adequate pavement friction can be constructed at a reasonable cost. The policy states, "Side friction factors used in design should be conservative for dry pavements and should provide an ample margin of safety against skidding on pavements that are wet" [36]. There are established design values based on research and experience for side friction and superelevation.

Driveways and Intersecting Roadways

The driveway criterion is measured in number of driveways per mile with the following ranges:

- Low: Less than or equal to five.
- Moderate: Greater than five but less than or equal to 10.
- High: Greater than 10.

The intersecting roadway criterion is measured in ADT with the following ranges:

- Low: Less than or equal to 500.
- Moderate: Greater than 500 but less than or equal to 750.
- High: Greater than 750.

The FHWA-related factor similar to Form 2088's driveway factor is potential conflicting movements or maneuvers. Figure 11 shows crash rates and intersection sight distance.

A Policy on Geometric Design of Highways and Streets [36] indicates that the most significant factor in reducing accident rates is full access control, which minimizes the frequency and variety of events that drivers encounter. Roadways without access control have higher accident rates than roadways with access control (this statement is specifically related to crashes associated with driveways and intersections).

Wet-Surface Crashes

The wet-surface crash criterion is measured in percentage with the following ranges:

- Low: Less than or equal to 5 percent.
- Moderate: Greater than 5 percent but less than 15 percent.
- High: Greater than or equal to 15 percent.

FHWA does not indicate a factor related to Form 2088's wet-surface crashes. Several references for comparisons of various design factors to crash reduction can be found in Pratt et al. [28].

Technical Advisory T 5040.38 Pavement Friction Management [37] indicates that the wet-surface crashes should be used to help evaluate a pavement friction management program's effectiveness. This test of effectiveness is accomplished through a crash rate analysis. To monitor the effectiveness, the following wet safety factor (WSF) is defined as a suitable metric:

$$\boldsymbol{WSF} = \frac{\mathbf{DC} \times \mathbf{PWT}}{\mathbf{WC} \times \mathbf{PDT}} \quad (1)$$

Where:

DC = number of dry-weather crashes.
WC = number of wet-weather crashes.
PDT = percent of dry-pavement time.
PWT = percent of wet-pavement time.

T 5040.38 states, "This factor is the reciprocal of the risk of having a wet pavement accident relative to having a dry pavement accident. Within analysis areas (similar PDT and PWT) the DC and WC are summed to determine the WSF for the analysis area. The WSF for each analysis area is weighted by VMT and aggregated to determine a composite statewide WSF. A desirable trend is increasing with an upper limit of 1.0. A WSF less than 0.67 suggests a potential wet-weather problem. This criteria is based upon the conservative estimate of the overall likelihood of a wet-weather crash being 1 1/2 as great as a dry pavement crash" [37].

Cross-Slope

The cross-slope criterion was measured in inches per foot, which then changed in 2012 to percentage with the following ranges:

- Low: 3/8 in/ft to 1/2 in/ft | 2012 change: Less than 2 percent.
- Moderate: 1/4 in/ft to 3/8 in/ft | 2012 change: 2 percent to 3 percent.
- High: Less than 1/4 in/ft | 2012 change: 3 percent to 4 percent.

The FHWA-related factor similar to Form 2088's cross-slope factor is the same factor. Even though superelevation is a cross-slope, it is specific to horizontal curves and discussed in that section. Cross-slope is not generally designed based on wet-surface crash reduction criteria; however, a minimum cross-slope is needed to ensure pavement drainage.

Surface Design Life

The surface design life criterion is measured in years. The ranges were changed in 2012. The following ranges have been used:

- Low: Less than or equal to three years | 2012 change: Greater than 10 years.
- Moderate: Greater than three years and less than or equal to seven years | 2012 change: Greater than five years and less than or equal to 10 years.
- High: Greater than seven years | 2012 change: Less than or equal to five years.

FHWA does not indicate a factor related to Form 2088's surface design life. While the surface design life is not generally designed based on wet-surface crash reduction criteria, the reduction in friction over time can impact the wet-surface crashes. Deterioration rates based on pavement surfaces are not well correlated in the literature. Additional work is needed in this area; however, Pratt et al. [28] developed some typical ranges.

