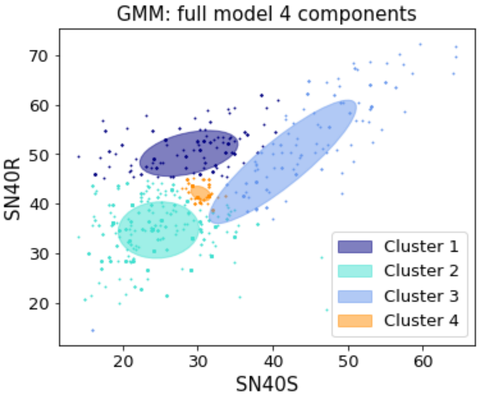
Division of Engineering Research on Call Task 3 --- Investigation on Pavement Friction Demand Categories and Highway Condition-based Friction Demand SN Threshold



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16. Abstract

Though faced with continuously increasing maintenance due to aging infrastructure and limited funding, Ohio Department of Transportation is striving to maintain and improve the efficiency and safety of the state highway system. One of the major tasks is reducing highway crashes. Skid resistance is currently the road surface characteristic that has the best-established relationship with crash risk. ODOT's Highway Safety Section monitors wet/dry pavement crash rates to identify areas of concern and the pavement friction testing are performed and the skid data is collected. It is known that pavement sections have varying friction demand based on the speed, type of facility, geometrics, ingress/egress, and a host of other factors. Unfortunately, there is no straightforward methodology that we are aware of to determine friction demand in terms of friction skid numbers (SN) for different roadway conditions in the current pavement friction management (PFM) system.

In order to address this problem, in this project, a comprehensive review of the current practice of managing skid resistance to address safety concerns was carried out. Then a comprehensive database was constructed from four ODOT-maintained databases. Next, a preliminary friction demand site categories were proposed and discussed with ODOT Subject Matter Experts based on literature and existing pavement management practices. Some criteria in the definition of site categories have been further adapted by analyzing Ohio crash data. Then, based on the proposed friction demand site categories, two strategies have been employed to determine the friction demand for each site category, namely 1) AASHTO method III and 2) clustering analysis. Based on the clustering analysis results, investigatory levels of SN40S and SN40R for each friction demand site category were recommended.

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Table of Content

1 Introduction

Although most highway crashes involve multiple causative factors, previous crash investigations have consistently shown a link between wet crashes and pavement surface conditions/characteristics. Skid resistance is currently the road surface characteristic that has the best-established relationship with wet crash risk. ODOT's Highway Safety Section monitors wet/dry pavement crash rates to identify areas of concern and the pavement friction testing are performed and the skid data is collected. Similar pavement sections may need similar treatment and can be grouped together. Different pavement groups may have different needs for maintenance and remediation. On the other hand, pavement sections have varying friction demand based on the speed, type of facility, geometrics, ingress/egress, and a host of other factors. Unfortunately, there is no straightforward methodology that we are aware of to determine friction demand in terms of friction skid numbers (SN) for different roadway conditions in the current pavement friction management (PFM) system.

1.1 objective

To address the aforementioned problem and provide a technical document for guiding pavement engineers in determining the most appropriate and cost effective solutions for remediating or restoring friction in highway sections where insufficient friction currently exists, there are mainly three questions that need to be answered:

- What is the current status of PFM practices at both national and international level?
- How to synthesize the existing research findings into the best practice for Ohio?
- How to improve the PFM practice and update the developed guidance by using existing and additional data?

In order to answer the above three questions, the main focus of this project is designed as synthesizing the current information available on pavement friction management, listing friction demand variables, determining friction demand categories, and providing recommendations for database preparation and conducting possible exploratory research in advanced machine learning techniques for improving PFM practices and updating the existing guidance. The detailed scope of this project is described in the next section "Scope of Work".

1.2 Scope of Work

This study aims at completing the following three research tasks:

Task 1: Conduct literature search to identify current pavement friction management practices and synthesize them into the best practice for establishing the friction demand categories in Ohio. To be more precise, the main emphasis of this synthesis is listed below:

- Management of friction data;

- Data collection practices;
- Interpretation of data;
- Determination of friction demand;
- Process to remediate unsafe conditions;
- Use of macro texture data collected using laser scanning technology.

Task 2: Based on the information gathered from Task 1, the following items will be accomplished in this task:

- Develop a detailed list of friction demand variables that one would consider when evaluating a location for friction demand.
- Provide a recommendation of Friction Demand by category and threshold for smooth and rib SN 40 numbers.

Task 3: Thoroughly investigating the feasibility of using more advanced machine learning techniques. Major efforts will be spent on the following three points:

- Provide the merits of a machine learning approach, what data is needed, what data is available, and what value this approach would have with missing data.
- Provide guidance to ODOT as to the data most needed for machine learning and to determine friction demand. This will help ODOT determine the significance of and need to gather data not readily available.

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2. Literature Review

2.1 Friction and Texture Measurement Methods

ASTM and AASHTO have developed a set of surface characteristic standards and measurement practice standards to ensure comparable texture and friction data reporting.

The most common method for measuring pavement friction in the U.S. is the locked-wheel method (ASTM 274) (ASTM, 1997). This method is meant to test the frictional properties of the surface under emergency braking conditions for a vehicle without anti-lock brakes. Unlike the side-force and fixed-slip methods, the locked-wheel approach tests at a slip speed equal to the vehicle speed, which means that the wheel is locked and unable to rotate. The results of the locked-wheel test are reported as a friction number (FN, or skid number SN).

Locked-wheel friction testers usually operate at speeds between 40 and 60 miles/hour (64 and 96 km/hour). Testing can be done using a smooth (ASTM E 524) or ribbed tire (ASTM E 501) (Henry & Saito, 1983). The ribbed tire is primarily influenced by micro texture but can still be influenced in part by macro texture, and hence is not very insensitive to the pavement surface water film thickness. The smooth tire is sensitive to both micro and macro texture.

In the United States, ASTM E-274 is used by 38 states and Puerto Rico. 31 states and Puerto Rico use the ASTM E-501 "Standard Rib Tire for Pavement Skid- Resistance Tests", whereas 7 states use the ASTM E-524 "standard Smooth Tire for Pavement Skid-Resistance Test", and 4 states use both tires (JJ Henry, 2000).

The history of the test tire standard evolution (E-249 to E-501 to E-501 + E-524) demonstrates the increased interest in the use of the smooth tire for skid testing. In summary, the ribbed tire was chosen as the test tire for the E-274 locked wheel method for two reasons: (1) a five-ribbed tire was already available as a standard for use in an earlier method, and (2) ribbed tires are not sensitive to the water flow rate. The grooves in the ribbed tire provide channels for the water to flow out of the tire pavement interface. These channels are much larger than the flow area provided by the macrotexture. Therefore, measurements with the ribbed tires are also insensitive to macrotexture, but are predominantly influenced by microtexture.

The side-force method (ASTM E 670) measures the ability of vehicles to maintain control in curves and involves maintaining a constant angle, the yaw angle, between the tire and the direction of motion. Since the yaw angle is typically small, between 7.5 and 20°, the slip speed is also quite low; this means that side-force testers are particularly sensitive to the pavement micro-texture but are generally insensitive to changes in the pavement macro-texture. The two most common side-force measuring devices are the Mu-Meter and the Side-Force Coefficient Road Inventory Machine (SCRIM). The primary advantage offered by side-force measuring devices is the ability for continuous friction measurement throughout a test section (Henry, 2000). This ensures that areas of low friction are not skipped due to a sampling procedure at selected locations (e.g., using locked-wheel friction testers).

Fixed-slip devices measure the friction experienced by vehicles with anti-lock brakes. Fixed-slip devices maintain a constant slip, typically between 10 and 20 percent, as a vertical load is applied to the test tire (Henry, 2000). These devices are also more sensitive to microtexture, as the slip speed is low.

For measuring skid resistance, the majority of the US states use the ASTM locked wheel test method with the standard ribbed tire. Outside the United States, side force and fixed slip methods are commonly used, and the test tires are, in most cases, smooth tread tires. Friction measurements using a ribbed test tire do not adequately assess macrotexture and it is suggested that a macrotexture measurement be made in addition to friction measurements, particularly when the ribbed test tire is used (Henry, 2000).

All above methods are existing techniques for collecting a mechanical or physical response to the given micro or micro and macro texture present to give us an idea on available friction. The derived friction numbers are indicators of the available friction that can be provided by the given surface texture condition to a standard testing tire.

Although recent developments in laser technology have made it possible to measure macrotexture depth, namely mean profile depth (MPD) at highway speeds, such measurements have not been used extensively in the United States. Besides, it needs to be declared that these laser-based systems only attempt to measure macrotexture depth and no other characterization of macrotexture (e.g., shape, pattern, skew, etc.). Therefore, these systems are only attempting to quantify one parameter of macrotexture. The effect of other texture parameters is remaining unclear and may containing certain information regarding pavement friction.

Survey results indicated that five state agencies measure macrotexture depth and only three of these states measure it routinely. Macrotexture evaluation is used much more extensively for pavement management, construction, and surface restoration outside the United States (Henry, 2000). One drawback to laser profile meter is that a pavement’s surface macrotexture does not entirely determine its skid resistance. On the other hand, from the highway surface side, the tire-pavement friction is fundamentally influenced by the micro and macro texture presents. Most measurements made with locked wheel testing systems have been primarily done with ribbed tires, which is mostly sensitive to micro texture. Therefore, correlation between a single surface friction indicator (either macro texture depth or friction number) and skid resistance is often difficult to extrapolate into any general guidance.

A detailed summary of several available devices are shown in Table 1

Table 1: The most adopted friction measurement devices

Device	**Operational Mode**	**% Slip(yaw angle)**	**Speed (km/h)**	**Country**
DWW Trailer	Fixed slip	86	30-90	Netherlands
Griptester	Fixed slip	14.5	30-90	Scotland
Runway Friction Tester	Fixed slip	15	30-90	US
Saab Friction Tester (SFT)	Fixed slip	15	30-90	Sweden
Skiddometer BV-l I	Fixed slip	20	30-90	Sweden
ASTM E-274 Trailer	Locked wheel	100	30-90	US
Dagonal Braked Vehicle (DBV)	Locked wheel	100	65	US(NASA)
Japanese skid tester	Locked wheel	100	30-90	Japan
LCPC Adhera	Locked wheel	100	40-90	France
Polish SRT-3	Locked wheel	100	30-90	Japan
Skidclometer BV-8	Locked wheel	100	30-90	Sweden
Stuttgarter Reibungsmesser (SRM)	Locked wheel, fixed slip	100, 20	30-90	Germany
MuMeter	Side force	13(7.5°)	20-80	UK, US
Odoliograph	Side force	34(20°)	30-90	UK
SCRIM	Side force	34(20°)	30-90	UK
Stradograph	Side force	21(12°)	30-90	Denmark
British Pendulum Tester	Slider	100	10	UK
DFTester	Slider	100	0-90	Japan
IMAG	Variable fixed slip	0-100	30-90	France
Komatsu skid tester	Variable fixed slip	10-30	30-60	Japan
Norsemeter SAUIAR	Variable slip	0-90	30-60	Norway
Norsemeter Oscar	Variable slip, fixed slip	0-90	30-90	Norway
Norsemeter ROAR	Variable slip, fixed slip	0-90	30-90	Norway

2.2 Management of friction data

In June 2010, FHWA issued the new Technical Advisory 5040.38: Pavement Friction Management (PFM) (FHWA, 2010, https://www.fhwa.dot.gov/pavement/t504038.cfm), superseding the previous Technical Advisory 5040.17 (FHWA, 1980): Skid Accident Reduction Program. This new advisory provides guidance to highway agencies towards developing or improving pavement friction management programs (PFMPs) to ensure pavement surfaces are designed, constructed, and maintained to provide adequate and durable friction properties that reduce friction-related crashes in a cost-effective manner. Pavement friction data management is one of the essential components of PFM.

It is generally accepted that agencies should utilize a risk-based approach to determining the frequency and extent of friction testing on the highway network. The facilities with the highest traffic volumes, the highest likelihood of changes in friction over time, and the highest friction demand (the level of friction needed to safely perform braking, steering, and acceleration maneuvers) justify the most frequent monitoring of friction. Many agencies monitor friction on the most important parts of their network on an annual basis. Portions of the network that are lower-risk may justify friction monitoring on a 2 or 3 year cycle. The spatial interval for friction tests is typically 1-2 tests per mile with some US highway agencies performing 3-5 friction tests per mile. The left wheel path is generally considered to have the most traffic due to passing maneuvers and is the most frequently tested. Network friction monitoring is generally not necessary in both wheel paths. Friction test results also have a seasonal variability. If friction testing is performed throughout the year, seasonal variation should be established and the test results normalized to the influence of normal seasonal variation(John Henry, 2000; J. C. Wambold & Henry, 1994). As mentioned above, ideally, friction information should be collected on a network level annually. To achieve good standardized testing conditions, several factors must be considered when collecting friction data and they are shown in Table 2 (Speir, Barcena, & Desaraju, 2009):

Table 2: Factors Affecting Friction Testing (Hall et al., 2009; Speir et al., 2009)

Factors	Consideration
Season for testing	Because significant variations in measured friction may occur across seasons within a given year, friction testing should be limited to a specific season or time of year when friction is typically lowest. This will help maintain some consistency in year-to-year measurements and reduce variability in measured data. For agencies that cannot perform all testing requirements within a given season, the following can be considered to reduce test variability: • Develop correction factors, as needed, to normalize raw friction test data to a common baseline season. • For a given pavement section, initial and subsequent testing must be done within a specific season (e.g., pavement sections originally tested in fall should subsequently be tested in fall).
Test speed	The standard speed recommended by AASHTO T 242 for pavement friction tests is 40 mi/hr (64 km/hr). However, since most agencies conduct friction tests without traffic control and because posted or operational speeds vary dramatically throughout a network, it is very difficult for the operator to conduct testing at just this speed. For such situations, the operator typically adjusts test speeds to suit traffic conditions and to assure a safe operation. Thus, it is recommended that friction values corresponding to testing done at speeds other than 40 mi/hr (64

	km/hr) be adjusted to the baseline 40 mi/hr (64 km/hr) value to make friction measurements comparable and useful.
Test lane and line	Friction measurements must be done in the most heavily trafficked lane, as this lane usually carries the heaviest traffic and is, therefore, expected to show the highest rate of friction loss (worst case scenario).
Ambient conditions	Because ambient conditions can have an effect on pavement friction, it is important to standardize ambient test conditions to the extent possible and document ambient test conditions so the measurements can be corrected as needed. The following should be noted when setting ambient conditions for testing: • Testing in extremely strong side winds must be avoided because these can affect the measurements by creating turbulence under the vehicle that causes the water jet to be diverted from the correct line. • Testing must be avoided in heavy rainfall or where there is standing water on the pavement surface. Excess water on the surface can affect the drag forces at the pavement–tire interface and influence the measurements. • Measurements shall not be undertaken where the air temperature is below 41°F (5°C).
Contamination	Contamination of the pavement surface by mud, oil, grit, or other contaminants must be avoided

2.3 Interpretation of data

The present locked wheel testers for roadway surface friction evaluation are fully automated. As with any testing using subject-driven, instrumented devices, the major concerns of the end usefulness of the testing results are accuracy and precision. Although a level of uncertainty is always inherent to any measurement process, it must also be appropriately quantified or assessed. Therefore, several state DOTs, e.g., Florida Department of Transportation (FDOT) initiated field studies to assess the level of precision of its own locked-wheel testers for field measurements (Choubane, Holzschuher, & Gokhale, 2004). Friction measurements were acquired using multiple friction locked-wheel testers (testing unit) concurrently on a number of asphalt section sites. The collected friction data was first analyzed to determine the friction characteristics at each test location, in terms of a friction number at 40 mph using a standard ribbed (SN40R) and smooth tire (SN40S). The results were then used as a basis for an evaluation of the repeatability (within-unit precision) and reproducibility (between-unit precision) of the friction units. The major findings include 1) a high level of repeatability and reproducibility of the friction measurements was obtained regardless of the surface texture type or level of serviceability; 2) the effect of the surface textures on the friction testers' repeatability and reproducibility was negligible.

According to ASTM E 274, the relationship of observed friction numbers to a true friction level is elusive (ASTM, 1997). Pavement surface characteristics are affected by many variables such as environmental conditions, testing time, site condition, etc., and measured values are only valid until one of these conditions significantly changes. In order to correctly interpret, compare and analyze the measured pavement friction number, Austroads (AGAM05F-09) (Hillier & Soet, 2009) lists factors that can influence the level of pavement-tire surface friction: (Vicroads, 2018):

1. **Vehicle Speed** In dry conditions, the level of surface friction is considered to be constant with increasing vehicle speed. However, in wet conditions, the level of surface friction reduces rapidly with increasing vehicle speed.

2. **Texture** The microtexture (fine scale texture of less than 0.5 mm wavelength) of the surfacing aggregate is the main contributor to sliding contact resistance and is dependent on the actual tire contacting the road. Microtexture is the dominant factor in determining wet skid resistance at low to moderate speeds. Microtexture is still important at high speeds but the macrotexture (coarse texture in the range of wavelength 0.5 mm to 15.0 mm) becomes dominant, as it provides rapid drainage routes between the tire and road surface. This allows microtexture contact to occur and also causes tire rubber deformation. As both components of friction (adhesion and hysteresis) are related to speed, the friction available to the vehicle is not constant during a single braking operation. When a wheel becomes "locked" during braking, microtexture becomes far more significant with the generation of a large amount of heat. The skid resistance of wet roads is reduced by the lubricating action of the film of water on the road surface. Drainage channels, provided by the macrotexture of the road surface and the tread on the tire, assist in removing the bulk of the water and are of increasing importance as the speed becomes higher. A tire can only displace the remaining water film if there is sufficient microtexture on which the tire can build up high contact pressures to establish areas of "dry" contact between the road surface and the tire.

To classify the characteristics of pavement surface texture and their impact on pavement surface performance, the Permanent International Association of Road Congress (PIARC) has defined a scale based on the wavelength of the deviations, which is shown in Figure 1 (PIARCWorldRoadAssociation, 1987).

