RELATIONSHIP BETWEEN SKID RESISTANCE NUMBERS MEASURED WITH RIBBED AND SMOOTH TIRE AND WET-ACCIDENT LOCATIONS

FINAL REPORT

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Due to the recent strategic initiative adopted by the Ohio Department of Transportation (ODOT) to reduce highway crashes, there is a current need to determine if surface friction testing results can be correlated to wet weather crash data in Ohio. The establishment of such correlations would allow ODOT to develop a proactive wet-pavement accident reduction program that would effectively predict locations where wet-pavement crashes may likely occur. Under this study, research was conducted to determine if surface characteristic measurements can be correlated to wet-weather accidents and guidance was provided on the identification of desirable or target friction numbers as a function of site categories and friction demand. A comprehensive literature review was first conducted on pavement surface characteristics, including a review of international research activities. This was followed by a field testing program to evaluate smooth- and ribbed-tire surface friction, as well as pavement macrotexture and roughness, at 90 locations throughout the state. The 90 sections that were selected represent three different site categories: signalized intersections, unsignalized intersections, and congested freeways. These site categories were considered to have the most potential to reduce rear-end crashes. The surface characteristics data from the 90 pavement sections were then analyzed with regards to crash data using both trend analysis and regression modeling techniques. Based on the findings from the field testing program and the available information in the literature, preliminary recommendations were developed for ODOT to consider in its quest for improving the safety of its roadway network.

The main body of this report includes an abbreviated summary of the extensive literature search of both U.S. and international studies, a detailed description of the field testing program, a summary of the data analysis procedures, a summary of the findings and conclusions, and a summary of the final recommendations for implementation. Three appendices are also included as part of the final report. Appendix A presents a comprehensive Annotated Bibliography, Appendix B provides a comprehensive synthesis on pavement surface characteristics (surface texture, friction, noise and roughness), and Appendix C presents data plots that were generated as part of the data analyses.
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Disclaimer

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1. INTRODUCTION

Background

The safety of the nation’s roadways is a current critical national issue. Each year there are over 41,000 fatalities and almost 2.5 million injuries on United States (U.S.) highways, and it has been estimated that inadequate highway pavement conditions contribute to nearly 30 percent of annual highway fatalities (Larson 2005). In addition, an examination of historical crash data indicates that 13.5 percent of fatal crashes and 18.8 percent of all crashes occur under wet pavement conditions (Dahir and Gramling 1990). Statistics such as these have led to the strong interest at both the Federal and state level in advancing accident reduction programs with specific attention focusing on better understanding the relationship between measurable surface characteristics (e.g., friction and texture) and the occurrence of wet-pavement crashes.

The Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) have adopted initiatives to help improve highway safety in the United States. Safety management systems were first mandated by the Intermodal Surface Transportation Efficiency Act of 1991, and while these systems were made optional in 1995, the FHWA later prepared updated guidelines for their development (FHWA 1996). These activities were followed in 1998 by the development of the AASHTO Strategic Highway Safety Plan (AASHTO 1998) and the establishment of NCHRP Project 17-18 to support national implementation of the AASHTO Strategic Highway Safety Plan. Under the NCHRP 17-18 project, a number of implementation guides for specific emphasis areas have been developed.

The Ohio Department of Transportation (ODOT) is also actively involved in finding methods to reduce highway crashes. The agency adopted a strategic initiative in 2006 to “refine, refocus, and respond to Ohio’s high-crash locations,” with specific goals being to:

- Reduce crash frequency by 10 percent by 2015.
- Reduce rear-end crashes by 25 percent by 2015.
- Reduce the state fatality rate to 1.0 per 100 million vehicle miles travel by 2008.
- Reduce the number of annual fatalities to 1100 by 2008.

ODOT is applying a variety of strategies to help meet those goals, including geometric design and traffic engineering improvements, as well as the need for improved pavement surface characteristics. The combination of inadequate pavement surface characteristics and wet pavement conditions is known to significantly contribute to the occurrence of roadway crashes, particularly at critical locations such as horizontal curves, ramps, intersections, and work zones.

Problem Statement

Because of the role that pavement surface characteristics play in wet-pavement crashes, a number of highway agencies have tried to correlate surface friction testing results to wet-pavement crash data in an effort to identify problem locations with a high potential for wet weather crashes. The theory behind this activity is that if a measurable surface characteristic can
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be effectively correlated to crash data, a network testing program could locate and then correct potential wet weather crash locations prior to the crashes occurring.