Pratt et al. [28] evaluated initial and terminal SNs. Table 15 shows the typical range of service life for various pavement surfaces, texture depth, and SNs. The terminal SN is the value measured at the end of the study.

Table 15. Typical Pavement Life and Texture.

Treatment Type	Approximate Service Life, yr	Approximate Mean Texture Depth, mm	Approximate Skid Number Initial	Approximate Skid Number Terminal
HFST	7–12	>0.059 (1.5)	<70	55
Seal Coats	3–15	>0.039 (1.0)	60	55
Thin Asphalt Overlays	8–15	Dense Graded: 0.013 (0.4) to 0.024 (0.6)	50	30
		Stone-Matrix Asphalt >0.039 (1.0)		
PFC	10–15	0.059 (1.5) to 0.118 (3.0)	35–65	20–55
Abrading and Texturing	8	Diamond Grinding 0.028 (0.7) to 0.047 (1.2)	Shot Blasting 53 Abrading 48	Shot Blasting 48 Abrading 38
	2	Grooving: 0.035 (0.9) to 0.055 (1.4)		
Water Blasting	—	Varies	—	—

Note: — means data not available.

The crash rates during wet weather are influenced by pavement friction. Figure 13 is a graph of crash modification factor versus the SN. Crashes increase significantly when the SN is less than 40.

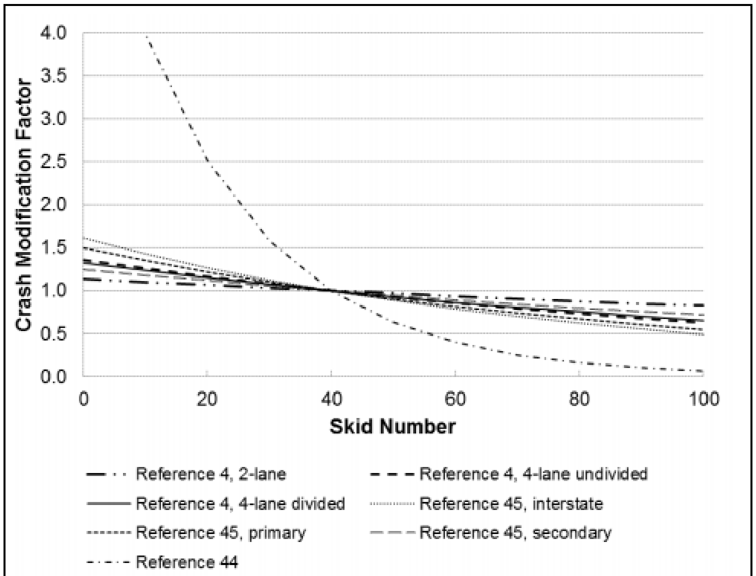

Figure 14. Skid Number CMFs for Total Crashes.

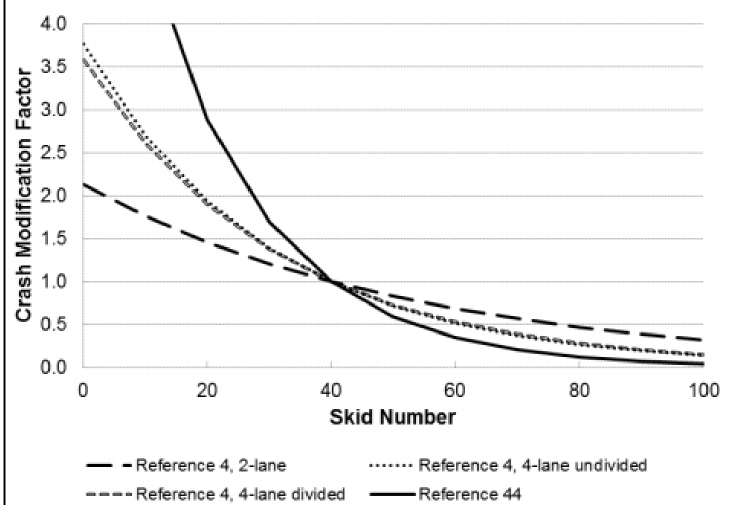

Figure 15. Skid Number CMFs for Wet-Weather Crashes.

Figure 13. Skid Number versus Crash Modification Factor for Dry- and Wet-Weather Crashes (Figure 14 and 15 in the Report) [28].