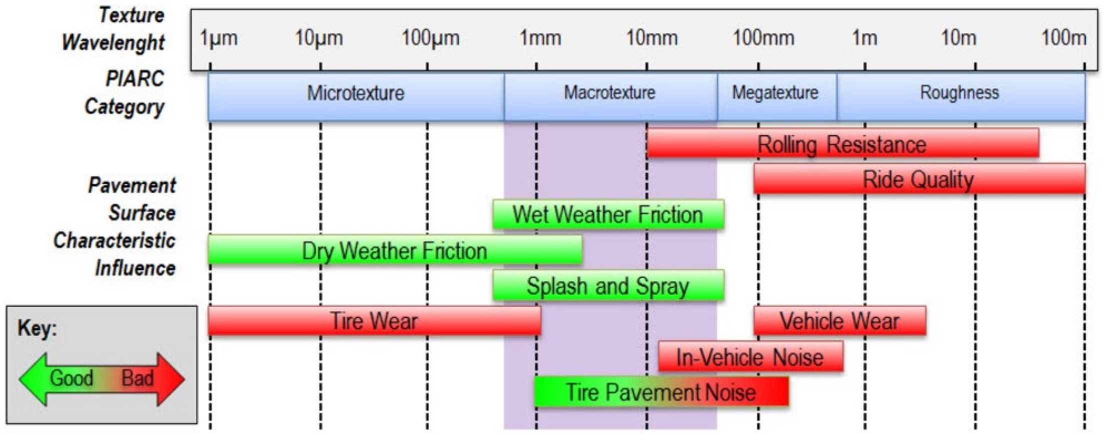


Figure 1. Texture Wavelength (m) Influence on Surface Characteristics

3. **Water Depth and Tire Characteristics** In wet conditions, the degree of contact that can be established between the vehicle tire and the road surface is largely determined by vehicle speed, the capacity of the surface to shed water, the depth of the water film present and the operational characteristics of the tire (tread depth, width, tire pressure). Hydroplaning is the condition where the vehicle tires are completely supported by a layer of water and there is no contact with the road surface. Whilst high speed and a thick film of water on the road surface can encourage a vehicle to hydroplan, a relatively thin layer of water can also cause a problem if combined with low texture depth and "smooth" tires. Although hydroplaning may be uncommon, partial hydroplaning can often occur where a high proportion of tire/road contact is lost. This occurs as a wedge of water builds up at the front of the tire contact area, and extends back as speed increases, thus separating more of the tire from the road.

4. Seasonal Effects During dry periods, the dominant effect of skidding resistance is the polishing of the microtexture under the action of traffic, but when the road is wet for prolonged periods it tends to regain its former harshness. In England during the summer months, surfaces are wet about 15% (Sabey, 1967) of the time and polishing predominates, but in winter the wet surface time rises to about 60% (Sabey, 1967) and they become harsher again. In England, therefore, there is a significant seasonal variation regarding pavement friction (Gargett, 1990). Wet skid resistance appears to change during the seasons with minimum values normally occurring during summer or early autumn. The change between winter and summer can be well over 25% (Gargett, 1990).

5. Temperature Surface friction decreases with an increase in road surface temperature, due to both tires and bituminous materials being visco-elastic. The hysteresis component of the total surface friction reduces as the road surface temperature increases.

6. Road Geometry The highest rates of loss of surface friction are found at sites where the highest vehicle stresses are imparted onto the surface aggregates, such as at tight curves and the approaches to intersections. At these sites, polishing of the surface aggregate occurs more rapidly than on other parts of the network. Crossfall and superelevation will also have an effect on the propensity of water to pond or be retained on a road surface.

7. Surface contamination In addition to water (including ice and snow), the presence of contaminants such as mud, dust, loose gravel, oil, manure etc. results in a lower level of surface friction, when compared to the same road surface in dry, clean conditions.

8. Surfacing Aggregates Locations where severe braking, cornering or accelerating occurs (i.e. high stress locations), the polishing action of traffic is greater and the skid resistance reduces to a lower level than at maneuver-free sites. Consequently, the greatest difficulty in obtaining the required performance of surfacing aggregates is encountered at high stress locations, where high skid resistance is most needed. This is significant because road users are unable to visually recognize any local reduction in skid resistance. Sites where polishing is often found include: approaches to intersections, roundabouts, traffic-signals and railway level crossings, pedestrian and school crossings, curves, and on steep gradients.

9. Surface type and age The level of surface friction provided by some surfacing types (e.g. surfaces that incorporate polymer modified binders, such as stone mastic asphalt and open graded asphalt) immediately after placement can be less than the level that would normally be anticipated. The skid resistance of these surfaces improves to anticipated levels after trafficking removes excess bitumen from the aggregate surface.

For the road surface to play its part in reducing the likelihood of wet weather crashes, the resistance to skidding must be appropriate to the friction demanded by the vehicles. As these demands vary from site to site and from vehicle to vehicle, the corresponding required levels of skid resistance will also vary. Given there is no clear indicator between “safe” and “dangerous” conditions, there is no skid resistance value above which there will be guaranteed freedom from wet weather skidding crashes. As skid resistance increases, its influence as a factor in crashes will be reduced. Vehicle design, speed, road geometry and type and condition of tires are some of the other factors.

Information to consider gathering and assessing when undertaking a site assessment for the influence of skid resistance on crash risk includes: Measured skid resistance; Texture depth; Weather records; Crash history; Road surface condition; Potential for hydroplaning; Traffic volumes, including heavy vehicles; Prevailing speed of vehicles; Road geometry and signing; Properties of road surface aggregate

2.4 Determination of friction demand

Early attempts to relate accident data to skid resistance measured with a ribbed tire were unsuccessful. Rizenbergs et al. (Rizenbergs, Burchett, & Warren, 1977), using accident data from Kentucky, plotted the ratio of wet-to-dry accident frequency against skid number (Figure 2). It is evident from this plot that there is no direct correlation between this measure of wet pavement safety and the skid number measured with the ribbed tire.

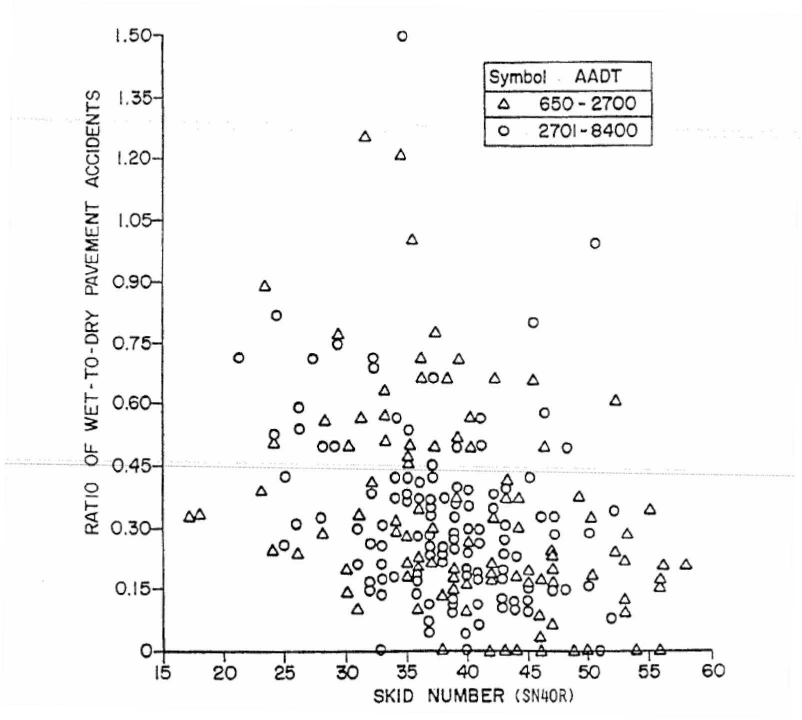


Figure 2 Ratio of wet-to-dry pavement accidents versus skid number (Rizenbergs et al., 1977)

During the late 1970s after the smooth tread tire standard was introduced, there was increased interest in its use, particularly with respect to accident frequency. A 1970 Connecticut study concluded that "A good correspondence between low smooth-tire skid numbers and accident experience can be seen" and "Ribbed-tire correspondence was quite poor" the further concluded that on pavements has smooth tire skid numbers (SN40S) greater than 25 there were fewer wet skidding accidents.

In 1984, the Florida Department of Transportation began collecting smooth and ribbed tread tire data at wet accident sites. They reported data for pavements where more than 50 percent of the total accidents occurred during wet weather and for pavements where less than 25 percent of the total accidents occurred during wet weather. These data are plotted in Figure 3. Note that a horizontal line drawn at SN40S = 25 separated the two categories quite well. Only three accident rate sites have a value of SN40S greater than 25 and only one low accident rate site has value of less than 25. There was no corresponding vertical line at a value of SN40R, which separates the two categories as well. This indicates that the smooth tire skid resistance data are a better indicator of safety than data from ribbed tire measurements.

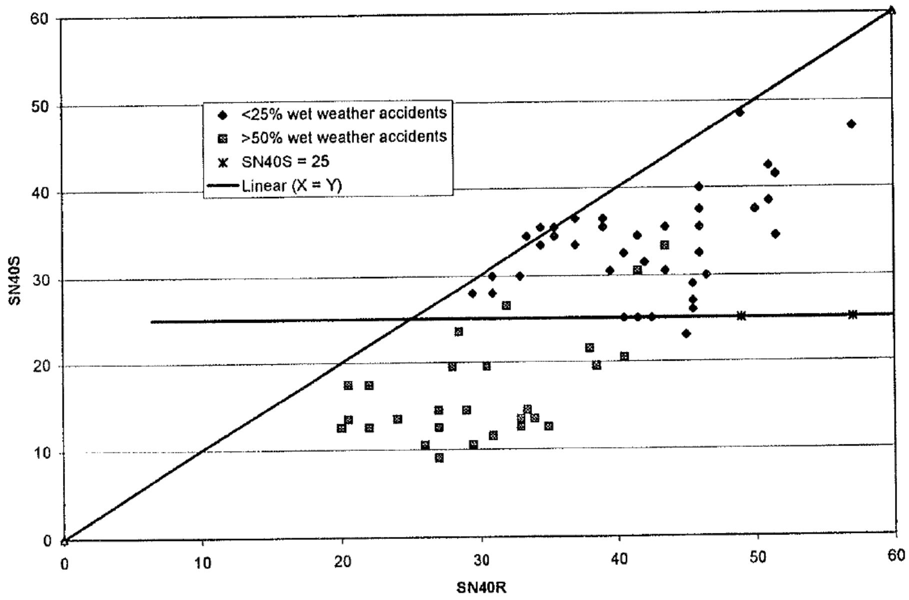


Figure 3 SN40S versus SN40R on accident sites in Florida, adapted from Hewett and Miley (1992)

Najafi, Flintsch, and Medina (2017) conducted a research to link roadway crashes with tire-pavement friction via a case study. They concluded that 1) Friction was found to be a significant factor affecting the ratios of both wet- and dry-condition vehicle crashes on urban roads. Contrary to other studies that only emphasize the effect of friction on wet-condition crashes, this study revealed that friction impacts the rate of dry-condition crashes as well; 2) the relation between skid number and crash rate is not linear and that a logarithmic transformation was necessary for linking the data together. Transformation improved the coefficient of determination (R^2) of the models. In this study, it is mentioned that the American Association of State Highway and Transportation Officials Guide for Pavement Friction Management outlines several methods for highway agencies to establish Investigatory Level (desirable) and Intervention Level (minimum) thresholds for pavement friction and texture (Hall et al. 2009), however, most of these methods require historical data for pavement friction, which are not readily available for most states.

In NCHRP Synthesis 291, “Evaluation of Pavement Friction Characteristics” (JJ Henry, 2000), a questionnaire was designed to determine the current practices used to evaluate the frictional characteristics of pavements in the U.S. and other countries. All 41 states that responded indicated that they performed skid testing on a regular basis along their interstate and primary highway systems. Among these states and one territory, 10 have either suggested or formally established “intervention levels” for minimum acceptable skid resistance levels (Table 3).

Table 3: The intervention levels of some states

Agency	Interstate	Primary	Secondary	Local
Arizona	34(MuMeter)	34(MuMeter)	34 (MuMeter)	
Idaho	SN40S > 30	SN40S > 30	SN40S > 30	
Illinois	SN40R > 30	SN40R > 30	SN40R > 30	SN40R > 25

Kentucky	SN40R > 28	SN40R > 25	SN40R > 25	SN40R > 32
New York	SN40R > 32	SN40R > 32	SN40R > 32	
South Carolina	SN40R > 41	SN40R > 37	SN40R > 37	
Texas	SN40R > 30	SN40R > 26	SN40R > 22	
Utah	SN40R > 30-35	SN40R > 35	SN40R > 35	
Washington	SN40R > 30	SN40R > 30	SN40R > 30	SN40R > 30
Wyoming	SN40R > 35	SN40R > 35	SN40R > 35	
Puerto Rico	SN40R > 40	SN40R > 40		

PFM is an essential component of a good pavement management program. PFM includes detailed definitions of friction levels and friction site categories. Friction levels are typically broken down into two categories: Investigatory Levels and Intervention Levels, which are defined below.

The Investigatory Level is the point in a friction deterioration curve where an agency should start monitoring the friction and/or crash levels more carefully at a particular site and begin the process of planning for some sort of restorative action.

The Intervention Level is the point in a friction deterioration curve where an agency must either take immediate corrective action, such as applying a restorative treatment, or provide proper cautionary measures, such as posting “Slippery When Wet” signs and/or reduced speed signs.

Friction site categories and friction levels are created based on highway features/environment, highway alignment, traffic characteristics, and frictional needs. Consideration should be given to developing friction categories based on highway design speed and traffic information since these factors are directly related to the microtexture and macrotexture needs of a given roadway (Hall et al., 2009). Other factors that are commonly used to develop friction categories and levels include the functional class of the roadway, regional weather patterns (wet/dry), the number of lanes, and the percent trucks on a roadway.

Recently some states have established their own site categories and corresponding friction levels. The Maryland State Highway Administration (MDSHA) has proposed the following friction levels and site categories in Table 4 (Speir et al., 2009). The locked wheel system with ribbed tire is used for friction testing.

Table 4: Site categories and friction Levels proposed by MDSHA

Site Category	Site Description	Threshold SN40R	Investigatory SN40R	Intervention SN40R	Demand Category
1	Approach rail road crossings, traffic lights, pedestrian crossings, Stop and Give Way controlled intersections (SH only).	55	50	45	High
2	Curves with radius=<250m, downhill	50	45	40	High

	gradients > 10% and > 50m long, Freeway/highway on/off ramp.				
3	Approach to intersections, downhill gradients 5 to 10%.	45	40	35	High
4	Undivided Highways without other geometric constraints which influences frictional demand	40	35	30	Low
5	Divided highways without any other geometrical constraints which influences frictional demand.	35	30	25	Low

Ohio Department of Transportation conducted a research project to determine if surface characteristic measurement can be correlated to wet-weather accidents. Two different regression analysis approaches were tried: 1) single variable regression analysis that looked at the influenced of one variable at a time on crashes, and 2) multiple linear analysis approach that looked at the influence of chosen combinations of different variables on crashes. While hopeful that one of these two approaches would uncover a strong correlation between at least one of the surface-related variables and crashes, no such strong correlation was discovered. Therefore, the one primary conclusion from the study is that there was not one single variable (i.e., SN40R, SN40S, macrotexture, or even wet/total crash ratio) that was found to be a good surrogate for identifying sections needing a skid resistant overlay or for proactively predicting crash rates. Because of this conclusion, ODOT proposed a similar approach as New York SKARP procedure until better predictive models can be developed that incorporate laboratory testing information of the various mix designs used in ODOT. The proposed site categories and corresponding friction levels, which can be conducted in a three-step form (Larson, Hoerner, Smith, & Wolters, 2008). The details are shown in Table 5.

Table 5: Site categories and friction Levels proposed by ODOT

Check	Variable	Intervention Level	Investigatory Level
1	a. If wet/total crash rate, and	>=35 percent	>=25 percent
	b. Annual average number of wet pavement crashes (2 or 3 year average), then	>3 for rural settings >5 for urban settings	>2 for rural settings >3 for urban settings
	c. Check minimum friction number	SN40R < 32 or SN40S < 23	SN40R < 42 or SN40S < 32
2	Minimum macrotexture	Use the appropriate MTD value from table 8 in chapter 4	< 0.04 in (1.0 mm) (sand patch) (Based on UK criteria)

3	Roughness spikes based on 20-ft (6.1-m) sliding base length	Use current ODOT requirements	> 300 in/mile (4.7 m/km)

Utah DOT launched their Skid Correction Program in 2013 (Anderson, 2012) to identify and reduce the negative safety impacts associated with unacceptable levels of skid resistance on pavement surfaces. The suggested critical friction numbers are shown in Table 6. The ribbed tire skid number is used for setting the criteria.

Table 6: Friction demand values suggested by Utah DOT

Functional Class	Unacceptable (SN40R)	Marginal (SN40R)	Acceptable (SN40R)
Interstate Highways	Less than 30	30 to 40	Greater than 40
Non-Interstate Highways	Less than 35	35 to 45	Greater than 45

The UK has implemented a policy for managing the skid resistance of its trunk road network since 1988 and was reviewed and modified in 1998 (Roe, Parry, & Viner, 1998). The revised site categories and investigatory levels are shown in Table 7, where dark shading indicates the range of investigation levels that will generally be used for roads carrying significant levels of traffic; light shading indicates a lower investigation level that will be appropriate in low risk situations, such as low traffic levels or where the risks present are mitigated, providing this has been confirmed by the crash history; none shading on the left side indicates friction level cannot be tolerated while on the right side indicates no friction problem. Exceptionally, a higher or lower investigation level may be assigned if justified by the observed crash record and local risk assessment.

Table 7: UK site categories and investigatory levels

Site category and definition		Characteristic Skid Coefficient (CSC) Investigatory level at 50km/h							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
A	Motorway	░	■						
B	Dual carriageway non-event	░	■	■					
C	Single carriageway non-event		░	■	■				
Q	Approaches to and across minor and major junctions, approaches to roundabouts				■	■	■		
K	Approaches to pedestrian crossings and other high risk situations					■	■		
R	Roundabout				■	■			
G1	Gradient 5 to 10% longer than 50m				■	■			
G2	Gradient > 10% longer than 50m				░	■	■		
S1	Bend radius < 500m – dual carriageway				■	■			
S2	Bend radius < 500m – single carriageway				░	■	■		

The state of Victoria, Australia developed their site categories and investigatory levels in Table 8, where dark shading indicates investigation level of roads with more than 2500 vehicles per lane per day and light shading indicates investigation level of roads with less than 2500 vehicles per lane per day, while cells with none shading indicates roads with no friction problem. The SCRIM coefficient identified with the test speed 20km/h (SFC20) or 50 km/h (SFC50) is adopted as the friction indicator.