Due to the recent strategic initiative adopted by ODOT, there is a current need to determine if surface friction testing results can be correlated to wet weather crash data in Ohio. Moreover, testing with both the ribbed tire and smooth tire should be investigated to determine if one is more suitable in developing reliable correlations. The establishment of such correlations would allow ODOT to develop a proactive wet-pavement accident reduction program that would effectively predict locations where wet-pavement crashes may likely occur.

**Objectives**

The overall objectives for this project may be summarized as follows:

- Determine if surface characteristic measurements can be correlated to wet-pavement crashes in Ohio.
- Provide improved guidance on the use of ribbed versus smooth tires for pavement surface friction testing in Ohio, including the identification of suggested minimum surface friction numbers associated with each tire type.
- Provide recommended desirable or target surface friction number as a function of site categories and friction demand.

The products of this research effort will help refine ODOT’s surface characteristic testing program so that the most effective testing methods and procedures are employed, and should help ODOT achieve their long-term goal of reducing total crashes by 10 percent and rear-end crashes by 25 percent by the year 2015.

**Report Approach**

A comprehensive literature review was first conducted (and later updated) on pavement surface characteristics, including a review of international research activities. A field testing program was set up in cooperation with ODOT to evaluate smooth- and ribbed-tire surface friction, as well as pavement macrotexture and roughness, at 90 locations throughout the state. The 90 sections that were selected represent three different site categories: signalized intersections, unsignalized intersections, and congested freeways. These site categories were considered to have the most potential to reduce rear-end crashes. ODOT performed this field testing during the summer and fall of 2007. ODOT also provided a database containing crash data and related information for each of the 90 pavement sections selected and evaluated. The surface characteristics data from the 90 pavement sections were then analyzed with regards to crash data to determine if any significant relationships exist. The analysis included both trend analysis and regression modeling techniques. Based on the findings from the field testing program and the available information in the literature, preliminary recommendations were developed for ODOT to consider in its quest for improving the safety of its roadway network.
Report Organization

This final report documents the entire research effort. Chapter 2 provides an abbreviated summary of the extensive literature available both in the U.S. and internationally to emphasize the complexity of the problem. Both historical and recent research activities are addressed to provide a general summary of the state-of-the-practice. Chapter 3 describes the field testing program that was conducted under the study, including an overview of the pavement sections included in the study and the actual field testing activities. Chapter 4 describes the data analysis work and the development of the preliminary recommendations. Chapter 5 presents a summary of the findings and preliminary recommendations from the study including a discussion of minimum and desirable friction, texture, and roughness criteria for a network-level evaluation, and a procedure for assessing friction on new construction or maintenance projects. Finally, Chapter 6 presents the final recommendations for implementation.

Three appendices are included as part of the final report. Appendix A presents a comprehensive Annotated Bibliography of relevant documents that were reviewed as part of this study. Appendix B provides a comprehensive synthesis on pavement surface characteristics, not only including surface texture and friction, but also noise and roughness. Appendix C presents data plots that were generated as part of the data analyses described in chapter 4.

An Executive Summary document for the project is provided separately. The Executive Summary presents a brief overview of the project and highlights the findings and recommendations.
2. SUMMARY OF LITERATURE REVIEW

Introduction

The last several years have seen a veritable explosion of information on roadway and highway safety, specifically on the role that pavement friction, texture, and roughness play in reducing total and particularly wet-pavement crashes. Under this project, a detailed literature review of both national and international sources was conducted on pavement surface characteristics, which resulted in the development of the Annotated Bibliography presented in Appendix A. Those documents served as the foundation for the preparation of a synthesis document on pavement surface friction and texture, which provides a summary of both national and international practices for measuring and assessing those important surface characteristics, and their impact on highway safety. That synthesis is presented in Appendix B. A short summary of some of the highlights gleaned from that detailed synthesis is presented in this chapter.

Historical Overview of Highway Safety

Highway Safety

Highway safety has been identified as a significant roadway issue for nearly 100 years, yet over the years there have been few national attempts to address it. Herbert Hoover, as Secretary of Commerce, convened the first national conference on highway safety in 1924 (Tignor 2006). Later, national, high-profile conferences on highway safety were supported by President Truman in 1946, 1947, and 1949, and by President Eisenhower in 1954 (Tignor 2006).