Macro-Texture of Proposed Surface

The macro-texture of the proposed surface criterion is measured by description. The ranges were changed in 2012. The following ranges have been used:

- Low: Coarse | 2012 change: Fine.
- Moderate: Medium | 2012 change: Medium.
- High: Fine | 2012 change: Coarse.

Examples of coarse macro-texture are mixtures such as porous friction course, stone matrix asphalt, seal coat, and nova chip. Examples of medium macro-texture are mixtures such as dense-graded type C, coarse matrix high binder, Superpave, and micro-surface. Examples of fine macro-texture are mixtures such as dense-graded type D and type F.

The FHWA-related factor similar to Form 2088's macro-texture of proposed pavement is the same.

Technical Advisory T 5040.36 Surface Texture for Asphalt and Concrete Pavements [32] describes the macro-texture as being in the wavelengths of 0.5 mm to 50 mm. Macro-texture is generally provided in asphalt pavement by proper aggregate gradation. T 5040.36 indicates that Superpave mixtures should generally provide adequate macro-texture; however, the technical advisory says that for areas without supplies of durable non-polishing aggregates, another surface with high-durability aggregates optimized for friction may be needed.

Aggregate Micro-Texture

The aggregate micro-texture of proposed surface criterion is designated by the SAC. The original ranges and 2012 ranges are the same; however, the micro-texture was not assigned a numerical scoring value in the original form. The following ranges have been used:

- Low: SAC C.
- Moderate: SAC B.
- High: SAC A.

The FHWA-related factor similar to Form 2088's micro-texture of proposed pavement includes the micro-texture, aggregate properties, and material costs.

T 5040.36 [32] describes the micro-texture to be wavelengths of 1 μm to 0.5 mm. Micro-texture is generally provided in asphalt pavements by the relative roughness of the aggregate particles. T 5040.36 indicates that Superpave mixtures should generally provide adequate micro-texture, but it says that for areas without supplies of durable non-polishing aggregates, another surface with high-durability aggregates optimized for friction may be needed.

Gandhi et al. [38] performed a study that looked at conditions for Puerto Rico. The wet-pavement to dry-pavement ratio compared to pavement friction was found to be statistically significant. They used a polished stone value (PSV) instead of the PV due to the way the testing was performed. The aggregate properties that affect friction are PSV and AIR (carbonate content). When PSV and AIR were used along with the texture depth, there was a small improvement in the correlation. It was found that the surface friction was generally higher than 40 when the texture depths were greater than or equal to 0.03 inches. The researchers made the following recommendations:

- Only require PSV (minimum 48) on major highways and high-risk areas of primary highways. Reduce PSV to 45 on low-risk areas.

- Use a carbonate content requirement with a maximum of 10 percent for expressways and high-risk areas and 25 percent for primary highways. Replace the PV specification with a limit on carbonates for secondary highways.
- Have a texture depth not less than 0.03 inches on high-speed facilities.

Hall et al. [39] developed a guide that provides a thorough explanation of the pavement friction and surface texture. The guide discusses four categories of factors that influence pavement friction, pavement surface characteristics, vehicle operational parameters, tire properties, and environmental factors. Figure 14 shows the categories and factors. The critical factors within a highway agency's control are pavement surface characteristics and slip speed. Slip speed is represented by the coefficient of sliding friction.

Pavement Surface Characteristics	Vehicle Operating Parameters	Tire Properties	Environment
• **Micro-texture** • **Macro-texture** • Mega-texture/ unevenness • **Material properties** • Temperature	• **Slip speed** ➢Vehicle speed ➢Braking action • Driving maneuver ➢Turning ➢Overtaking	• Foot Print • **Tread design and condition** • Rubber composition and hardness • **Inflation pressure** • Load • Temperature	• Climate ➢Wind ➢**Temperature** ➢**Water (rainfall, condensation)** ➢**Snow and Ice** • **Contaminants** ➢Anti-skid material (salt, sand) ➢Dirt, mud, debris

Note: Critical factors are shown in bold.

Figure 14. Categories of Friction Factors [39].

The guide has a detailed description of the factors and how they affect friction. There is an extensive list of devices to measure friction, including their test methods.

Pratt et al. [28] referenced the SN thresholds developed in the study by Long et al. [40]. The SN thresholds are related to a crash reduction ratio. Table 16 summarizes the recommendations.