Table 8: VictRoads site categories and investigatory levels

Site Category	Site Description	Investigatory Levels of SFC50 (At 50 km/hr or equivalent – as reported) (For 6 and 7 use Investigatory Levels of SFC20)						
		30	35	40	45	50	55	60
1	• Signalized intersections • Pedestrian/school crossings • Railway level crossings • Roundabout approaches	▨	▨	▨	▨	▨	■	
2	• Curves with radius ≤ 250 m and > 100m • Gradient ≥ 5% and ≥ 50 m long Freeway/highway on/off ramps	▨	▨	▨	▨	■		
3	Intersections	▨	▨	▨	■			
4	Maneuver-free areas of undivided road	▨	▨	■				
5	Maneuver-free areas of divided road	▨	■					
6	Curves with radius ≤ 100 m	▨	▨	▨	▨	▨	▨	■
7	Roundabouts	▨	▨	▨	▨	▨	■	

The Queensland Department of Transport and Main Roads (Australia) (QDMR) used the Norsemeter ROAR (Road Analyzer and Recorder) device to measure skid resistance that is expressed in terms of the International Friction Index. QDMR also developed site categories and corresponding investigatory levels of skid resistance shown in Table 9. The International Friction Index (IFI) is adopted as the pavement friction indicator. It reports the frictional properties of a pavement with two terms: the speed constant, S_p, which is a function of the pavement macrotexture and the friction number F60, which depends on a measured friction value, the slip speed and the speed constant (J. Wambold, Antle, Henry, & Rado, 1995). The speed constant is used to adjust the friction values measured at any slip speed to a friction value at 60 km/h.

Table 9: QDMR ROAD investigatory level of skid resistance

Skid resistance demand category	Description of Site	F60 investigatory level		
		40-50 km/h	60-80 km/h	100-110 km/h
High	Curves with radius <= 100 m. Roundabouts. Traffic-light-controlled intersections. Pedestrian/school crossings. Railway level crossings. Roundabout approaches.	0.30	0.35	NA

Intermediate	Curves with radius <=250m. Gradients >5% and >50m long. Freeway and highway on/off ramps. Intersections. Curves with advisory speed >15km/h below speed limit.	0.25	0.30	0.35
Normal	Maneuver – free areas	0.20	0.25	0.30

South Australia Department of Planning Transport and Infrastructure (SADPTI) recommended that skid resistance maintenance strategies should be based on the investigatory levels for skid resistance (micro-texture) and macrotexture. And hence two different site categories and investigatory levels are suggested for skid resistance and surface texture separately. The site categories and investigatory levels are shown in Table 10 and 11. Grip Number (GN or Grip No.) is the coefficient of friction as measured by the GripTester.

Table 10: SADPTI recommended skid resistance investigatory levels (Griptester)

Road Situation	Minimum Grip No.	Maximum Vehicle Speed k/h
Difficult sites - steep grades, traffic light approaches, tight bends, roundabouts.	0.50-0.55	60-80
Urban Arterial Roads	0.45	60
Rural Arterial Roads	0.45	110
Urban/Lightly Trafficked	0.40	60
Urban Arterial Expressway	0.45	90-100

Table 11: SADPTI typical indicative investigatory levels for surface texture

Road function	Texture depth MTD (mm)
Freeways and other high-class facilities with free-flowing traffic conditions	0.4
Highways (greater than 80km/h) Other major main roads to stopping and turning (less than 80km/h)	0.6
Other local roads (sealed)	0.4
'Guide to the selection of road surfacings', (2003), AP-G 63-03, Austroads, Sydney.	

Transit New Zealand developed their own definition of site categories and investigatory levels (Cenek, Davies, Loader, & McLarin, 2004). Transit New Zealand's policy for skid resistance is largely contained within the T/10 specification. This specification was introduced in 1998 and aims to standardize the risk of a wet skid crash across the State Highway network by assigning investigatory skid resistance levels for different site categories, which are related to different friction demands. A description of these site categories and associated investigatory levels are summarized in Table 12.

Table 12: Transit New Zealand T/10 Skid Site Categories

Site category	Description	Notes	Investigatory level (SC)
5	Divided carriageway		0.35
4	Normal roads	Undivided carriageways only	0.4

3	Approaches to road junctions		0.45
2	Curve < 250m radius Gradient > 10%		0.5
1	Highest priority	Railway level crossing, approaches to roundabouts, traffic lights, pedestrian crossings and similar hazards.	0.55

In McGovern, Rusch, and Noyce (2011), several state practices to reduce wet weather skidding crashes and define friction demand were reported. They are listed below:

1) California: In 1972, Caltrans developed their Traffic Accident Surveillance and Analysis System (TASAS) to identify high-collision concentration locations. Included in this system was a methodology for identifying locations with a high concentration of wet crashes known as Wet Table C. Caltrans State Office of Traffic Safety Program analyzes the crash data to develop the Wet Table C on an annual basis. The Wet Table C identifies locations with a minimum of 9, 6, or 3 wet crashes within a 36-, 24-, or 12-month period, respectively and are significantly higher than the statewide average. Wet collisions are identified by those with a road surface coded as “wet.” A significance test is conducted to determine if the defined highway segments, ramps, or intersections have a wet crash count significantly higher than the number of crashes required for significance (NR). For a segment to have significantly high crashes, the segment crash count must be greater than or equal to NR. For each location identified in Caltrans’ Wet Table C, a safety investigation is conducted. Relevant data are gathered and analyzed to identify contributing factors and potential countermeasures. The most effective improvement strategy is then employed using crash details, such as a site’s collision history, field investigation, friction test results, a review of the site’s geometrics, and additional data elements to investigate crash patterns, such as direction of travel and time of day.

2) Michigan: The investigation of the sites identified by the Safety Programs Section with a skid number of less than 30 (SN40R) is carried out by the individual regions. The regions consider four factors in the evaluation:

- Wet surface friction tests result is less than 30 (SN40R);
- Estimated reduction in wet crashes is equal to at least three crashes per year per spot (intersection approach) or 0.5-mile segment location;
- A field review to identify factors not related to surface friction qualities, such as “wheel tracking” or a clogged drainage structure that may contribute to a higher percentage of wet crashes; and
- The time-of-return on the investment is five years or less.

3) New York: During April of each year, the Office of Modal Safety and Security identifies locations with high wet crash frequencies and prepares the Priority Investigation Location (PIL) list. The tests are conducted with a skid trailer according to ASTM E 274 requirements using a ribbed tire meeting ASTM E 501 requirements. The Wet Road Accident PILs are categorized into two classes depending on the friction test results:

Class 1 – Locations where one or more friction test results are below 32 (FN40R); or

Class 2 – Friction test results are greater than or equal to 32 (FN40R).

Following the friction testing, the results are transmitted to the regions for review and consideration in the regions' capital programming and preventive maintenance paving activities. The regions must investigate all locations with a friction number below 32. All sites with a friction number less than 26 must be remediated immediately. A friction number of 32 provides a stopping distance consistent with AASHTO design standards for highway sight distance and is consistent with design requirements for curves. A friction number of 26 was identified as a threshold coefficient of crash frequency based on analysis of wet weather PIL locations that had been friction tested.

4) Florida: The State Safety Office conducts an analysis to identify wet weather crash locations on the state roadway network using Florida's Crash Analysis Reporting (CAR) System. For identifying wet weather crash locations, the State Safety Office conducts an analysis of wet weather crashes on the state roadway network using five years of crash data through the CAR system. The analysis identifies sections with either a minimum of four wet weather crashes with 25 percent or more wet weather crashes or 50 percent or more wet weather crashes during a five-year period. The analysis uses a sliding window with 0.3-mile segments and increments of 0.1 miles. Skid tests are typically conducted at a speed of 40 miles per hour in the left wheel path using a standard two-wheel trailer towed by a one-ton pick-up truck conforming to ASTM E 274 requirements. District Safety Engineers (DSEs) review the most recent friction test results of the identified segments to determine if the friction number is low, 28 (FN40R) or less for posted speed limit of 45 miles per hour or less and 30 (FN40R) or less for posted speed greater than 45 miles per hour. If the friction number is low for locations identified through the crash analysis, the DSEs review the work program to determine if the roadway is programmed for resurfacing. When the location is not included in the work program, the DSE must further investigate the site to identify potential contributing crash factors. The DSE reviews the traffic crash reports and field conditions (e.g., geometrics, surface condition, drainage, etc.). If inadequate pavement friction is identified as a contributing factor, the DSEs identify the appropriate mitigation techniques.

5) Virginia: In 1976, the Virginia Transportation Research Council (VTRC) developed a procedure for systematically identifying and evaluating wet crash sites or low skid number sites and established the Wet Accident Reduction Program (WARP). The Traffic Engineering Division conducts an analysis of the crash data on an annual basis to identify Potential Wet Accident Hotspots (PWAH). Crashes are located at 0.1-mile intervals and serve as the principal database for identifying PWAHs. The identification process is as follows: 1. Crashes involving snow and ice are discarded. 2. Crash files are scanned by district, county, route, and mile point. 3. When a wet weather crash is registered, an additional 0.2 miles on either side of the site is scanned for additional wet weather crashes. 4. If one or more wet weather crashes are found, an additional 0.2 miles of the road is scanned for wet weather crashes. 5. Locations are classified as PWAHs when: a. There are a minimum of three wet weather crashes, each separated by less than 0.2 miles; and b. The proportion of wet weather crashes (wet/(wet+dry)) is at least 20 percent higher than the ratio for all roads in the area. PWAH locations are tested using the following guidelines:

- Tests are conducted at a minimum frequency of one test for every 0.1 mile; for sites less than 1 mile in length, as many tests as possible are conducted with up to one test for every 0.05 mile.
- Unless a jurisdictional or construction project interferes, each section should have a minimum of three tests evenly spaced at 0.1-mile intervals beyond the limits of the referenced site (both before and after). If the skid number is less than 24 (SN40S), the sections are extended until three consecutive skid numbers greater than 24 (SN40S) are recorded. This ensures that any questionable areas are accurately identified.
- If possible, a minimum of one test is conducted within 200 feet prior to an intersection with a stoplight or stop sign.
- Data is reported by county-relative mileposts. Straight line diagrams from the Highway Traffic Records Inventory System (HRTIS) are used by the operator for reference and locating starting nodes in the field.
- Friction test results are uploaded into the HRTIS at the completion of testing for a district.

Locations with a friction number less than 20 (SN40S) are flagged for review by the districts. A friction number of 20 (SN40S) was selected as the threshold, to be consistent with other agencies. However, a more recent study conducted by VTRC and Virginia Tech has recommended use of a higher value (25-30).

2.5 Process to remediate unsafe conditions

According to the 2011 State Practices to Reduce Wet Weather Skidding Crashes (McGovern et al., 2011), the states have been focusing on spot improvements. While many of the states are implementing systematic improvements, such as rumble strips and raised pavement markings, no state has implemented systemic improvements focused specifically on addressing skidding-related wet weather crashes (McGovern et al., 2011).

Table 13 provides a summary of the mitigation techniques used by several states to improve pavement friction.

Table 13: State mitigation techniques

State	Mitigation Techniques
California	Improvements include super-elevation changes, open-grade asphalt concrete (OGAC) overlays, pavement grooving, high-friction surface treatments, or drainage improvements.
Florida	A specification for asphalt concrete friction courses has been developed for ramps, curves, or other locations with wet weather crashes. Specific provisions are provided for different aggregates usages, including the use of granite. Florida is currently working on specifications for hybrid mixes with granite and limestone. The District 4 office (Broward County) has experimented with the use of high-friction surface treatments in areas were friction-based crashes are a concern.
Michigan	If an identified location is not in the current work plan for resurfacing, typically the regions will do an overlay, ultrathin overlay, mill and resurface, microsurfacing, paver placed surface seal, chip seal, or diamond grinding. Signing is used only as a short-term solution.
New York	Treatments typically include resurfacing with one and one-half inches of hot mix asphalt using the appropriate friction aggregates, or a thin cold emulsion microsurfacing (using noncarbonate aggregates). Superpave hot mix asphalt is the standard for New York State contracts.
Virginia	For asphalt pavement, micro surface treatments are widely used to restore pavement with inadequate friction characteristics. Seal coats or chip seals are also used to restore pavement friction characteristics and extend the life of pavements. Depending on the pavement distress condition, the section could also be overlaid. For Portland Cement Concrete (PCC) pavements, diamond grinding increases concrete pavement friction. Saw cut grooving (longitudinal or transverse) is used traditionally to restore adequate frictional characteristics of PCC pavements.

It needs to be noticed that site investigation are a key element for identifying appropriate mitigation techniques for locations identified as potential wet weather crash locations.

2.6 Use of macro texture data collected using laser scanning technology.

Because all friction test methods can be insensitive to macro-texture under specific circumstances, it may be valuable to complement the data with macro texture measurement. Currently, there are two different types of macro-texture measurement devices: “static” and high-speed measuring devices.

“Static” macrotexture measuring device

The CT Meter ((Hanson & Prowell, 2004)) is a recognized standard device used to measure the pavement macrotexture in the U.S. and has mostly replaced the sand patch test. The CT meter is a widely accepted device for measuring macrotexture in the transportation engineering community. The test procedure is presented in ASTM E2157. The CT Meter uses a laser to measure the profile of a circle 284 mm (11.2 in) in diameter or 892 mm (35 in) in circumference. (See Figure 4 for a picture of the CT Meter.) The profile is divided into eight segments of 111.5 mm (4.4 in). The average mean profile depth (MPD) is determined for each of the segments of the circle. The reported MPD is the average of all eight segment depths.

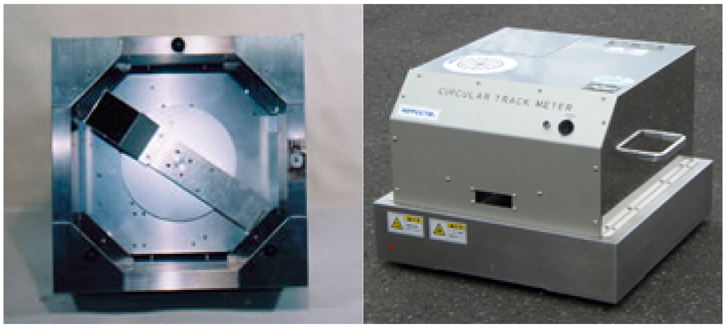


Figure 4. The CT Meter

High-Speed Macro-texture measuring device

High-speed devices use laser-based sensors to collect a high-resolution profile of the pavement surface and determine the macrotexture at higher speeds. These systems can be easily installed on a vehicle to collect data at regular traveling speeds. High-speed macrotexture measuring devices include the Dynatest Laser Profiler, Ames system, and SCRIM system (Keeney, 2017). ODOT Office of Technical Services (OTS) has been operating an inertial road profiler with a laser macrotexture subsystem, and collecting a large amount of data using the profiler. In 2017, Keeney et al. conducted a research on comparing two available high-speed macrotexture measuring devices: 1) laser module on a SCRIM system, and 2) portable Ames system. The SCRIM system is a multi-function pavement evaluation system that can measure the pavement macrotexture and friction, along with GPS location, road geometry (gradient, cross-slope, and curvature) and front video to provide supplemental information on the area of interest. The Ames 8300 Survey Pro High Speed Profiler is a portable system that simultaneously collects macrotexture and profile data using high-speed laser sensors that can be mounted on the back and/or front end of a vehicle. The system also has a GPS, forward facing camera, temperature gauge, speed gauge, distance monitor, and a battery power reader. The system uses a LMI-Selcom Optocator 2008-180/390 texture sensor rated at 62.5 kHz (Olmedo, Leal, Cimini, & Springer, 2015) and is set up to operate between 25 and 65 mph. To provide good readings, the sensor has to be located within 180-mm from the pavement surface. Several findings from this study are listed below:

1) Both system showed good repeatability, with an average repeatability of 0.105 mm for the Ames system and 0.113 mm for the SCRIM system.
2) The Ames system produced measurements that are closely comparable with those produced by the CT Meter.

3) The SCRIM system producing measurements that also correlate very well with the CT Meter but the measurements are consistently lower, showing an average bias of -0.231.
4) The Ames systems produce measurements that are on average 0.238 mm higher than the SCRIM measurements
5) Both system failed to produce accurate measurements on the longitudinally textured concrete section.

3. Data Source and data processing

3.1 General description

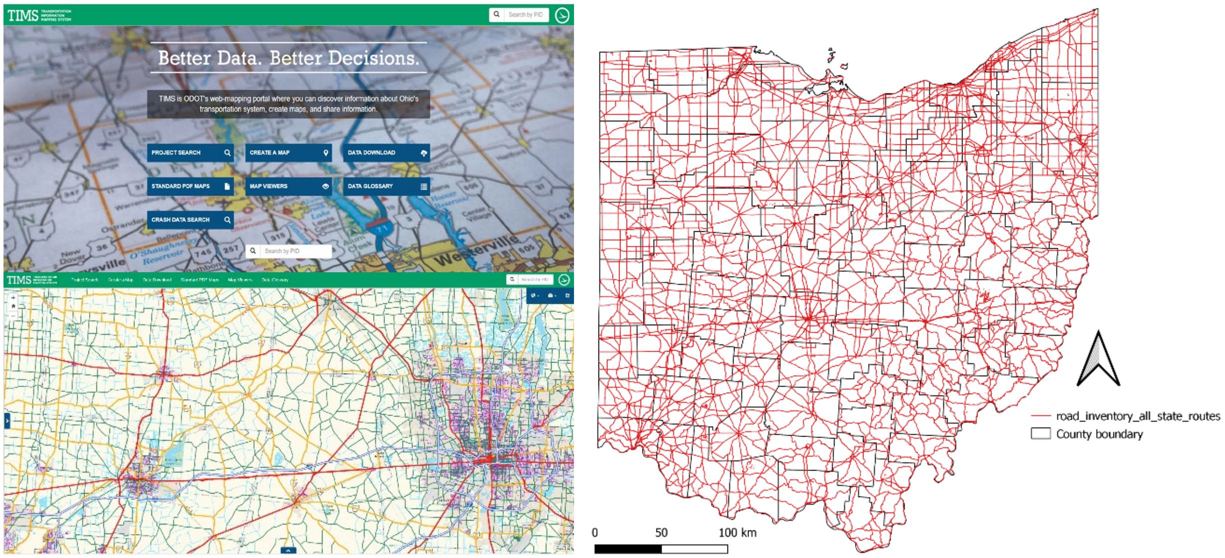
Traffic crashes are complex events that result from a combination of driver-related, vehicle-related, and highway-related factors. In order to support a roadway safety study such as the present project, several types of data are needed, namely crash data (which contains driver, vehicle, weather, and other crash-related information), pavement condition data, roadway inventory data, and traffic data.