It was not until 1966 that major national legislation—the Highway Safety Act of 1966—was enacted to address the increasing highway safety problem. Subsequent hearings by the Special Subcommittees on the Federal-Aid Highway Program of the Committee on Public Works were held in 1968 and 1971 (Tignor 2006). Due to the lack of progress in making substantial reduction in annual fatalities and serious injuries, there has been a recent proposal to hold another national conference on highway safety.

While the most recent highway bill—Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)—has increased funding for highway safety, the inherent problem still remains. Background information for that legislation suggests that poor pavement conditions (including poor friction and texture) contribute to (but not necessarily cause) up to 30 percent of the annual highway crashes (Larson 2005). The 41,000 annual fatalities and 2.5 million serious injuries that are experienced annually on the nation’s highway network are considered unacceptable. In 2000, it was estimated that the national cost of highway fatalities exceeds $230 billion per year (Noyce et al. 2007).

Great Britain, Canada, and Australia, among other countries, have implemented far-reaching highway safety program and over the years have achieved significant decreases in crash rates. While the European community reduced fatalities by 59 percent from 1970-2004, there was only a 19 percent reduction in the United States (Larson 2005). If the U.S. would have matched the reduction in crash rates realized by some of those countries, there would have been 200,000 fewer fatalities in the U.S. from 1979-2002 (Evans 2006). Clearly, a more proactive approach to this problem in the U.S. is needed.
Wet-pavement crashes have plagued highway safety efforts for many years. A 1980 report by the National Transportation Safety Board concluded that in the United States fatal accidents occur on wet pavements at a rate of from 3.9 to 4.5 times the rate of occurrence on dry pavements (NTSB 1980). The Nationwide Personal Transportation Survey of 1990 reports that of the almost 25 million reported accidents, 18.8 percent occurred on wet pavements (FHWA 1990). The literature also supports that up to 70 percent of the wet-pavement crashes can be prevented or minimized by improved pavement friction and texture (Henry 2000).

Pavement Friction

One of the earliest studies on pavement friction was conducted in 1934 by Moyer, which indicated that wet pavement friction or “skid resistance” decreases with increasing highway speed (Moyer 1934). It is often assumed that the friction on any dry surface is adequate; however, this is clearly a fallacy as it is consistency shown that when the wet pavement crashes have significantly been reduced, there is usually a corresponding decrease in dry pavement crashes as well. Unfortunately, the role of microtexture and macrotexture in reducing the unacceptable number of annual deaths and serious injuries is still not well understood, and is a major focus of much of the current research.

The First International Skid Prevention Conference was held in 1958 in Charlottesville, Virginia (HRB 1959). Proceedings of that original conference were recently re-published and made available. The first major guidance in the U.S. on pavement surface friction was published by the National Cooperative Highway Research Board (NCHRP) in 1967 (Kummer and Meyer 1967), which even to this day continues to be a major resource document. Corsello (1993) provided an update to the guidance in NCHRP Report 37 using more current information on pavement friction testing (note, however, that caution is advised when considering the friction numbers recommended in that report because Washington State’s hard, durable aggregates are significantly different than the soft limestone aggregates found in other states).

In the early 1970s, a considerable amount of work on pavement skid resistance and friction was conducted. For example, an Anti-Skid Program Workshop was sponsored by the Highway Research Board in 1971 (Marsh 1971), a Symposium on Skid Resistance of Highway Pavements was sponsored by ASTM in 1972 (ASTM 1973), and a major HRB Synthesis was produced in 1972 (HRB 1972). These activities were followed by the publication of AASHTO’s Guidelines for Skid Resistant Pavement Design (AASHTO 1976) (which, incidentally, is currently being updated under NCHRP Project 1-43) and by the Second International Skid Prevention Conference, which was held in Columbus, Ohio, in 1977. The proceedings from that conference are found in Transportation Research Record 621 (TRB 1977a), with ancillary conference papers found in Transportation Research Records 622 through 624 (TRB 1977b; TRB 1977c; TRB 1977d).

Also in the 1970s, the Federal Highway Administration produced several valuable resource documents on pavement friction and safety, including a report on Pavement Texture and Available Skid Resistance (FHWA 1977) and two technical advisories:

- T 5140.10, Texturing and Skid Resistance of Concrete Pavements and Bridge Decks, September 18, 1979 (updated in 2005).
- T 5040.17, *Skid Accident Reduction Program*, December 23, 1980 (which is currently in the process of being updated).