Table 16. Skid Number Recommendations.

SN Range	Recommended Action	Suggested Threshold Values		
$SN < SN_1$	Potential project for short-term treatment action(s)		All-Weather Crashes	Wet-Weather Crashes
$SN_1 < SN \leq SN_2$	Detailed project-level testing recommended	SN_1	14	17
$SN_2 < SN \leq SN_3$	Vigilance recommended	SN_2	28	29
$SN < SN_3$	Increased SN may have little effect on reducing crash rates	SN_3	74	74

The evaluation included categories based on the following:

- Speed: Low (0 to 55 mph) and high (55 to 80 mph).
- ADT: Low (0 to 2,500), medium (2,500 to 4,500), and high (greater than 4,500).
- Curve: Yes or no.

Selection of Surface Aggregate Classification

The form does not rank one criterion in a category higher than another criterion. All of the criteria are assigned the same numerical value based on the criteria threshold ranges.

Technical Advisory T 5040.36 Surface Texture for Asphalt and Concrete Pavements [32] provides guidance for aggregate and indicates that to follow proper mixture design procedures for Superpave (this document emphasizes Superpave as standard asphaltic concrete mixture). T 5040.36 indicates that the following aggregate characteristics are important for surfaces exposed to wear from traffic and weather:

- "Aggregate angularity. Frictional resistance of the wearing course is improved when angular aggregates are used in the Hot Mix Asphalt (HMA) mixture.
- "Aggregate soundness. Soundness is an indication of an aggregate's resistance to weathering.
- "The recommended range for sodium sulfate soundness is 12-15% maximum and for magnesium sulfate soundness is 15-20% maximum for 5 cycles.
- "Aggregate toughness. Toughness is an indication of an aggregate's resistance to abrasion and degradation during handling, construction, and in-service.
- "The recommended specification value for a Los Angeles abrasion loss ranges from 35 to 45 percent maximum. (Consideration should also be given to utilizing the Micro-Deval Abrasion Test (AASHTO specification TP58).)
- "Polish resistance. The use of aggregates that polish easily should be avoided.
- "It is recommended that polishing resistance of aggregates be measured in the laboratory, prior to use.
- "An appropriate test and value for the specific pavement should be established. A set of tests for evaluating aggregate polish value is Accelerated Polishing of Aggregates Using the British Wheel (AASHTO specification T-279) and Surface Frictional Properties Using the British Pendulum Tester (AASHTO specification T-278). AASHTO specification T-278 may also be used to evaluate the polishing condition (BPN) of pavement surfaces. Other methods may be used to characterize polish-resistance of aggregates." [33]

LITERATURE REVIEW SUMMARY

This subject has been studied by many researchers for several years. The most recent information that contained thresholds was shown in this study. Several of the documents that were reviewed discussed various factors that affect friction, but only a few contained thresholds.

Most of the research with criteria involved pavement friction and the measurement of pavement friction. The other factors, besides pavement friction, have design criteria based on conditions other than wet-weather accident reduction. In general, the discussions concerning the other factors mention that while wet-weather accidents are a consideration, they are not designed specifically for wet-weather accident reduction.

Table 17 is a summary of the main requirements in the reviewed specifications.

Table 17. Specification Summary.

Location	Polish Value	ADT	Aggregate Mineralogy	After-Construction Skid Test	System[1]	Other[2]
United States and Puerto Rico	5	6	4	4	3	1
New Zealand	1	—	—	—	—	—
Australia	1	1	—	—	—	—
England	1	—	—	—	—	—
Scotland	1	—	—	—	—	—
Wales	1	—	—	—	—	—
Northern Ireland	1	—	—	—	—	—
Total	11	7	4	4	3	1

Note: — means not applicable.
[1] Wear Index, SAC, SRL.
[2] Studded tire wear.