During this research project, ODOT provided a number of different data files and data sources to the research team. These data files and data sources include geo-referenced roadway inventory, traffic volume, and crash data. In separate data tables, ODOT provided multiple years (2011-2018) friction testing results at selected locations using both ribbed tire and smooth tire locked wheel testing systems, which were at project level. All of the data from different sources needed to be cleaned, preprocessed, and linked together.

3.2 ODOT road inventory data

In this research project, we extracted the roadway database from the Roadway Information System (RIS). RIS is a database of various physical and administrative data related to the roadway networks that are either maintained by or are of special interest to ODOT. This collection of highway information is maintained by the Office of Technical Services, Transportation Information Management Section (TIMS).

Ohio's roads are represented as segments in ODOT's RIS and have associated data elements that describe roadway geometrics and characteristics. All road segments are identified with a unique key database field, called NLFID, through which attribute data elements can be linked. By specifying the NLFID, we select all state route segments from the road inventory database.



Better Data. Better Decisions.

TIMS is ODOT's web-mapping portal where you can discover information about Ohio's transportation system, create maps, and share information.

Figure 5. ODOT's Roadway Information System (RIS) and the state route network

3.3 ODOT annual average daily traffic (AADT) and speed zone data

The annual average daily traffic (AADT) and speed zone data are also available from RIS and they are also geo-referenced (Figure 6). All the raw data files (i.e., ArcGIS shape files) were downloaded from RIS and preprocessed (selecting state routes and linking together different datasets) by the open-source GIS software QGIS (QGISDevelopmentTeam, 2015).

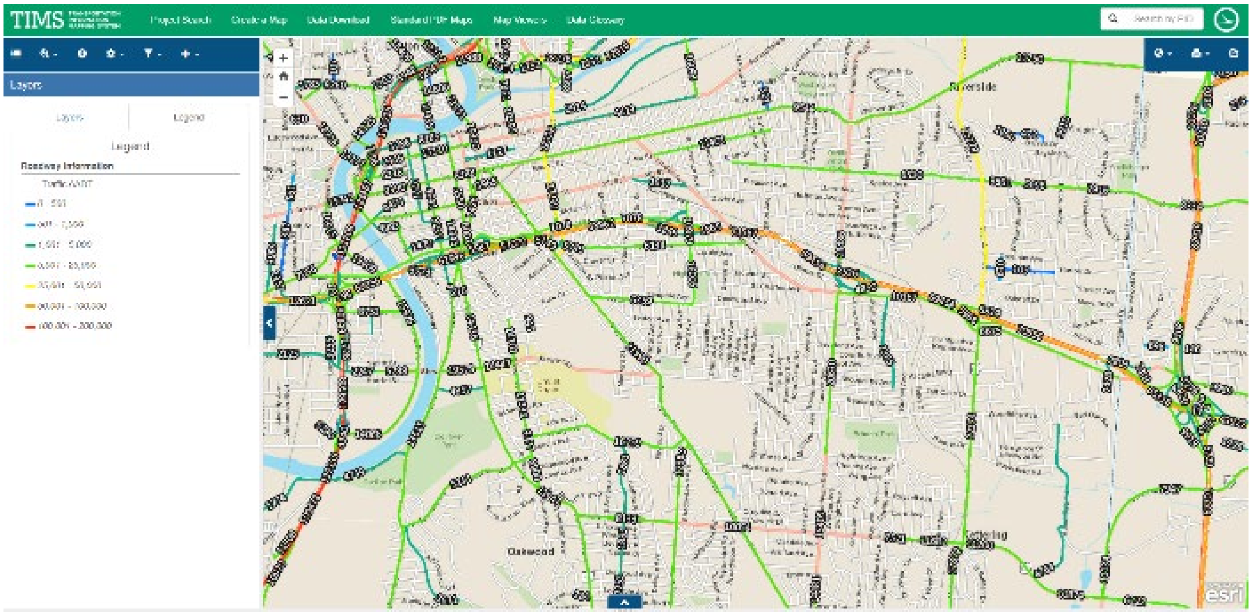


Figure 6 AADT map from RIS

3.4 ODOT crash data

The crash data comes from the GCAT (GIS Crash Analysis Tool). GCAT uses GIS to produce data entries that are spatially located (valid latitude/longitude coordinates). GCAT provides a convenient highway safety crash analysis tool for ODOT, metropolitan planning organizations (MPOs) and county engineers.

The crash data from GCAT is provided by the Ohio Department of Public Safety. The data obtained for this study contains detailed crash information for the period 2015 to 2018. The crash data for each year are stored in a text file format (.csv text file) and subdivided into four separate files subject to the maximum size for data downloading. For this study, only the crash data were used. No information regarding personal identification, vehicle type, or citations were of interest, or use, in this study.

3.5 ODOT Friction Testing data

Multiple years (from 2011 to 2018) friction testing data using locked wheel systems were provided. Both ribbed and smooth tire testing results are available. All of ODOT's data was collected at 40 mph with minimal tolerance. ODOT does not currently have a network-level friction measurement database. All friction testing jobs were conducted at a project level and documented using a spreadsheet. Friction testing was completed at each site using both a ribbed tire (ASTM E 501) and a smooth tire (ASTM E 524) at 40 miles/hour. Pavements in both directions were tested. The friction testing results were recorded together with GPS coordinates of each testing points as well as the mile-point along the roadway alignment. In this study, four years data (2015-2018) were used. The number of friction readings are summarized in Table 14.

Table 14: summary of the number of friction readings

	2015 (46 projects)		2016 (33 projects)		2017 (42 projects)		2018 (21 projects)	
	SN40S	SN40R	SN40S	SN40R	SN40S	SN40R	SN40S	SN40R
Number of readings	2767	2766	1370	1262	2492	2568	1600	1514

3.6 Data processing

The four data sources, namely road inventory, AADT, crash, and friction were originally designed and developed to serve different management goals for ODOT; therefore, each database was developed with specific standards regarding the referencing system used (e.g., NLFID and county milepoints, GPS locations, road segments with control begin and end locations). In order to create a comprehensive database, the four data sources had to be integrated based on a single referencing system to ensure proper spatial relationships of crashes, friction data, and geometric and traffic features. Data integration is only feasible if these data sources share the same referencing system so that information from different sources can be correctly linked. Therefore, understanding the definition of each referencing system and how they are employed for each data source is extremely important for identifying the appropriate data integration approach.

A Linear Referencing System is a system that incorporates a technique for identifying the location of a point or a segment along the highway system by retrieving the spatial information stored and maintained in each database. According to ODOT roadway information manual (Kidner, 2013), Ohio's roads are represented as linear segments in ODOT's RIS and have associated data elements that describe roadway geometrics and characteristics. All road segments are identified with a unique key database field, called NLFID, through which attribute data elements can be linked. Each NLFID segment is further divided into multiple roadway pavement friction management (PFM) sections with CONTRAL_BEGIN and CONTRAL_END milepoints. Therefore, any point event can be identified by using milepoint along a specific NLFID segment and any local roadway geometrical information can be derived from the data of the specific PFM section with defined CONTRAL_BEGIN and CONTRAL_END. It needs to be clarified that the roadway PFM sections with corresponding CONTRAL_BEGIN and CONTRAL_END milepoints are the basic elements during the data processing.

In the crash database, the county log number (i.e., the milepoint) along the NLFID segment is used to locate the crash events. In the friction database, each friction reading has a milepoints (i.e., the county log number) and also the nearest CONTRAL_BEGIN and CONTRAL_END milepoints. The road inventory and AADT data have complete geometrical information and traffic volume of PFM sections, which can be referred to using NLFID and CONTRAL_BEGIN and CONTRAL_END milepoints. Therefore, the four database can be linked together and the linking process is shown in Figure 7. As briefly discussed above, both crash data and friction data have milepoint or county log number information, if the linear referenced distance between a crash event and a friction reading is less than 0.1 mile, this crash event can be linked with the pavement friction measurement. On the other hand, each friction reading was recorded with the nearest CONTRAL_BEGIN and CONTRAL_END milepoints and the NLFID, which can be utilized to extract the corresponding geometric information from the road inventory database.

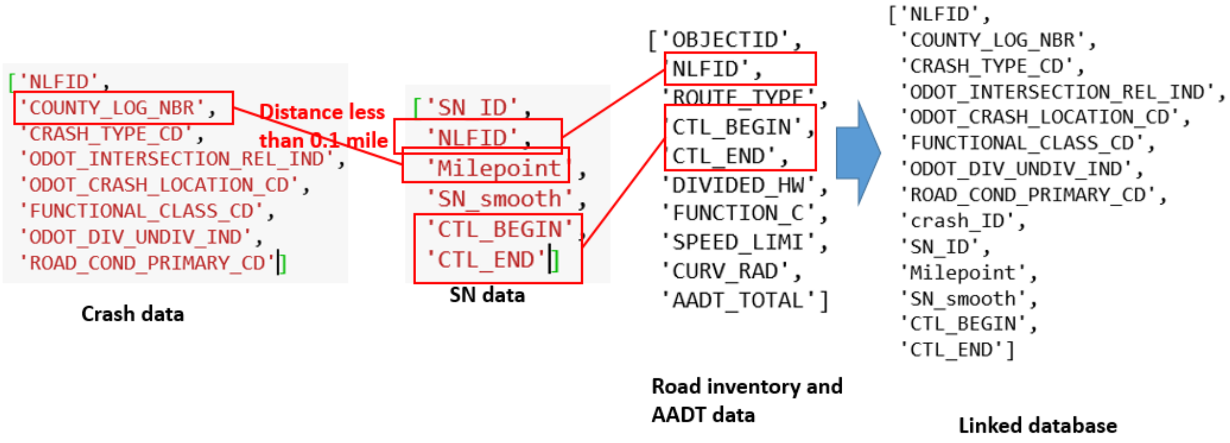


Figure 7. Linking information from four databases

In summary, an integrated database was developed in support of this analysis using the aforementioned data sources. The integrated database contains reliable data providing sufficient information for the analysis. In the next section, the integrated database will be used to quantify the relationship between crash risk and skid resistance of different pavement friction site categories.

4. Data analysis

4.1 Defining preliminary pavement friction demand site categories

According to Hall et al. (2009), ideally, friction demand categories should be established for individual highway classes, facility types, or access types. Also, the number of demand categories should be kept reasonably small (say, 3 to 5 per highway class, facility type, or access type), so that a sufficient number of pavement friction management (PFM) sections are available for each category from which to define investigatory friction levels. ODOT subject matter experts closely collaborated with the research team in discussing and defining the friction demand site categories based on literature search and engineering experiences.

It should be noticed that determining and refining the friction demand site categories and corresponding criteria is an iterative process, which involves initial (or current) friction demand categories – data collection and analysis – testing and validation – refined (or updated) categories. As this project is considered to be the initial effort. We are aiming at first setting up the preliminary friction demand categories, and then conducting the first iteration using existing Ohio data, which was described in the above section.

The proposed preliminary site categories is shown in Table 15 and the details in determining the preliminary criteria for site conditions with priority are provided in the following Section 4.2. Some potential issues could be identified from Table 15. For example, due to mix of speed ranges within and between the categories, there exists possible overlapping among the criteria of different fiction demand categories. Some modifications on the site condition with priority will be proposed based on unsupervised machine learning analysis in the following sections.

Table 15: Preliminary friction demand site categories

Friction demand category	**Preliminary General site condition**	**Preliminary site condition with priority (additional friction demand is needed)**
C_1 High	• Undivided roadway sections with geometric constraints (limited sight distances according to design speed and/or tight horizontal curves); • Divided or undivided roadways at signalized intersections; Pedestrian/school crossings; • Railway crossings; • Roundabout approaches; • Interstate ramps with high speed limit at service interchanges with stop condition;	Satisfying general condition and with at least one additional following condition: 1) Speed limit >= 40 mph with traffic (ADT) >15,000; 2) a. Curvature radius < 525 feet with speed limit <45mph; b. Curvature radius < 590 feet with speed limit (45~55mph); c. Curvature radius < 820 feet with speed limit (55~65mph); d. Curvature radius < 1870 feet with speed limit >=65mph; 3) Speed limit > 40 mph where pavement with rutting issue (refer to Section 4.3 for details).

	- Interstate to interstate ramps at service interchanges without stop condition.	
C_2 Moderate	- Urban Arterial Roads; - Divided highways with geometric constraints (limited sight distances according to design speed and/or tight horizontal curves), - Undivided highways without any other geometrical constraints which influences friction demand; - Maneuver-free areas of undivided road; - Ramps associated with lower speed limit at service interchanges;	Satisfying general condition and with at least one additional following condition: 1) Speed limit > 55 mph with traffic (ADT) > 10,000; 2) a. Curvature radius < 2300 feet with speed limit < 45mph; b. Curvature radius < 3400 feet with speed limit >= 45mph;
C_3 Low	- Divided highways without any other geometrical constraints which influence friction demand; - Maneuver-free areas of divided roads; - no ramp in this category	Satisfying general condition and with the additional following condition: Speed limit > 60 mph with traffic (ADT) > 5000. General condition does not include curvature issue,

4.2 Analysis using Ohio data for determining preliminary criteria of Site condition with priority

A quantitative analysis on Ohio crash data was performed to determine the criteria for identifying the site conditions with priority, which contains the following four steps (take Site Category_1 (C_1) “High” for example):

Step 1: Draw the scatter plot of all road sections in category_1 as shown below in Figure 8;

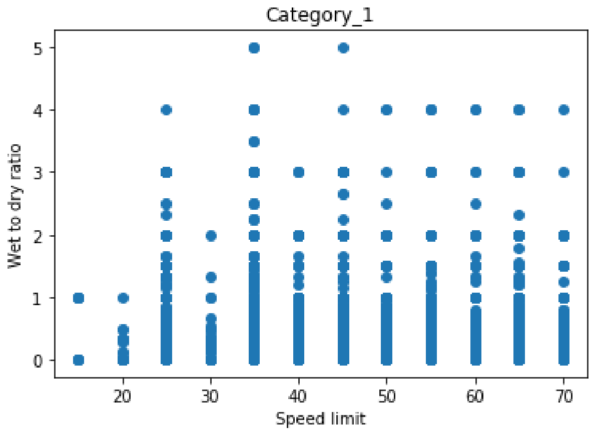


Figure 8. Speed limit – wet/dry crash ratio of all road sections in category_1

Step 2: Fit the probability distribution of wet to dry ratio corresponding to each speed limit by using exponential distribution (an example of speed limit = 25 mph is shown below in Figure 9).

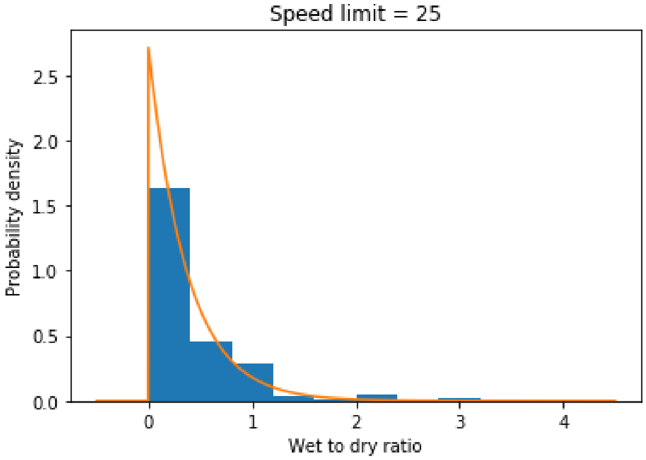


Figure 9. The fitted exponential probability density function of wet/dry ratio corresponding to speed limit = 25 mph.

Step 3: Get the 97.5% quantile value of wet/dry ratio for each speed limit and then draw the scatter plot in Figure 10. This quantile value can be considered as the extreme crash rate under each speed limit condition hence indicates the crash risk level corresponding to each speed limit.

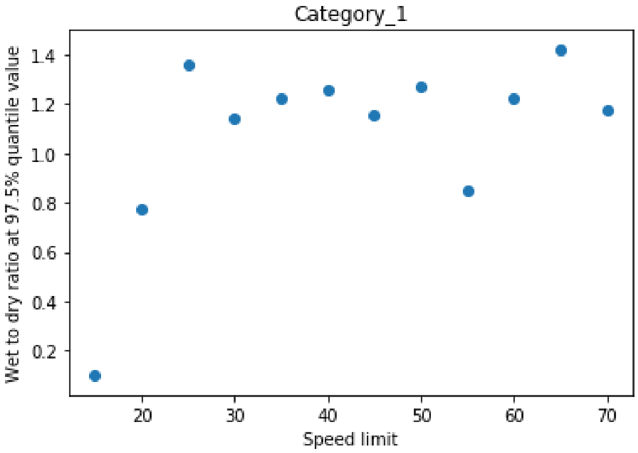


Figure 10. The 97.5% quantile value of wet/dry ratio for each speed limit

4) By checking the trend visually, the spherical model is employed to fit the mapping from speed limit to the 97.5% quantile value of wet to dry ratio. The form of the spherical model is Equation (1).

$$\gamma(h) = \begin{cases} c\left[\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right], & for\ h \leq a \\ c, & for\ \ h > a \end{cases} \tag{1}$$

The fitting result is shown in Figure 11, the critical point a=41.07 as indicated by the dash-dot line. This point is the boundary between the two parts of the fitted curve. The crash risk is increasing before this point can be reached, while the crash risk is stable when the speed limit is beyond this point. Therefore, for Ohio data, Speed limit >= 40 mph seems to be a reasonable choice.