Other valuable source documents produced in the U.S. over the last 20 years include the NCHRP Synthesis on wet-safety programs in 1990 (Dahir and Gramling 1990), the FHWA report on portland cement concrete (PCC) surface texturing in 1996 (Hibbs and Larson 1996), and the NCHRP Synthesis on pavement friction characteristics (Henry 2000). As can be seen, up until recently, much of the available information and major research in the U.S. was conducted in 1980 or before. With the advanced technology currently available (Ogle 2007), many of the critical issues are being revisited to provide improved guidance.

**International Resources**

**Introduction**

As discussed previously, highway safety is a worldwide problem. Worldwide there are over one million annual deaths and over 50 million annual injuries, with an even larger problem in developing countries as compared to the more developed countries. Some of the major international safety-related activities are described in this section.

Since 1988, there have been five International Symposiums on Pavement Surface Characteristics, which are held every four years. The previous conferences were held:

1. June 8-9, 1988 in State College, PA.

The 6th symposium is scheduled for October 20-22, 2008, and will be held in Portoroz, Slovenia. These conferences address all aspects of pavement surface characteristics, including friction and texture, and draw a worldwide audience. Unfortunately, these international conferences attract limited U.S. participation.

In addition to the above international symposiums, there have been two International Surface Friction Conferences. The first was held May 1-5, 2005 in Christchurch, New Zealand and the second, May 11-14, 2008 in Cheltenham, England (proceedings from both conferences are available at [www.saferroads.org.uk](http://www.saferroads.org.uk)). These conferences have highlighted the road safety approaches used by other countries, most notably the United Kingdom (U.K.). As such, they provide a significant amount of detail on the development of the U.K. friction policy, results obtained from monitoring the process, and significant information on implementing the process in the U.K. and other countries, particularly Australia and New Zealand.

Another important international effort was the PIARC 1st International Experiment to Harmonize Friction and Texture (PIARC 1995), which produced the International Friction Index (IFI)
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currently being evaluated for application in the U.S. PIARC also developed a *Road Safety Manual*, which was released in 2005 (PIARC 2005).


The above items are intended to be a sample of the significant research available throughout the world that can help others to proactively address the highway safety problem and reduce the annual number of fatalities and serious injuries. Because the U.K. process is probably the most comprehensive program in the world, and because it is similar to that proposed as the basis for the guidelines developed under NCHRP 1-43, an overview of the U.K. procedures is provided. More specific references and significant research findings are included in Appendix B.

**Summary of U.K. Friction Program**

In 1989, the U.K. implemented their Skid Resistance Policy for managing skid resistance of its trunk road network (Viner, Sinhal, and Parry 2005). In 2004, after 15 years of operation, a revision to the policy was implemented (Viner and Caudwell 2008). A summary of some of the key features of the U.K. program follows.

A database of pavement condition, road geometry, traffic flow, and crash data for English trunk roads was developed for an accident analysis. A GIS package was used to assign the accident locations, recorded as 10 digit grid references, to individual road lengths. The mean and 95 percentile accident risk were calculated for the different bands of skid resistance, with the overriding goal being to basically equalize risk in the different site categories used. A total of 13 site categories were originally established in 1988, but these were later reduced to 10 categories in 2004. The categories are based on friction demand for the various sites (Viner, Sinhal, and Parry 2004). In 2007, an Interim Advice Note was issued to provide additional guidance on selecting the appropriate Investigatory Level (IL) for some of the 10 site categories that were identified (Highway Agency 2007). The Investigatory Level is not a proven high accident location, but instead identifies locations where additional evaluation is desired to determine whether or not low friction or texture depth is likely to be contributing to higher crash rates. The assignment of various friction Investigatory Levels based on friction demand for each site category varies substantially from the single minimum friction number approach currently used throughout much of the U.S.

Another major difference is that the U.K. has required a minimum texture depth (usually 0.06 in [1.5 mm]) since 1976. If the texture depth at a specific site is less than 0.04 in (1.0 mm), as measured by the sand patch test, the required skid resistance (as measured by the SCRIM) is increased by 0.05 SR (Viner, Sinhal, and Parry 2004). Research is currently underway to evaluate if this criteria should be reduced for smaller maximum size coarse aggregate thin surface treatments (Woodward et al. 2008; Roe and Caudwell 2008). The increased use of thin surface treatments (where the existing pavement structure is adequate) is critical to reduce the
demand for high quality aggregate and binder materials and also to reduce overall transportation costs.