TxDOT's program has been in use since 1999 without a comprehensive review of the criteria in Form 2088. Some things to note from the literature review:

- Not all the identified criteria were used in the original selection form. This could have been due to the availability of data or similarity to other criteria.
- The PV testing criteria that were used by TxDOT prior to WWARP set the high ADT at 5,000, but Form 2088 uses 5,000 as the low criterion.
- FHWA T 5040.36 recommends that polishing resistance of aggregates be measured in the laboratory prior to use; however, TxDOT no longer requires the PV test to determine the SAC.
- It is critical to the success of a program to review the procedures within that program. Part of that review of the surface aggregate selection is monitoring the in-place skid resistance of the pavement. TxDOT research 0-6713 recommended pavement friction based on SNs (Table 16). A testing change was made in 2000 to the skid test performed by TxDOT. The skid testing speed was increased from 40 mph to 50 mph and the tire was changed from ribbed to smooth. For comparison with other states, it is important to ensure which skid test method is performed.

CHAPTER 5. RECOMMENDATIONS

FORM 2088 RECOMMENDATIONS

Form 2088 Rainfall

The current ranges are reasonable and no changes are recommended.

Form 2088 Traffic

The current ranges are too high based on a review of other agencies and historical TxDOT values. The TxDOT safety assessment tool is based on rural two-lane (2L) and rural multi-lane (ML) ADT ranges. Table 18 provides a summary of the ADT ranges. The values developed by Long et al. [40] are recommended for determining the ranges for the SN wet-weather crash criteria.

Table 18. Average Daily Traffic Summary.

Agency	Low	Medium	High
ALDOT	ADT ≤ 500	500 < ADT ≤ 1,000	ADT > 1,000
LaDOT	ADT ≤ 2,500	2,500 < ADT ≤ 7,000	ADT > 7,000
PennDOT	ADT < 1,000	1,000 < ADT < 3000 3,000 < ADT < 5,000 5,000 < ADT < 20,000	ADT > 20,000
TNDOT	ADT ≤ 5,000	5,000 < ADT ≤ 15,000	ADT > 15,000
TxDOT	ADT ≤ 5,000	5,000 < ADT ≤ 15,000	ADT > 15,000
TxDOT Historical PV	ADT ≤ 750	750 < ADT ≤ 2,000 2,000 < ADT < 5,000	ADT > 5,000
TxDOT Safety Assessment Tool	2L: ADT < 400 ML: ADT < 2,000	2L: 400 to 2,000 2L: 2,000 to 8,000 ML: 2,000 to 40,000	2L: ADT > 8,000 ML: ADT > 40,001
TxDOT SN	< 2,500	2,500 to 4,500	> 4,500
Australian Northern Territory	< 300	300 to 6,000	> 6,000

Form 2088 Speed

The current ranges should be adjusted. FHWA's T 5040.36 and TxDOT's *Roadway Design Manual* indicate that high speed is greater than or equal to 50 mph. Flintsch et al. [34] indicated that water film thickness has a noticeable effect when the speed is higher than 40 mph. The researchers recommend changing the speed levels to low as less than 40 mph, medium as 40 mph to 50 mph, and high as greater than 50 mph.

Form 2088 Trucks

Other agencies use the equivalent single-axle load (ESAL) estimate instead of percentage of trucks. The TxDOT current percent of trucks assuming a 2 percent growth rate and a truck factor of 2.1 is shown in Table 19. Based on this information, the researchers recommend changing the criteria from percentage of trucks to 20-year flexible ESALs with low as less than 1,000,000, medium from 1,000,000 to 3,500,000, and high greater than 3,500,000.

Table 19. Equivalent Single-Axle Load Estimate.

	Project Information				Calculations for Traffic Estimate			Flexible ESAL Estimate	
Source	Initial ADT (2018)	Final ADT (2038)	% Trucks	Design Period	Growth Rate	AASHTO Growth Factor	Cumulative Trucks in Design Direction	Assumed ESALs/Truck	Cumulative ESALs
Form 2088	5,000	6,900	8	20	2.0%	24.2974	1,773,708	1.20	2,128,450
Form 2088	15,000	20,800	15	20	2.0%	24.3824	10,012,041	1.20	12,014,449
Proposed ADT Change	2,500	3,450	8	20	2.0%	24.2974	886,854	1.20	1,064,225
Proposed ADT Change	4,500	6,200	15	20	2.0%	24.2691	2,989,649	1.20	3,587,579
							INDOT	Low	3,000,000
								High	10,000,000
							WVDOT	Break at	3,000,000

Form 2088 Vertical Curve

The current ranges are reasonable, and no changes are recommended.