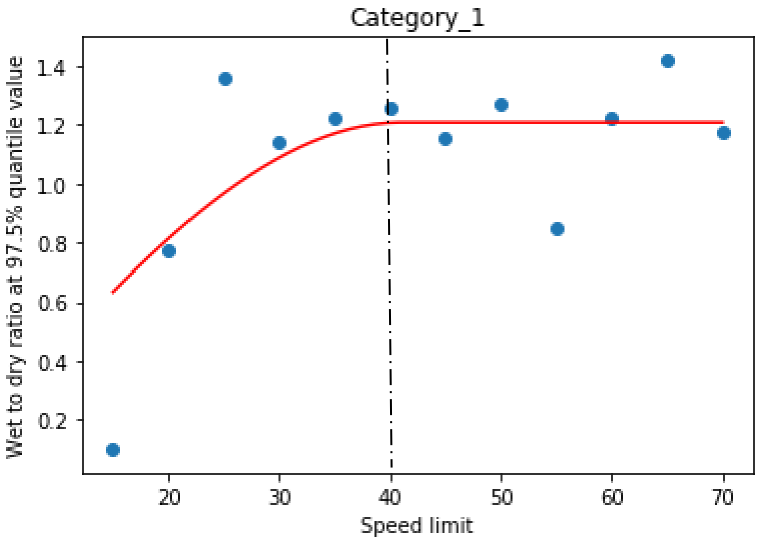


Figure 11. Fitting result of the mapping from speed limit to the 97.5% quantile value of wet to dry ratio

Regarding how to set the criteria for the curvature of radius, speed limit is paired with it. The speed limits are split into several levels: 20~35mph, 35~45mph, 45~55mph, and >55mph. A statistical analysis has been performed to determine a reasonable critical curvature radius corresponding to each speed level. The detailed steps are shown below (Category 1 dataset for example):

Step 1: Draw the 3-D scatter plot of the wet-to-dry ratio, speed limit and log10(curvature radius) in Figure 12:

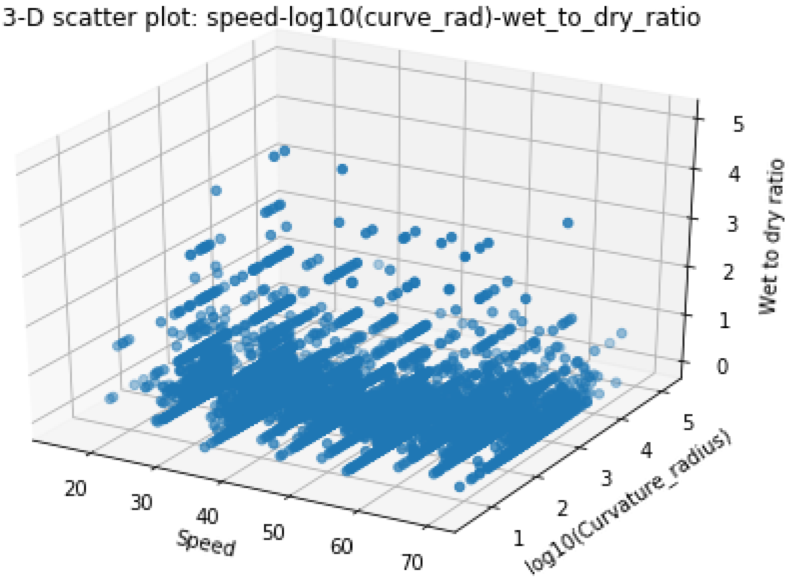


Figure 12. 3-D scatter plot of the wet-to-dry ratio, speed limit and log10(curvature radius)

Step 2: Extract data corresponding to a certain speed limit level (say 20~35 mph in Figure 13):

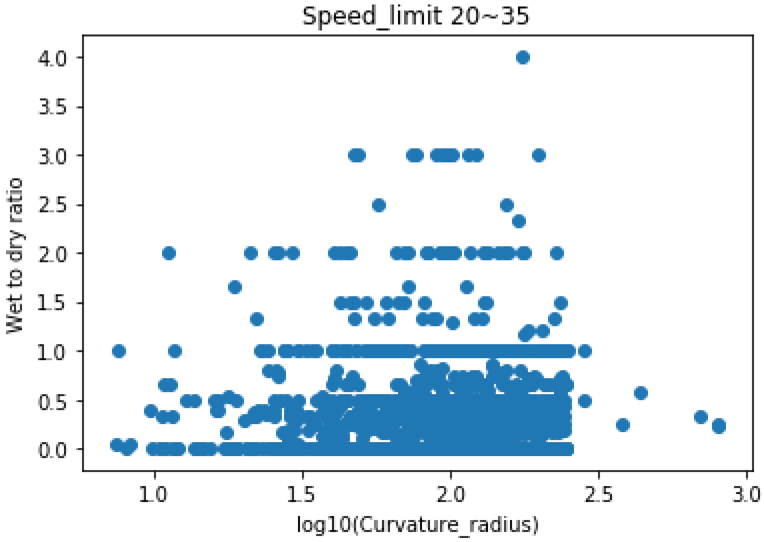


Figure 13. Scatter points of crash rate vs. log10(curvature radius)

Step 3: Fit the wet-to-dry ratio to an exponential distribution and estimate the 0.5 quantile value (Figure 14):

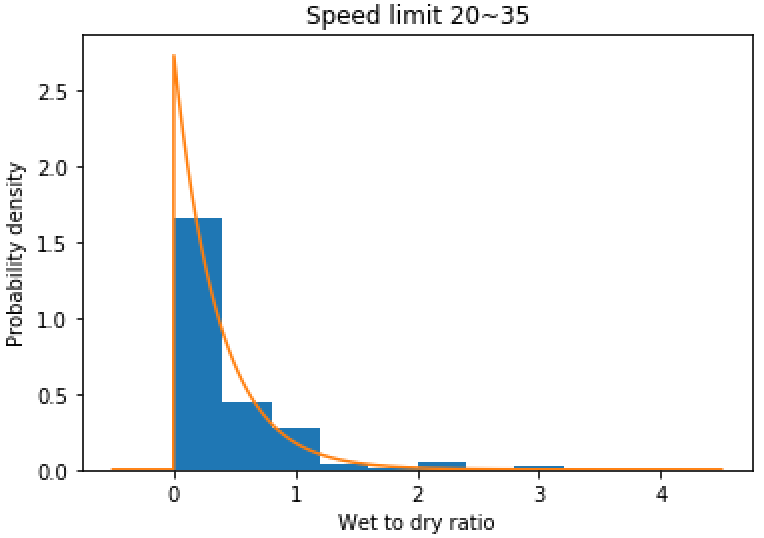


Figure 14. The fitted wet-to-dry ratio using exponential distribution

Step 4: Collect data points with wet-to-dry ratio greater than the 0.5 quantile value (i.e., wet crash related “dangerous sections”), and fit the corresponding curvature of radius to a gamma distribution, the 75% quantile value (seems to be a reasonable percentage coverage, higher value will result in much greater curvature radius which is not practical) is set to be the criterion (Figure 15).

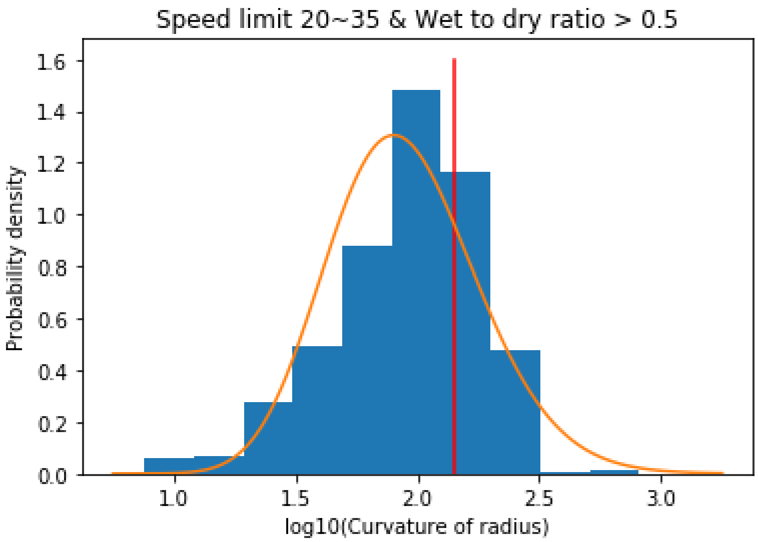


Figure 15. Fitting the corresponding curvature of radius to a gamma distribution and identifying the 75% quantile value.

Step 5: Identify the critical curvature of radius: 463 ft. (141m) for 20~35 mph.

The same process (from 2 to 5) is applied to each speed level of category 1 and the results are rounded and shown in the table below:

Table 16: Critical radius corresponding to each speed limit level for Category 1

Speed limit level (mph)	Critical radius
20 - 35	500 ft. (150 m)
35 - 45	525 ft. (160 m)
45 - 55	590 ft. (180 m)
55 - 65	820 ft. (250 m)
>= 65	1870 ft. (570 m)

The same analysis has been performed on the datasets of Category 2. For Category 2, the speed limit is 55 mph with traffic (ADT) > 10,000. The speed limit – curvature radius table is shown below:

Table 17: Critical radius corresponding to each speed limit level for Category 2

Speed limit level	Critical radius
< 45 mph	2300 ft. (700 m)
>= 45 mph	3400 ft. (1030 m)

For Category 3, the crash data size is much smaller than the other two Categories and hence reasonable critical values are difficult to be derived from statistical analysis. Empirical value of the speed limit with ADT > 5,000 is adopted based on the literature search.

Table 16 and 17 are derived from the available Ohio crash data and road inventory data. Generally speaking, the amount of data is considered to be sufficient to draw reasonable conclusions. However, possible biases cannot be completely avoided. It is recommended to revisit the two tables when additional data (i.e., new crash data) can be available.

Regarding incorporating rutting information into the site condition with priority, rutting information at network level (if available) may be needed for further data analysis. In this study, as the data source is not sufficient for a quantitative analysis, a literature search has been conducted in providing some general guidance and the details are shown in the following section.

4.3 Relationship between rut depth and driving safety under wet-weather condition

Hydroplaning can occur when relatively thick water layers or films are present and vehicles are traveling at higher speeds. Hydroplaning occurs when a vehicle tire is separated from the pavement surface by the water pressure that builds up at the pavement–tire interface (Horne & Buhlmann, 1983), causing friction to drop to a near-zero level. It is a complex phenomenon affected by several parameters, including water depth, vehicle speed, pavement macrotexture, tire tread depth, tire inflation pressure, and tire contact area. Relatively thick water films form on a pavement surface when drainage is inadequate during heavy rainfalls or when pavement rutting or wearing creates puddles. Loss of direct pavement–tire contact can occur at speeds as low as 40 to 45 miles/hour (64 to 72 km/hour) on puddles about 1 in (25 mm) deep and 30 ft (9 m) long (Hayes, Ivey, & Gallaway, 1983).

It was found that depending on the rut depth and the surface frictional property of a pavement, the severity classification of a rut may be governed by either hydroplaning risk or safety requirement of braking distance. The traditional method of using the same set of critical rut depths for all pavement sections in a road network is not ideal for effective handling of rutting maintenance. According to past literature, there is no clear and definite relationship between rut depth and traffic accidents. One of the primary problems encountered in such statistical correlation studies has been the difficulty to separate the effect of rut from those of other factors, pavement or non-pavement related. These studies suggest that statistical analysis on the basis of traffic accident data is not an ideal method to classify rut severity with respect to safety.

Since the early 1970s, pavement engineering researchers have produced experimental evidence that ponding of pavement ruts could lead to hydroplaning and loss of skid resistance. Barksdale (1972) concluded that in pavements with rut depths of approximately 0.5 in. (12.7 mm), ponding is sufficient to cause automobiles traveling at speeds of 50 miles/hour (80 km/h) or faster to hydroplane. Lister and Addis (1977) also found from their experience in the United Kingdom that pavements with ruts deeper than approximately 0.5 in. (12.7 mm) could result in ponding of water and cause hydroplaning or loss of skid resistance.

In 1989, the AASHTO Joint Task Force on Rutting stated in their report that wheel path ruts greater than 1/3 to 1/2 inch (8.5 to 12.7 mm) in depth are considered by many highway agencies to pose a safety hazard because of the potential for hydroplaning, wheel spray, and vehicle handling difficulties (AASHTO, 1989). Conversely, (Sousa, Craus, & Monismith, 1991) stated in a Strategic Highway Research Program (SHRP) study report that for rut depths that exceed 0.2 in. (5.1 mm), hydroplaning is a definite threat particularly to cars. In a study on preventive maintenance treatments for flexible pavements, Hicks, Moulthrop, and Daleiden (1999) adopted the following three severity levels for ruts on the basis of the potential for hydroplaning and wet-weather accidents:

- Low severity—Rut depth is less than 0.25 in (6 mm). Problems with hydroplaning and wet-weather accidents are unlikely;
- Moderate severity—Rut depth is in the range of 0.3 to 0.45 in (7 to 12 mm). Inadequate cross slope can lead to hydroplaning and wet weather accidents; and
- High severity—Rut depth is greater than 0.5 in (13 mm). The potential for hydroplaning and wet-weather accidents is significantly increased.

Despite the common understanding by researchers that hydroplaning and loss of skid resistance during wet weather should form the basis for classifying rut severity for pavement maintenance management, no quantitative engineering-based guidelines are currently available to assist pavement agencies to establish thresholds for assigning severity levels of ruts.

Table 18 shows examples of rut depth thresholds used by different highway agencies in severity level classification of ruts for pavement maintenance management. The rut depth thresholds for the "high severity" classification can be considered to be a severity level that warrants maintenance treatment.

Table 18. Rut Severity Classification by Highway Agencies

Highway agency	Low	Medium	High
Pavement Condition Index (Shahin, 2005)	0.25–0.5 in.	0.5–1 in.	> 1 in.
Pavement surface evaluation and rating manual, asphalt roads (Walker, Entine, & Kummer, 2002)	0–0.5 in.	>1 in.	>2 in.
Washington State Department of Transportation (WSDOT, 2000)	0.25–0.5 in.	0.5-0.75 in.	>0.75 in.
Ohio Department of Transportation	0.125–0.375 in.	0.375-0.75in.	>0.75 in.
Massachusetts Highway Department	0.25-0.5 in.	0.5-0.75 in.	>0.75 in
Ministry of Transportation and Infrastructure, British Columbia	3-10 mm	10-20 mm	>20 mm
California Department of Transportation	Schedule corrections when rut depth > 1 in:		

Fwa, Pasindu, and Ong (2011) mentioned that for a given rut depth, pavement sections belonging to different highway classes (hence different prevailing driving speeds) or having different pavement microtexture and macrotexture will have different skid resistance characteristics and hydroplaning potentials. In other words, based on the considerations of skid resistance (i.e., braking distance) and hydroplaning risk, the critical rut depth for different pavement sections may not be the same. Numerical simulation was employed by Fwa et al. (2011) to identify the critical rut depth for different pavement friction and driving speed. To be more specific, for a car traveling at a given speed of the road section analyzed, the critical rut depth is considered to be reached when one of the following two events takes place: (1) hydroplaning of any of the tires of the vehicle; and (2) the length of braking distance exceeds the design braking distance. The numerical analysis was performed for the following five cases of rut depths: 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm. The pavement surface types considered are characterized by the following static wet-pavement friction values represented as skid number SN_0 (which is equal to 100 μ_0, where μ_0 is the static friction coefficient): 47.5, 55, 60, 72.5, and 80. The values of other input parameters for the simulation analysis are:

1. Tire sub-model: Consider ASTM standard E501 rib tire (ASTM 2008) with a tread depth of 1.6 mm, wheel load of 4,800 N, and tire inflation pressure of 165.5 kPa; the elastic modulious and Poisson's ratios for the tire rim, tire sidewalls, and tire tread are 100 GPa and 0.3, 20 MPa and 0.45, and 100 MPa and 0.45, respectively. The density of the rim material is 2,700 kg/m^3, and that of the rubber material of the tire sidewalls and tire tread is 1,200 kg/m^3;
2. Pavement sub-model: The pavement elastic modulus is 30 GPa, Poisson's ratio is 0.15, and its density is 2;200 kg/m^3; and
3. Fluid sub-model: The properties of water at 25°C are considered. The density, dynamic viscosity, and kinematic viscosity of water at 25°C are 997.1 kg/m^3, 0:894 × 10^{-3} N-s/m^3, and 0.897 × 10^{-6} m^2/s, respectively.

The results are shown in Table 19 and Table 20.

Table 19. Hydroplaning Speeds for Rut Depth Levels

Rut depth (in.)	Hydroplaning speed (mph)
0.2	56.5
0.4	54.1
0.6	51.6
0.8	47.2
1.0	44.7

These values are valid for different pavement surfaces since the influence of pavement surface type on hydroplaning speed is practically negligible.

Table 20. Braking Distance for Different Rut Depth Levels and Pavement Friction Values

Speed (mph)	25	31	37	43.5	49.7
Design breaking distance (ft) (AASHTO 2004)	59.1	95.1	134.5	183.7	239.5
SN40S					
	Rut depth = 0.2 in				
27	42.7	72.2	111.5	173.9	278.9
30	39.4	62.3	98.4	154.2	249.3
33	36.1	55.8	88.6	141.1	236.2
39	29.5	45.9	75.5	118.1	203.4
45	26.2	42.7	68.9	108.3	187.0
	Rut depth = 0.4 in				
27	45.9	75.5	118.1	190.3	321.5
30	39.4	65.6	101.7	167.3	285.4
33	36.1	59.1	95.1	154.2	265.7

39	29.5	49.2	75.5	121.4	239.5
45	26.2	45.9	72.2	118.1	206.7
	Rut depth = 0.6 in				
27	45.9	78.7	124.7	196.9	324.8
30	39.4	65.6	108.3	177.2	295.3
33	36.1	62.3	98.4	164.0	278.9
39	29.5	52.5	82.0	137.8	242.8
45	26.2	45.9	75.5	128.0	229.7
	Rut depth = 0.8 in				
27	49.2	85.3	137.8	219.8	360.9
30	42.7	72.2	121.4	196.9	331.4
33	39.4	68.9	111.5	187.0	315.0
39	32.8	55.8	95.1	164.0	282.2
45	29.5	52.5	88.6	154.2	265.7
	Rut depth = 1.0 in				
27	49.2	88.6	147.6	236.2	354.3
30	42.7	75.5	134.5	216.5	328.1
33	39.4	72.2	124.7	203.4	311.7
39	32.8	59.1	105.0	183.7	278.9
45	29.5	55.8	98.4	167.3	262.5

The critical rut depth analysis requires the knowledge of the maximum allowed vehicle speed for the road section considered. The maximum speed logically refers to wet-weather vehicle operating conditions, and therefore is not equal to the roadway design speed or posted speed for fair-weather conditions. Under wet-weather conditions, vehicles are known to be traveling somewhat slower than the design or posted speed. This wet condition travel speed may be derived from past records of travel speed data.

Based on Table 20, recommended friction demand for different wet-weather driving speed and rut depth are summarized below:

Table 21. Suggested friction demand for different wet-weather driving speed and rut depth

Post speed(mph)	Rut depth (in.)	Friction demand (SN40S)
35	<0.6	Basic investigation level
	0.6 ~ 1.0	30
40	<0.2	Basic investigation level
	0.2 ~ 0.6	30
	0.6 ~ 1.0	40
45	< 0.2	30
	0.2 ~ 0.4	35
	0.4 ~ 0.6	40
	0.6 ~ 0.8	45 (high risk)
	> 0.8	Not permitted (high severity)

4.4 Determining the investigatory levels

The objective of this section is to develop separate investigatory levels for each friction demand site category. As mentioned in the literature review section, the effect of tire-pavement friction on the rate of vehicle crashes is well known among researchers. The AASHTO Guide for Pavement Friction has defined three methods to establish two distinctive friction threshold levels, investigatory level and intervention level. Sites with friction values below the investigatory level will be selected for detailed investigation to determine if there is a need for posting warning signs. Sites with friction values below the intervention level will be selected for corrective action, such as resurfacing or other programmatic maintenance treatment.