In addition to emphasizing the Investigatory Level (as opposed to an Intervention Level), SCRIM data are collected continuously annually on the network along with macrotexture data. The U.K. has a process to make seasonal corrections to the SCRIM data (Donbavand and Kennedy 2008), and produces a report annually on the results of their monitoring activities. Current data show that about 8 percent of their network is below the Investigatory Level established (Sinha and Viner 2008).

Several other factors also distinguish the U.K. program. First is the preparation of approved products list (HAPAS), which is used to provide appropriate levels of friction and texture where surface treatments are required at the specific sites. This generally allows alternative proprietary products to be used that are suitable to providing the necessary texture/friction for the various situations. A second significant factor is the use of Road Safety Audits to select the treatment proposed for sites below the Investigatory Level. If funding is not available to correct any skid related problems identified, advisory signs are erected until the required corrective actions can be taken.

The U.K. estimates that their skid resistance policy has a 5:1 benefit cost ratio (Sinha and Viner 2008). This has not yet been fully verified, but it is anticipated that the actual benefits may be higher with the refinements made in 2004. The U.K. does have one of the lowest accident rates in the world and they have been generally been successful at meeting their 10-year accident reduction goals (even with a very low initial rate). In addition, as further evidence of their success, variations of this approach have now been implemented in numerous countries around the world.

**Recent U.S. Initiatives**

In the last decade, there has been a significant increase in research and other activities conducted in the U.S. to address the highway safety problem. The most comprehensive approach is outlined in the AASHTO Strategic Highway Safety Plan, which was prepared in response to the AASHTO/FHWA goal of reducing the U.S. highway fatality rate to 1.0 fatality per 100 million vehicle miles of travel in 2008 (which, at present, appears unlikely of being attained in most states). This plan has been supported by a number of NCHRP research projects, particularly NCHRP Project 17-18, *Implementation of the Strategic Highway Safety Plan*, which has produced a number of major reports covering a wide range of highway safety related topics (NCHRP 2003). One of the series of these reports is NCHRP Report 500, Volume 21, “A Guide for Addressing Safety Data and Analysis in Developing Emphasis Area Plans” which is currently being published.

The NCHRP has also produced several synthesis documents in the area of pavement friction and highway safety, specifically:


In addition, a draft *Guide for Pavement Friction* was produced under NCHRP Project 1-43 in 2006 (Hall et al. 2006), and is currently being considered by AASHTO for possible adoption and publication. This document provides substantial guidance on developing improved skid resistance (friction and texture) programs, with detailed guidelines for highway agencies to implement improved processes suited for their specific conditions.

In 2006 and 2007, three other friction-related summary reports were prepared. A draft report, *Skid Crash Reduction Programs – Synthesis of Current Practice*, was prepared as the basis to help update the 1980 FHWA Technical Advisory T 504017, Skid Accident Reduction Program (Perera, Pulipaka, and Kohn 2007). Also, a report, *Assessment of Friction-Based Pavement Methods and Regulations*, was produced that included a survey of current practices in eight states (Shaffer, Christiaen, and Rogers 2006). Finally, a recent study on hot-mix asphalt (HMA) pavement friction (Noyce et al. 2007) contains an extensive literature review and a survey of practices in a number of States, mostly in the Midwest.

In addition, the work under NCHRP 17-25 will contain an appendix that includes an evaluation of crash modification factors for improving the pavement surface friction and texture (Lyon and Persaud 2008). This is believed to be the first time that skid resistance has been included as a countermeasure to reduce the number and severity of highway crashes, and is based on the successful New York DOT skid accident reduction program (SKARP) (Bray 2003). The New York program indicated that skid resistance improvements (using non-carbonate aggregates) can yield substantial safety benefits for both intersections and road segments, but the keys to achieving those benefits is that the projects must be targeted at locations that have low skid resistance and a correspondingly high frequency of wet-pavement crashes (Bray 2003). It is believed that this approach will be incorporated into the TRB Highway Safety Manual (and related safety analysis tools) now under development (Council and Harkey 2006). Also, Research Results Digest No. 329, “Highway Safety Manual Data Needs Guide” was just recently published.