Form 2088 Horizontal Curve

The current ranges are reasonable, but the degree of curve measurement has been replaced with radius of curve. No criteria changes are recommended.

Form 2088 Driveways and Intersecting Roadway Average Daily Traffic

These criteria are capturing the effects of the same factor. It is recommended to combine these criteria and use sight distance criteria of less than 550 ft and greater than 750 ft. For ease of evaluating this criterion, it is proposed that the percentage of driveways and intersections in no-passing zones compared to total driveways be considered. An initial break will be at 50 percent, but additional research is needed to determine the threshold values. Additional research is needed to develop the risk thresholds.

Form 2088 Wet-Surface Crashes

Since crashes are a combination of several factors, it is recommended to remove this criterion. Those factors are captured already; however, the existing pavement friction is not. Therefore, it is recommended to replace this criterion with existing pavement SN.

Form 2088 Cross-Slope

The current ranges are reasonable. No criteria changes are recommended.

Form 2088 Surface Design Life

The current ranges are reasonable. No criteria changes are recommended.

Form 2088 Macro-Texture and Micro-Texture

The researchers recommend changing to a composite surface texture measurement. Current requirements do not represent the pavement friction. For example, thin overlay mixtures would fall into the fine category; however, field skid testing indicates that these surfaces provide very good friction properties. More research is needed to determine the threshold values; however, based on current Maintenance Division recommendations, the value for hot-mix surfaces is greater than 38. Table 15 and Table 16 contain information concerning SN and wet-weather crashes. The research indicates that the agency should be vigilant when the SN is between 29 and 74; however, there are only a few pavements, if any, with an SN greater than or equal to 74.

Summary of Form 2088 Recommended Changes

The values recommended are specifically to update the current Form 2088. Future research will be needed to improve the overall system. Since SAC C is not used, there should be two instead of three levels of risk evaluated. There are eight friction demand factors and four pavement friction factors; therefore, the scoring is set up so that all factors have equal weight. The friction provided by the new surface is double the value of the friction demand since the friction demand is two times the number of pavement-friction-provided factors. Table 20 provides a summary of the proposed changes.

Table 20. Form 2088 Summary of Proposed Changes.

Friction Demand	**Current Criteria**			**Proposed Changes**		
Attribute	Low (1)	Moderate (2)	High (3)	Low	Moderate (1)	High (2)
Rainfall (in/yr)	≤ 20	> 20 ≤ 40	> 40	Remove	≤ 40	> 40
Traffic (ADT)	≤ 5,000	> 5,000 ≤ 15,000	> 15,000	Remove	≤ 4,500	> 4,500
Speed (mph)	≤ 35	> 35 ≤ 60	> 60	Remove	≤ 50	> 50
Trucks (%) or change to 20-yr Flexible ESALs in millions	≤ 8	> 8 ≤ 15	> 15	Remove	< 15% or < 3.5	≥ 15% or ≥ 3.5
Vertical Grade (%)	≤ 2	> 2 ≤ 5	> 5	Remove	≤ 5	> 5
Horizontal Curve (Change to Radius in Feet)	≤ 3	> 3 ≤ 7	> 7	Remove	≥ 820	< 820
Driveways (per mile)	≤ 5	> 5 ≤ 10	> 10	Remove		
Intersecting Roadways (ADT)	≤ 500	> 500 ≤ 750	> 750			
Intersection/Driveway Sight Distance (Percent in No Passing Zones)				Remove	< 50%	≥ 50 %
Wet Surface Crashes (%)	< 5	> 5 < 15	≥ 15	Remove		
Parameters set by the designer that affect pavement friction	Low (2)	Moderate (5)	High (8)	Low(2)	Moderate (2)	High (4)
Cross-Slope (%)	≤ 2	> 2 ≤ 3	> 3 ≤ 4	Remove	≤ 3	> 3
Surface Design Life (years)	≥ 10	> 5 ≤ 10	≤ 5	Remove	< 7	≥ 7
Macro-Texture (Combine to a composite surface friction measurement. Example SN values are shown.)	Fine	Medium	Coarse		≤ 38	> 38
Aggregate Micro-Texture	SAC C	SAC B	SAC A	Remove	SAC B	SAC A

FUTURE RESEARCH

The current SAC system does not include pavement friction as a variable in classifying the aggregate. Future research would include the development of a laboratory-measured friction system that is correlated to as-built SNs for the composite pavement or coarse aggregate. In addition, the change in SN over time should be evaluated to ensure that a minimum SN is maintained over the design life of the surface. The system may need to be further refined based on aggregate type. For example, a gravel aggregate source will perform differently than the igneous sources.