The first AASHTO method uses the friction deterioration curve by plotting friction loss versus pavement age. The friction value at which significant loss rapidly begins is selected as the investigatory level. The intervention level is defined at a fixed percentage below investigatory level (Figure 16).

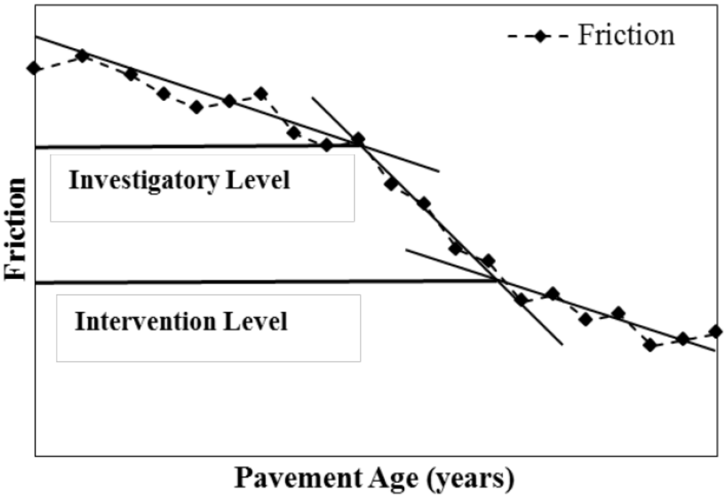


Figure 16. Friction deterioration curve (after Hall et al. (2009)).

The second AASHTO method uses both the friction deterioration curve and historical crash data. The investigatory level is set where there is a significant drop in friction level and the intervention method is set where there is a significant increase in crashes (Figure 17).

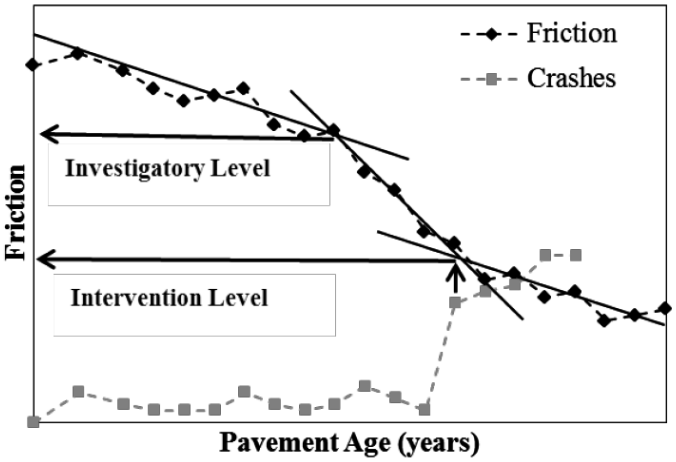


Figure 17. Investigatory and intervention friction level based on friction deterioration and crash rate (after Hall et al. (2009))

The third AASHTO method uses the friction distribution and crash rate for each roadway category to determine the investigatory and intervention levels of friction. The histogram of pavement friction and wet-to-dry crash ratio is plotted first (Figure 18). The mean and standard deviation of the friction distribution are then calculated. The investigatory level is set as the mean friction minus X (e.g., 1.5 or 2.0) standard deviations and it is adjusted to where wet-to-dry crashes begin to increase considerably. The intervention level is set as the mean friction minus Y (e.g., 2.5 or 3.0) standard deviations and it is adjusted to a minimum satisfactory wet-to-dry crash rate or by the point where enough funding is available to address the friction deficiencies (Hall et al. 2009). This method is more robust than other two approaches since an agency can adjust the intervention friction level based on available funding.

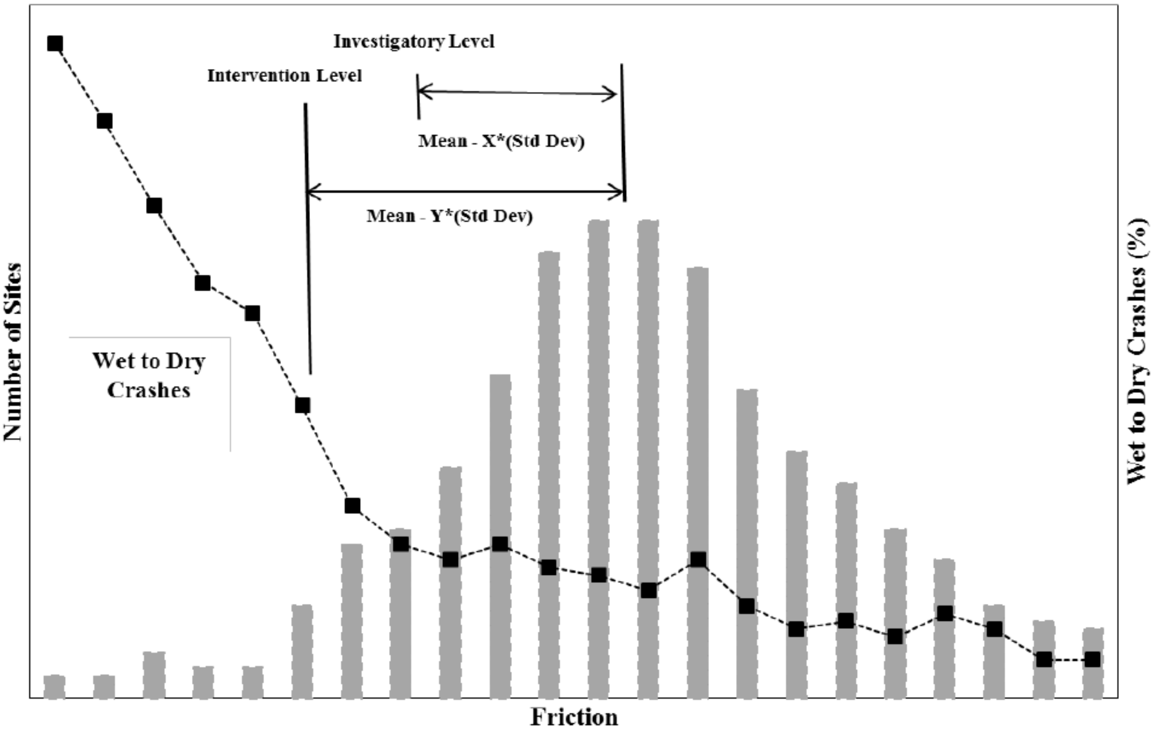


Figure 18. Investigatory and intervention level of friction based on friction distribution and wet-to-dry crash ratio (after Hall et al. (2009)).

It can be noticed that the first two methods suggested by the AASHTO guide require historical friction data for a specific roadway site, which is usually difficult to collect and was not available for this study. Thus, the research team can only perform the third method. For each site category, we follow Najafi, Flintsch, and Khaleghian (2019), friction numbers were grouped into bins with two-unit increments. As mentioned in the data processing section, the friction readings and crash events were then linked using route NLFID and milepost information. If the distance between the location of the crash and the nearest friction reading was less than 0.1 miles, the data were linked together. The total numbers of friction sites for each bin, as well as the ratio of wet-to-total crashes for each friction bin, were then calculated. This process was performed for both ribbed tire measurements and smooth tire measurements.

The histogram of friction numbers and wet-to-total crash ratio for each site category is provided in Figure 19 through Figure 21 together with corresponding distribution of speed limits.

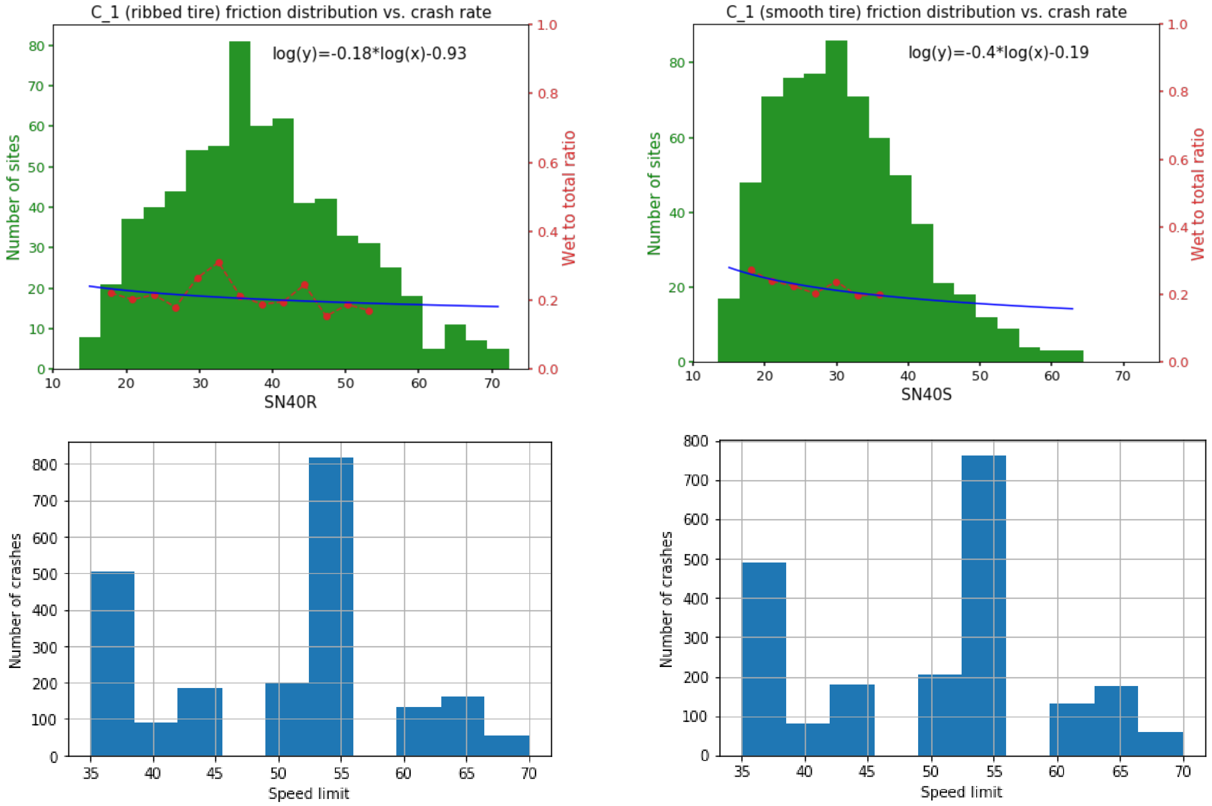


Figure 19. Friction-Crash analysis of Category 1 using AASHTO method III

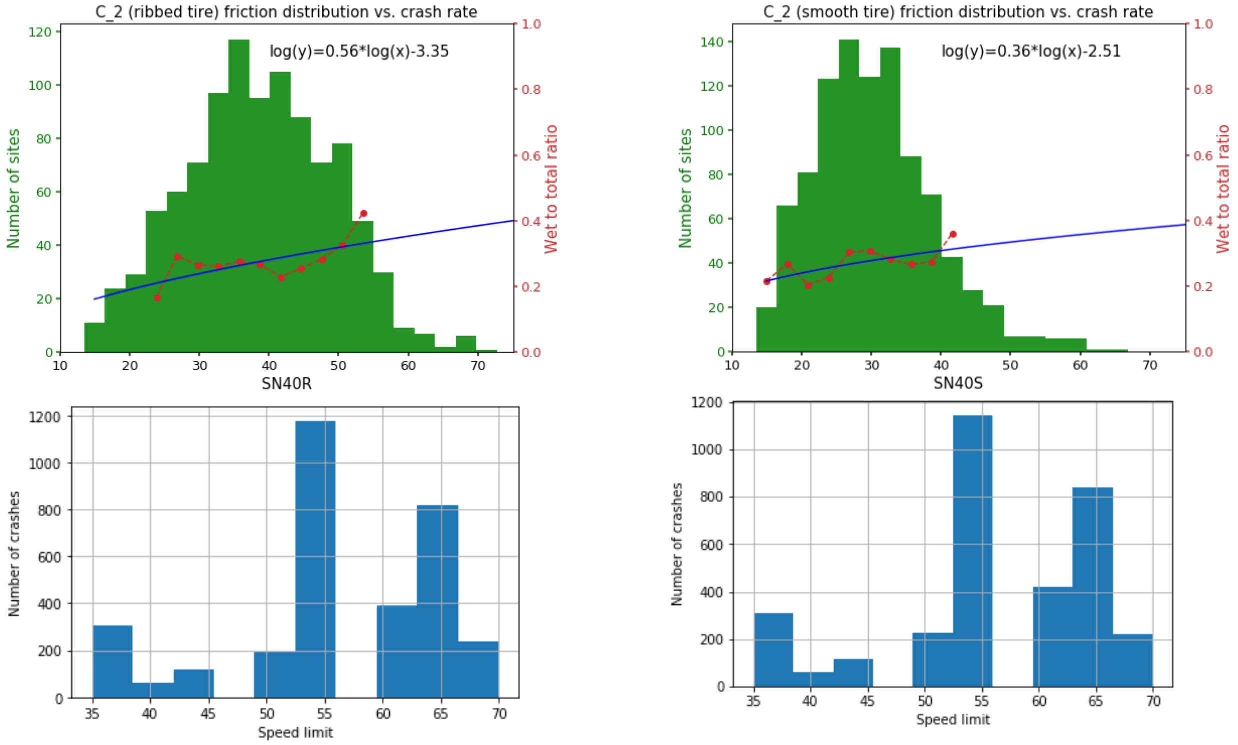


Figure 20. Friction-Crash analysis of Category 2 using AASHTO method III

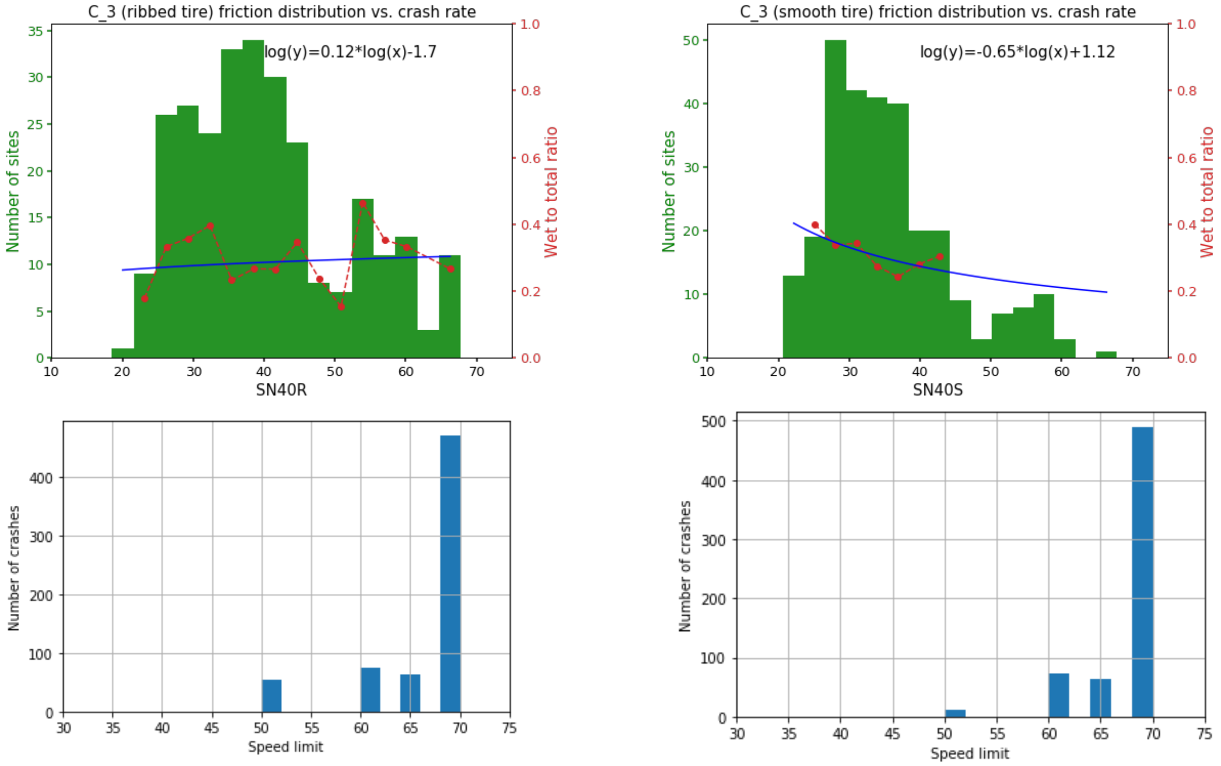


Figure 21. Friction-Crash analysis of Category 3 using AASHTO method III

For all cases, no significant drop can be observed in the wet-to-total crash ratios. It should also be noted that there are only a few sites with extremely low (and high) friction values. Defining friction threshold based on a small sample size may not be appropriate. In this study, wet-to-total crash ratios calculated from small sample size was not used. Even with calculated wet-to-total crash ratios from reasonable number of crash sites, the general trend of the wet-to-total crash ratios of Category 2 is not reasonable. The analyzing results indicate that it is difficult to use AASHTO method III to find investigatory levels for different categories. Hence there is a need to find an alternative approach.

In this project, the finite Gaussian mixture model (McLachlan & Peel, 2004) was implemented as an alternative to extract the statistical characteristics and the relationship between pavement friction and crash rate. The crash sites (with corresponding friction measurements SN40S and SN40R) is clustered into multiple groups based on the similarity of friction information, which contains the measurement pairs SN40S and SN40R, by using the Gaussian mixture model (GMM) to extract underlying patterns in the two-dimensional feature space (where SN40S and SN40R form a two-dimensional space). The general concept of a GMM is shown in Figure 22. Each dot in Figure 22 represents a crash event, similar crash events in terms of pavement friction condition will cluster together in the two-dimensional SN40S-SN40R space. Each cluster can be defined by a center point and the shape of the point cloud, and they correspond to the feature average and the covariance matrix. The motivation of using GMM is that the statistical pattern (i.e., average level and correlation between SN40S andSN40R) of pavement friction could be a driving force or indicator of different levels of wet-to-total crash rate. In addition, as mentioned above in the literature review section, ribbed tire is not sensitive to the macrotexture, and hence adding information by using smooth tire measurement can enhance the extracted friction similarity between any two crash sites.