TxDOT’s safety score spreadsheet captures several of the factors used in Form 2088 as well as other safety-related criteria. Since this form is required on all projects, the use of this form to determine risk and risk thresholds related to wet-surface crashes should be investigated.

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APPENDIX. VALUE OF RESEARCH STATEMENT

Table 21 shows the qualitative value of research.

Table 21. Qualitative Value of Research.

Qualitative Value							
Benefit Area	**Qualitative**	**Economic**	**Both**	**TxDOT**	**State**	**Both**	**Definition in Context to the Project Statement and Value**
Level of Knowledge	X			X			This project will significantly increase TxDOT's understanding and knowledge of the factors that affect surface aggregate selection by defining the factors including their associated characteristics.
Management and Policy	X			X			With positive outcome of research, knowledge, tools, and methods can be used as policy by management for improving the surface aggregate selection criteria.
Materials and Pavements		X			X		The characteristics and factors that affect selection of surface aggregate will help improve the current system.
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 surface aggregates will help improve engineering design accuracy.
Safety			X			X	Reduce risks to the traveling public, due to surface aggregate selection with the goal of reducing wet-weather accidents.

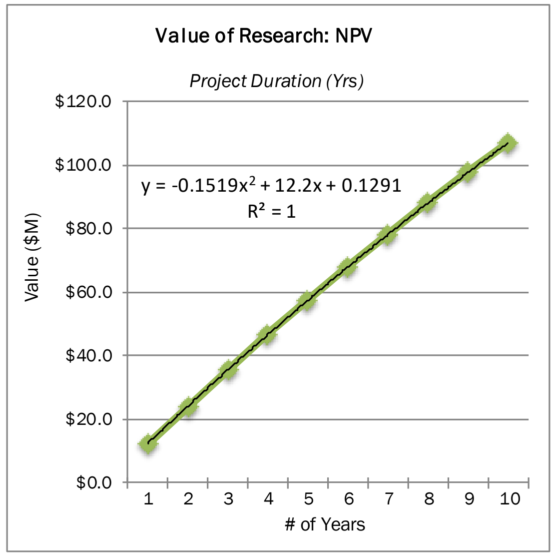
The economic value of research is based on the value of reducing wet-weather accidents. The National Safety Council developed a guide on the costs of motor-vehicle injuries [41]. This guide was used in the development of the economic analysis. A conservative value of a 1 percent reduction per year for 10 years for accidents occurring in a weather condition of rain was used to estimate the potential savings based on improving the WSCRP. This very conservative estimate of improvement provides a significant value based on the cost of research. The results are shown in Figure 15.

VoR	Project #	0-7077		
	Project Name:	SYNTHESIS: EVALUATION SELECTION CRITERIA FOR TXDOT FORM 2088, SURFACE AGGREGATE SELECTION FORM		
	Agency:	TTI	Project Budget	$ 65,000
	Project Duration (Yrs)	1	Exp. Value (per Yr)	$ 11,988,169
	Expected Value Duration (Yrs)	10	Discount Rate	2%

Economic Value

Total Savings:	$ 106,913,224	Net Present Value (NPV):	$ 106,978,224
Payback Period (Yrs):	2.2	Cost Benefit Ratio (CBR, $1 : $___):	$ 1,646
		Return on Investment (ROI, $1 : ___):	$ 1,853.39

Years	Expected Value
0	$0
1	$12,605,988
2	$12,479,928
3	$12,355,129
4	$12,231,578
5	$12,109,262
6	$11,988,169
7	$11,868,287
8	$11,749,605
9	$11,632,109
10	$11,515,787



Variable Justification

Selecting the appropriate surface aggregate characteristics will improve safety during wet condtions. There were 46,591 wet weather (rain) accidents in Texas in 2020 with an estimated value of $1,260,598,800. Improvements resulting in only an 1 percent decrease per year in wet weather related accidents would provide a value of over $10,000,000 per year.

Figure 15. Value of Research.