The GMM is fitted using friction data via expectation-maximization (EM) algorithm (McLachlan & Peel, 2004), which is a standard and well implemented method for finding the maximum likelihood model by optimizing the parameters under hidden conditions. In this study, the open-source python package scikit-learn (Pedregosa et al., 2011) is used to implement the EM algorithm.

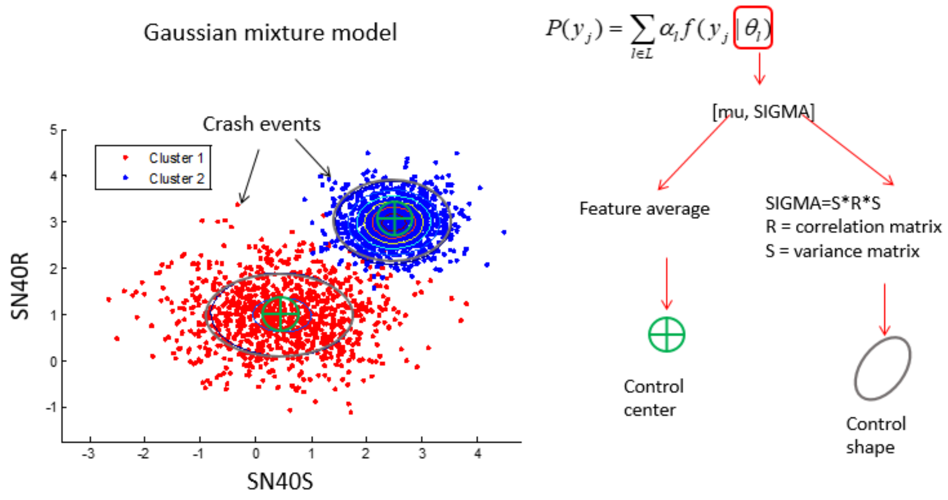


Figure 22. The general concept of a GMM

The crash events in Category 1 were grouped into 4 clusters. The wet-to-total ratio of each cluster is calculated. The clustering results and corresponding wet-to-total ratio are shown in Figure 23. The extracted statistical parameters are shown in the Table 22. It can be noticed that cluster 1 and 4 have similar wet-to-total ratio and cluster 2 and 3 have similar wet-to-total ratio. Four different clusters have different size and shape, which indicate different correlation between the two features (i.e., SN40S and SN40R) and different variation of the two features of each cluster. The variations in cluster size and shape are usually resulted from other roadway factors/conditions such as traffic volume and pattern, roadway geometry, and speed limits.

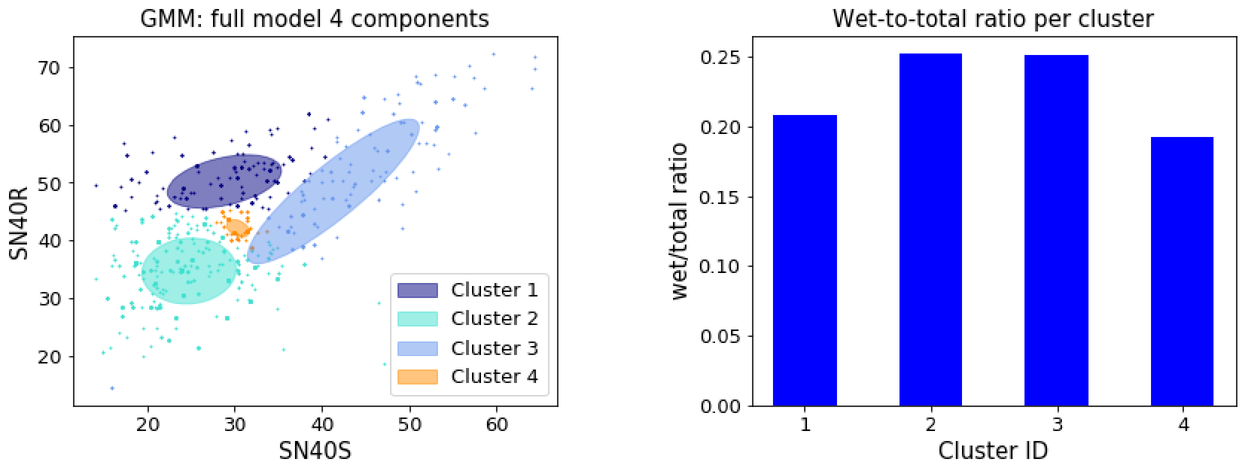


Figure 23. The clustering result of Category 1 and the wet-to-total ratio of each cluster

Table 22: Statistical patterns of Category 1 friction data

	Mean (SN40S, SN40R)	Correlation	STD SN40S	STD SN40R
Cluster 1	[28.82, 50.18]	0.4	6.54	4.59

Cluster 2	[24.78, 34.74]	0.06	5.39	5.69
Cluster 3	[41.33, 48.47]	0.89	9.79	12.4
Cluster 4	[30.41, 42.08]	-0.36	1.32	1.48

In order to further investigate the effect of curvature radius and traffic speed in crash events, the non-parametric probability distributions of curvature radius and speed limit histogram of each cluster are shown in Figure 24 and 25 respectively. It can be observed Cluster 2 and 3 concentrated more on the small curvature radius side compared with cluster 1 and 4. From Figure 25, it can be noticed that Cluster 1 and 3 have more high speed crashes whereas cluster 4 have more low speed crashes.

By comparing the extracted statistical pattern of different clusters and corresponding crash rates, we can have better knowledge on friction deficiency severity of each crash event cluster. In this study, we consider the high severity cluster(s) as the representative cluster(s) of prioritized sites. Similar to the AASHTO method III, by shifting the center of a cluster to a lower fractional value (say, 1 standard deviation), we can derive the investigatory level. In Category 1, Cluster 3 is chosen as the representative cluster for prioritized sites. The horizontal geometry criteria for prioritized sites is set to be curvature radius <=1640 feet. The investigatory level: SN40S>=35 and SN40R>=40 (both need to be satisfied); Cluster 1 and 4 are chosen as the representative clusters for roadway segments with general friction demand in Category 1. The investigatory level should be SN40S>=30 and SN40R>=40 (both need to be satisfied). This result confirms the investigatory level (SN40S>=30 and SN40R>=40 (both need to be satisfied)) for unsignalized intersections suggested in the 2008 ODOT roadway friction research project (Larson et al., 2008).

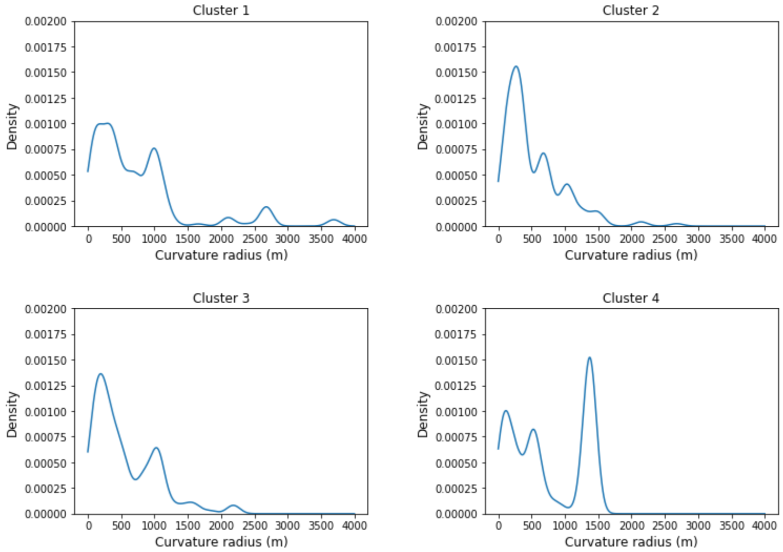


Figure 24. The non-parametric probability distributions of curvature radius of each cluster in Category 1.

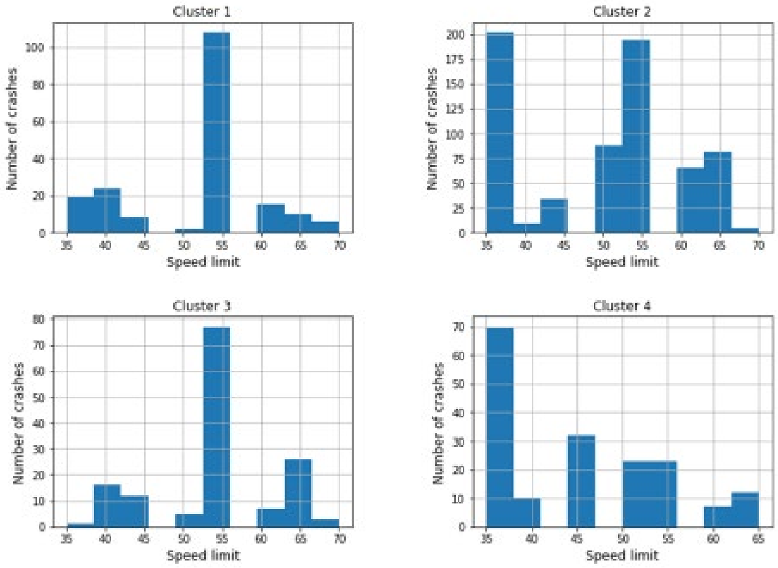


Figure 25. Speed limit histogram of each cluster in Category 1

The crash events in Category 2 were clustered into 4 clusters. The wet-to-total ratio of each cluster is calculated. The clustering results and corresponding wet-to-total ratio are shown in Figure 26. The extracted statistical parameters are shown in the Table 23. In this friction demand category, 4 clusters can be detected. Cluster 2 has the highest crash rate. Cluster 1 and 4 have similar crash rate, and cluster 3 has the lowest crash yet has the smallest average SN measurements. Again, four different clusters have different size and shape, which indicate different correlation between the two features (i.e., SN40S and SN40R) and different variation of the two features of each cluster.

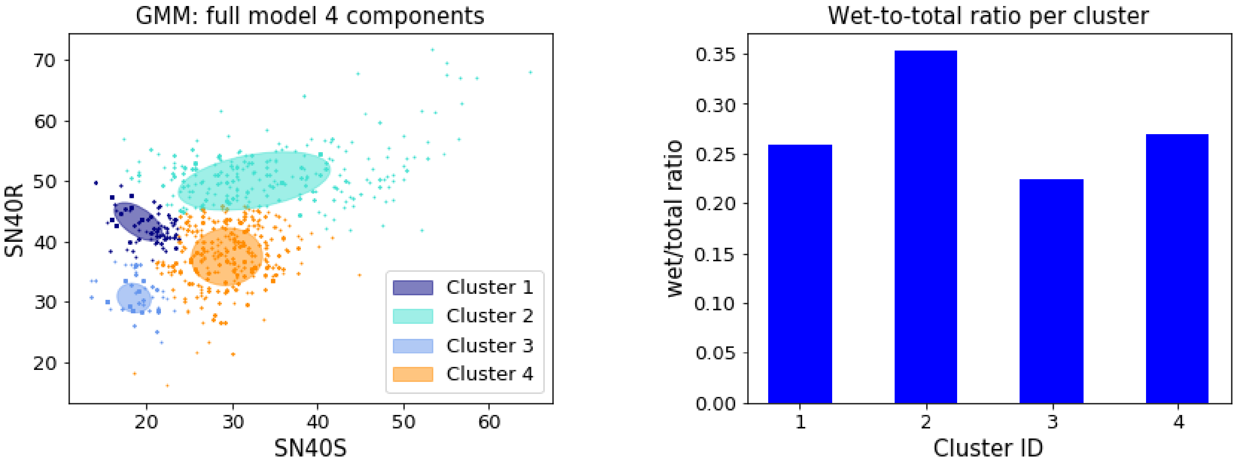


Figure 26. The clustering result of Category 2 and the wet-to-total ratio of each cluster

Table 23: Statistical patterns of Category 2 friction data

	Mean (SN40S, SN40R)	**Correlation**	**STD SN40S**	**STD SN40R**

Cluster 1	[19.04, 43.20]	-0.58	2.77	3.12
Cluster 2	[32.62, 49.92]	0.39	8.87	4.82
Cluster 3	[18.56, 30.59]	-0.12	1.96	2.40
Cluster 4	[29.41, 37.40]	0.04	4.15	4.75

The probability distributions of curvature radius and speed limit were plotted in Figure 27 and 28. It can be observed that Cluster 1 and 3 concentrate more on the small curvature radius compared with cluster 2 and 4. From the speed limit distribution of the four clusters, it can be noticed that most of the crash events in cluster 2 have high speed limit above 55, cluster 4 has more high speed crashes than low speed crashes. In contrast, Cluster 1 and Cluster 3 are generally comparable to each other regarding the speed limit. It seems that the speed limit plays a more significant role than curvature radius in Category 2.

By shifting the center of a cluster to a lower fractional value (say, 1 standard deviation), we can derive the investigatory level. In Category 2, Cluster 2 is chosen as the representative cluster for prioritized sites. The horizontal geometry criteria for prioritized sites is set to be curvature radius <=1640 ft. and the speed limit criteria for prioritized sites is set to be Speed limit >= 55 mph. The investigatory level: SN40S>=25 and SN40R>=45 (both need to be satisfied); Cluster 4 is chosen as the representative clusters for roadway segments with general friction demand. The investigatory level should be SN40S>=25 and SN40R>=35 (both need to be satisfied). This suggested investigatory level agrees with the investigatory level (SN40S>=28 and SN40R>=38 (both need to be satisfied)) for congested freeway in the 2008 ODOT roadway friction research project (Larson et al., 2008).

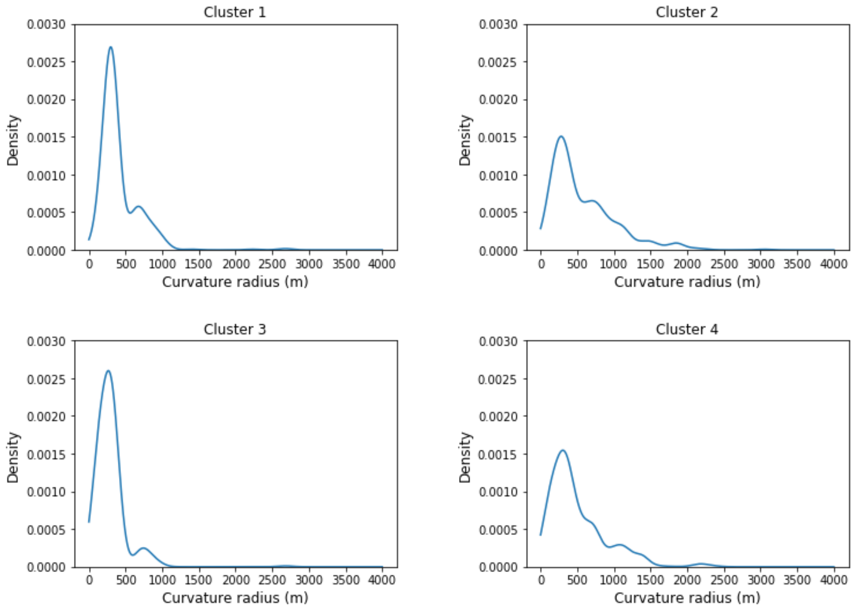


Figure 27. The non-parametric probability distributions of curvature radius of each cluster in Category 2.

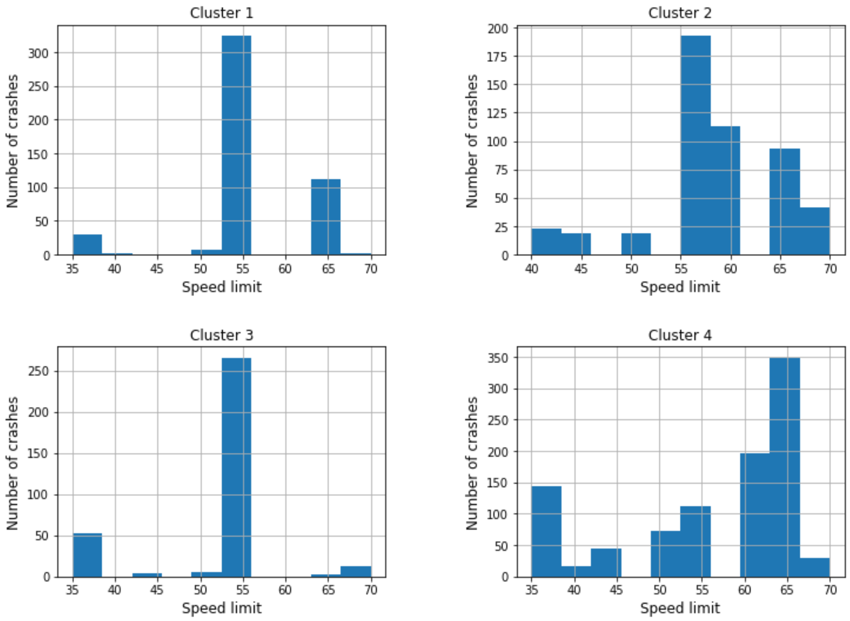


Figure 28. Speed limit histogram of each cluster in Category 1

The crash events in Category 3 were limited and only two clusters can be detected. The wet-to-total ratio of each cluster is calculated and shown in Figure 29. The extracted statistical patterns are shown in the Table 24. The difference of wet-to-total crash rate between the two clusters is small. Cluster 2 has lower friction numbers for both ribbed and smooth tires and has higher crash rate.

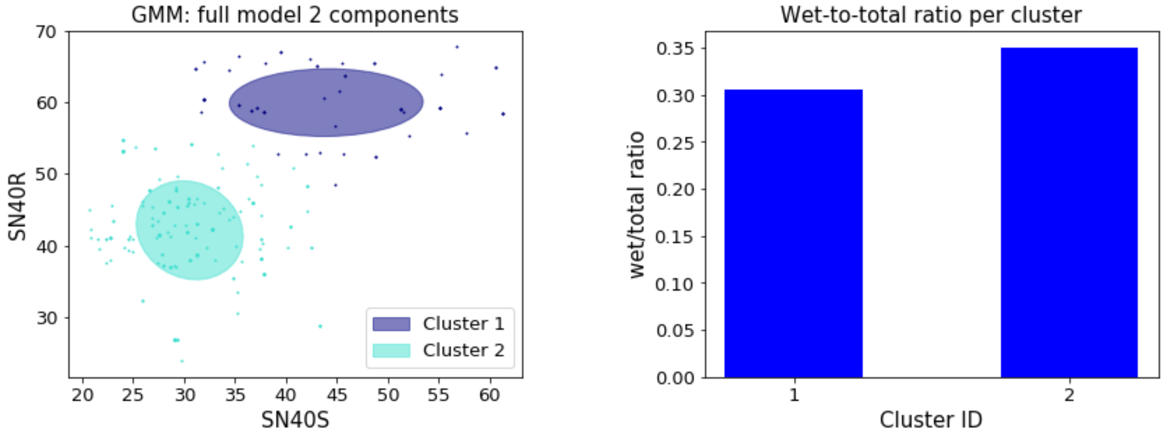


Figure 29. The clustering result of Category 3 and the wet-to-total ratio of each cluster

Table 24: Statistical pattern of Category 3 friction data

	Mean (SN40S, SN40R)	Correlation	STD SN40S	STD SN40R
Cluster 1	[43.97, 59.98]	0.02	9.5	4.73
Cluster 2	[30.57, 42.10]	-0.14	4.74	6.92

From Figure 29, it can be noticed that Cluster 1 in Category 3 is very scattered. This is because of the limited number of data points. The limited number of crash events agree with the general definition of this friction demand category (i.e., low friction demand), however, the insufficient data points add difficulties to the evaluation of the general friction demand. In addition, the probability density function of the curvature radium of Cluster 1 is flat (Figure 30) and all data points with the same speed limit 70 mph (Figure 31). Based on the literature research and existing practices listed in Section 2, a preliminary estimation of the investigatory level for general friction demand is set to be SN40S>=20 and SN40R>30. If Cluster 2 with the higher crash rate is considered to be the cluster representing the priority sites, the criteria for speed limit is set to be 70 mph and the curvature radius <= 6560 ft. The investigatory level is set to be SN40S>=25 and SN40R>=35.

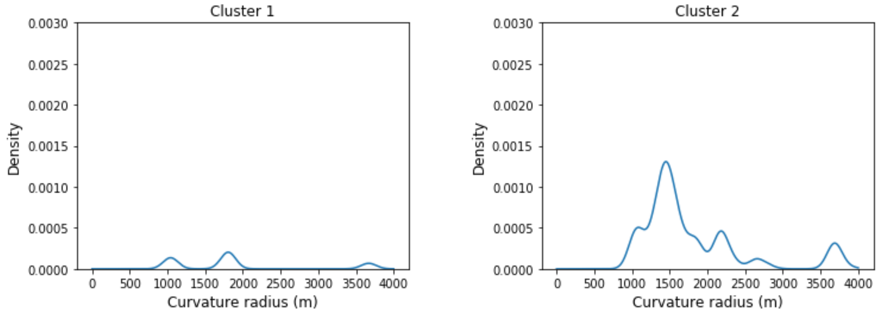


Figure 30. The non-parametric probability distributions of curvature radius of each cluster in Category 3.

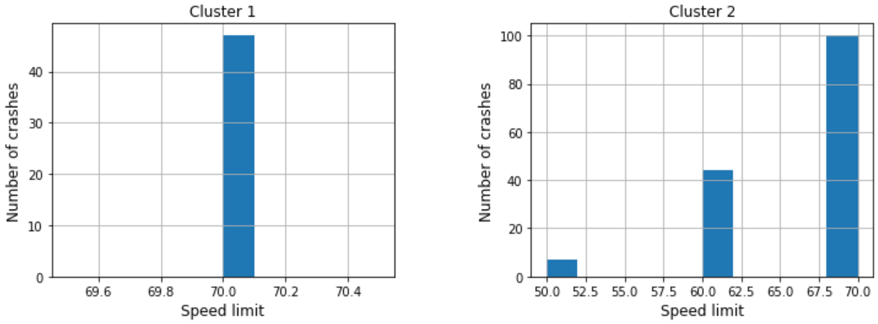


Figure 31. Speed limit histogram of each cluster in Category 3

4.5 Summary of data analysis results

Based on the crash-friction data analysis in section 4.4, there is a need to revisit Table 15 in order to make the site category definitions align better with Ohio crash and friction data. Since the above analysis focuses on the effects of horizontal curvature radius and speed limit, the modifications are mainly focus on these two aspects. The modified site categories are shown in Table 25

Table 25: The modified friction demand site categories

Friction demand category	General site condition	Site condition with priority (additional friction demand is needed)

High	• Undivided roadway sections with geometric constraints; • Divided or undivided roadways at signalized intersections; Pedestrian/school crossings; • Railway crossings; • Roundabout approaches; • Interstate ramps with high speed limit at service interchanges with stop condition; • Interstate to interstate ramps at service interchanges without stop condition.	Satisfying general condition and with at least one additional following condition: 1) Speed limit > 35 mph with traffic (ADT) >15,000; 2) Curvature radius <= 1640 ft; 3) Speed limit > 40 mph where pavement with rutting issue.
Moderate	• Urban Arterial Roads; • Divided highways with geometric constraints, • Undivided highways without any other geometrical constraints which influences friction demand; • Maneuver-free areas of undivided road; • Ramps associated with lower speed limit at service interchanges;	Satisfying general condition and with at least one additional following condition: 1) Speed limit > 55 mph with traffic (ADT) > 10,000; 2) Curvature radius < 1640 ft. with speed limit >= 55mph
Low	• Divided highways without any other geometrical constraints which influence friction demand; • Maneuver-free areas of divided roads; • no ramp in this category	Satisfying general condition and with the additional following condition: 1) Speed limit = 70 mph with traffic (ADT) > 5000, 2) Speed limit >= 60 and curvature radius <= 6560 feet.

The summary of the recommended investigatory levels are listed in Table 26.

Table 26: Recommended investigatory levels (**both SN40S, SN40R criteria need to be satisfied**)

Site category	**General Investigatory level [SN40S, SN40R]**	**Prioritized Investigatory level [SN40S, SN40R]**
C_1 High	[30, 40]	[35, 40]
C_2 Moderate	[25, 35]	[25, 45]
C_3 Low	[20, 30]	[25, 35]

It needs to be highlighted that both of the two criteria for SN40S and SN40R need to be satisfied for keeping pavement sections with low skid risk. If only one or none of the criteria is met, the agency must caution drivers by installing appropriate signs (e.g., slippery when wet and/or reduced speed) and then proceed with plans for a detailed investigation of the problematic sections. As both SN40S and SN40R measurements can be affected by micro- and macro-texture while SN40S is more sensitive to macrotexture, it could be difficult to conclude either one texture or both of them may be insufficient in case of friction measurements (either one or both) are below the investigatory level. A detailed site investigation will be triggered to (a) identify all other possible factors besides friction that are adversely impacting safety, and (b) determine the specific causes of inadequate microtexture and/or macro-texture so that a final conclusion on the friction inadequacy can be drawn. A comprehensive site investigation procedure can be found in Hall et al. (2009).

4.6 Discussion on machine learning methods in determining pavement friction investigatory levels

1) The merits of a machine learning approach

From the above analyzing results, it can be noticed that the unsupervised machine learning approach is more effective than the conventional AASHTO method III. The rationale behind the better performance can be summarized into the following three points.

a) Compared with the traditional univariate analysis, the unsupervised machine learning approach is capable to extract statistical patterns from multiple pavement friction information sources (i.e. SN40S, SN40R) and hence the similarity and/or heterogeneity of the site friction conditions at different locations (or even at a network level) can be analyzed in a comprehensive and automatic manner. Conceptually speaking, additional friction information sources from texture measurements (e.g., texture depth) also can be taken into consideration without any theoretical difficulty via Gaussian mixture models. Therefore, the unsupervised machine learning approach has high potential to accommodate additional pavement friction and texture measurement and become a unified pattern extraction method for determining the investigatory levels.

b) The center (i.e., mean) and correlation (i.e., covariance matrix) between different pavement friction information sources may contain critical information regarding vehicle-tire-pavement interaction under different road conditions. Similar road conditions may result in similar wet crash probability. Therefore, having an established Gaussian mixture model from available friction and crash data, the wet crash probability or expectation of a new site can be estimated by calculating the membership of belonging to each cluster of the Gaussian mixture and check the crash ratio corresponding to that cluster. Hence it is possible to identify high risk pavement sections from network level friction measurements before significant crash ratio can be observed. This advantage of the unsupervised machine learning approach is of great interest as it is critical to spot out the potential sites with inadequate friction in early stage during the pavement polishing and deteriorating process before numerous wet crash can happen.

c) Although large dataset can help the algorithm converge to an accurate and reliable model, the implemented unsupervised machine leaning approach requires a less minimum number of initial sites with both friction and crash data compared with AASHTO method III. However, less data points may result in biased and unreliable model, which can be gradually corrected as more and more measurements become available. When no reasonable answer can be drawn from AASHTO method III, the Gaussian mixture model extracted from the unsupervised machine learning approach still can provide useful information regarding the similarity among different sites and correlation between friction measurements, but the result must be used with caution and should be considered qualitatively. Since the whole framework is an iterative process, additional data can help on extracting more accurate clustered pattern and hence better modifying Table 25 and 26.

2) What data is needed, what data is available, and what value the unsupervised machine learning method would have with missing data?

In this project, though only two friction measurements have been used (i.e., SN40S and SN40R) for clustering analysis, the similarity regarding friction and clustered pattern can be detected already. In other words, the SN40S—SN40R data points can display some heterogeneity in the two-dimensional feature space (i.e., the SN40S—SN40R space). However, a feature space with lower dimensionality only represents part of the data characteristics and hence some possible patterns in the higher dimensional space cannot be revealed. This may result in under-fitting and missing some potential clusters in higher dimensional feature space. However, a good thing is that an under-fitted model will not significantly jeopardize the analyzing result of the general friction demand for each category, yet the identified prioritized sites may not be as good as the ones identified from higher dimensional feature space. The philosophy behind it is that some additional features (e.g., some macrotexture measurements) may help in distinguishing some sub-clusters and there may exist higher separability by adding new features so that the similarity can be better defined with more descriptive features and the number of prioritized sites may be even narrowed down. In future, some macrotexture measurements could be a promising additional feature to be added into the database.

From the above analyzing results, we notice that the detected clusters using SN40S and SN40R dataset also correspond to a distribution or pattern of the fixed information (i.e., the information may not change throughout the service life), say, the geometrical data of the roadway and/or the initial designed speed limit. Therefore, based on the extracted pattern from the existing complete data and the fixed information of a new site with missing data, the machine learning method can identify which cluster the new site may belong to and fill the missing feature with the mean, median or mode value of that specific cluster as a proper guess so that the rest features with observations of this data point can contribute into updating the model parameters during the modeling updating process.

3) Guidance for establishing machine learning-based pavement friction investigatory levels

This project is an exploratory study on implementing unsupervised machine learning methods for establishing pavement friction investigatory levels, hence only existing dataset can be leveraged. Though it is almost sure that additional data could improve the learning model (i.e., GMM in this study), it is difficult to say how much improvement they will provide before detailed investigation. Based on the current model performance using existing data, it is highly recommended to have a network-level friction and macro-texture measurements if it is feasible. The motivation is that not only a more accurate machine learning-based model will be established, but also it can be compared with AASHTO method III if the total number of observations is sufficient for implementing AASHTO method III. This comparison will be much appreciated since, at this stage, there is no quantitative evidence on that (a) the two methods will agree with each other, and (b) how much the machine learning method outperform the conventional AASHTO method III in terms of amount information needed and robustness.

In addition, ODOT links all data with NLFID and county log points. The current practice of different data management is effective and efficient. However, there is no such a dedicated joint database for pavement friction demand research. From the discussion with ODOT Subject Matter Experts and the above detailed analysis, the basic data unit (i.e., a crash event) should be linked with the nearest (distance < 0.1 mile) pavement friction measurement and macrotexture measurement (if available) as well as roadway geometry information. All the information are readily available but stored in different databases, hence the ODOT data management team (TIMS) is highly encouraged to perform the data preprocess to finalize a dataset which is readily available for the following machine learning analysis. The detailed process (which may not be optimal) employed by the research team is described in Section 3.6, however, the TIMS is capable to produce a richer and more reliable database with much less time efforts.

5. Findings and recommendations

5.1 major findings from this study

This research project report presented a detailed investigation in determining friction demand corresponding to different site categories in terms of friction skid numbers (SN) for Ohio roadway systems. First, a comprehensive review of the current practice of managing skid resistance to address safety concerns was carried out. Then a comprehensive database was constructed from four ODOT-maintained databases. Next, a preliminary friction demand site categories were proposed and discussed with ODOT subject matter experts based on literature and existing pavement management practices. Some criteria in the definition of site categories have been further adapted by analyzing Ohio crash data. Then, based on the proposed friction demand site categories, two strategies have been employed to determine the friction demand for each site category, namely 1) AASHTO method III and 2) clustering analysis. Major conclusions drawn from this study include the following:

1) Though data for friction-crash analysis can be diverse and existing research efforts demonstrated methods using different sources, the presented study developed and implemented a formal procedure to integrate the required data sources into an effective database in support of the following data analysis.
2) Based on the current data availability, the AASHTO method III in pavement friction management manual does not perform well for Ohio data. Possible reasons include a) limited number of crash events in each bin of the friction number interval, and b) the crash rate corresponding to the friction level with a low number of crash events (either very low or very high friction levels) is not statistically correct.
3) Clustering analysis using Gaussian Mixture Model is a promising tool in analyzing pavement friction data as the statistical similarity in terms of clustered pattern in the SN40S—SN40R space can be detected and extracted so that the drawbacks of traditional histogram-based (or bin size-based) AASHTO method III can be avoided by using clusters instead of bins to overcome the limited number of crash events and expanding the friction data from single measurement (either SN40S or SN40R) to friction number pairs, which can provide a better description of the pavement friction characteristics.
4) The statistical pattern of the joint dataset of SN40S and SN40R can reflect the similarity of the crash events and the further statistical analysis of the crash events in each cluster can reveal the underlying factors (e.g., curvature radius and speed limit) to some extent. Recommended investigatory levels for all friction demand site categories have been summarized.

The study has certain limitations that future research may focus on, including the following:

1) Due to the limited crash data which can be linked with pavement friction measurement, all crash records in the time interval 2014-2018 on the state roadway sections with friction measurement

data were used for the statistical analysis, including crashes of certain crash types that may not have a direct relationship with pavement conditions.

2) In the present research project, all available information has been taken into consideration in a qualitative manner. As mentioned in Section 4.1, determining the friction demand site categories and corresponding criteria for prioritized sites is an iterative process, which involves initial (or current) friction demand categories – data collection and analysis – testing and validation – refined (or updated) categories. At this stage, the definitions of friction demand categories are subjective to some extent as they are mainly based on previous relevant studies, though some tuning regarding the definition of priority sites have been performed using Ohio data and the machine learning method. Following this initial effort, future research should be carried out on topics regarding how to quantitatively identify factors that are related to wet weather crash risk in addition to literature synthesis and engineering experiences.
3) Fitting Gaussian mixture model is a data-driven strategy, which means the extracted statistical pattern only reflects the observed data. Therefore, possible biased estimation may be resulted when the number of crash events is limited (e.g., Category 3 in this study).

5.2 Recommendations for future practices

Based on the findings from this study, the implementation recommendations focus on the adoption of the major research outcome (i.e., Table 25 and 26) that can be used to better identify potential roadway sites with low skid resistance. To be more specific, the implementation procedure are divided into two parts 1) network-level friction evaluation, and 2) project-level new construction or maintenance.

1) Network-level friction evaluation

The literature review suggest that no single variable (i.e., SN40S, SN40R or macrotexture depth) correlates strongly with rate of crashes. By using clustering analysis, it seems that joint analysis of SN40S and SN40R using Gaussian mixture model is a promising means to extract similar crash sites and hence further conducting statistical analysis on multiple factors (e.g., speed limit, curvature radius, and AADT). In the future, joint analysis by adding macrotexture measurement data into the clustering analysis (i.e., clustering data in the SN40S—SN40R—macrotexture three-dimensional feature space) is expected to have better statistical patterns of the pavement friction and texture measurements.

The preliminary recommendations from this study focused on proposing and demonstrating a new alternative (i.e., Gaussian mixture model) to the AASHTO method III when the latter cannot perform well given limited data. Though this proposed method can provide meaningful results with database having a relatively small size, it is recommended that new data should be incorporated when they are available and the analysis should be periodically performed on an annual basis so that possible bias of the statistical patterns can be corrected in a timely manner.

One of the fundamental basis of the proposed method is an accurate and well-formatted friction measurement database. According to the current available friction measurements data from 2011 to 2018, the research team provide the following recommendation for possible improvements regarding the friction database maintenance:

The current data recording practices has some issues when the research team is trying to use the friction data. For example, the table formats are different across different years and sometimes even within a single year. The research team recommends to have all friction measurement files recorded in a same and standard format for better use in the future. NLFID needs to be provided for each measurement site. Additional keys such as COUNTY, ROUTE_NUM, and ROUTE_TYPE are recommended to be included. Macrotexture measurements from high speed laser devices are highly recommended to be incorporated as additional columns.

Though macrotexture data was not considered in this study, previous literature and experiments agree with that there is a general trend that increased macrotexture depth significantly reduces total and wet pavement crashes, particularly on high-speed roadways. It is strongly recommended that taking network-level macrotexture measurements (using laser profiler or similar technologies) into consideration and quantitatively analyze the correlation between friction and macrotexture at a per cluster basis by using the proposed clustering approach. This additional analysis will provide more insights into the correlation and variation of different pavement friction indicators.

2) Project-level new construction or maintenance

Generally, there is no universal single friction number that is safe or unsafe. Each site needs to be considered individually and based on the friction demand of the specific site. A four-step process to evaluate the surface friction was recommended in the ODOT 2008 pavement friction research report (Larson et al., 2008), which can be further improved by adopting the recommended friction demand categories and corresponding investigatory levels from this study:

Step 1: Determine the friction demand for the specific site category. Table 25 can be used as a guidance.

Step 2: Determine the friction intervention level for the specific project site category. It should be noticed that due to the many variables involved, it is more reasonable to define the investigatory levels instead of intervention levels in identifying potential risky roadway sections. For a new construction site or determining where corrective actions should be considered, a good practice for determining the intervention level may be done by reducing the investigatory level by a set amount. More engineering experiences should be involved in this regard.

Step 3: Select corrective action to address critical initial conditions. In this step, proper prioritization needs to be conducted. As minimum friction numbers are not specified for specific project sites, the highway agencies are recommended to use Table 25 to identify most critical sites and then to take special testing in order to determine the most appropriate action so that Table 26 can be satisfied.

Step 4: Adjust design, construction, and maintenance guidelines to minimize a recurrence of friction deficiency problem.

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