It is estimated that about 90 percent of the paved roads in the U.S. have an asphalt surface or wearing course. Therefore, the mix or thin surfacing design procedures to address friction and texture is a very critical item, and a substantial amount of research is currently underway (Noyce et al. 2007; Luce et al. 2007; Williams 2008). The mix design process is also emphasized in the draft pavement friction guide developed under NCHRP 1-43 (Hall et al. 2006).

Safety considerations are also an important part of the Transportation System Preservation Research, Development, and Implementation Roadmap published in January 2008 (FHWA 2008). One proposed project is to evaluate the safety aspect of pavement preservation. It is possible to impact the surface characteristics of a large percentage of a highway network in a relatively short period of time (i.e., 5 years), provided that a major effort is made to match the friction and texture provided with friction demand during the pavement preservation program. This was demonstrated by the New York DOT in the 1990s, when a successful pavement preservation program reduced the number of miles in poor condition in half and the number of miles in good condition was increased by about 20 percent (Zimmerman and Wolters 2003). In
conjunction with the State’s Skid Accident Reduction Program (SKARP) and Safety Appurtenance Program, New York achieved a 34 percent reduction in annual fatalities from 1990 to 2000.

While concrete surfaces represent a smaller share of the paved road mileage, they carry a significant portion of the automobile and truck traffic. As such, significant research tracks are outlined for friction- and texture-related issues (including safety, noise, splash and spray, and rolling resistance) in the Long-Term Plan for Concrete Pavement Research and Technology (Ferragut, Harrington, and Brink 2005; Ferragut et al. 2005; Ferragut et al. 2007). Some research on these topics is already underway. It is likely that friction prediction models developed during laboratory mix design evaluations will be different for hot-mix asphalt, bituminous surface treatments, and portland cement concrete pavement surfaces.

**Ohio Department of Transportation Efforts**

Over the last decade, the Ohio Department of Transportation (ODOT) has played an active role in safety-related research and initiatives. For example, ODOT has developed significant safety-related data collection and analysis procedures, has developed base crash rates for intersections and freeways to help identify those with higher than average rates, has developed various crash reduction factors for various countermeasures (other than friction and texture related items), and has implemented a significant Road Safety Audit Program. Furthermore, ODOT is conducting research on the friction qualities of various (particularly limestone) aggregates. In recognition of Ohio’s significant comprehensive safety-related databases, ODOT was included as part of FHWA’s Highway Safety Information System (HSIS) program, and is also one of the highway agencies testing the FHWA SafetyAnalyst program.

ODOT has an effective highway safety program as evidenced by the fact that they are one of the few states consistently reducing not only the highway fatality rates, but also the actual number of annual fatalities statewide. It is essential that not only the fatality rate be reduced, but also that there be a substantial reduction in the actual number of fatalities in each State, if a quantum improvement in highway safety is to be made. ODOT’s accomplishments in this area are significant.
3. FIELD TESTING PROGRAM

Introduction
In order to analyze the impact of different roadway characteristics on roadway crashes, roadway characteristic data needed to be collected from selected sites around the state of Ohio. The first step of this process was to determine what sites would be included in the study. Because it was important to use sections in this study that represented a large range of crash rates, the crash data were used to help identify the final sites. A total of 90 different site locations were ultimately selected for inclusion in the final data set. Once the 90 sites were identified, inventory and traffic data were collected from ODOT’s road inventory system and detailed crash information was collected from ODOT’s crash record system. Finally, field testing that collected friction, macrotexture, international roughness index (IRI), and rutting information was conducted to complete the analysis data set for this study. The remainder of this chapter describes the details of all aspects of the field testing program used for this project.

Selection of Site Locations
The first step in developing the design for the field experiment was to determine what types of projects or site categories should be included in the study. The selection of site categories was based on ODOT’s 2006 strategic initiative to focus on high crash locations, with the specific goals of reducing crash frequency by 10 percent and rear-end crashes by 25 percent by the year 2015. Based on the literature review, it was determined that the primary factor for selecting sites which might have poor skid resistant pavement surfaces was the wet/total crash rate. After discussions with ODOT personnel, the following three different site categories were chosen for inclusion:

- Congested freeway segments—Sections of freeway that are congested (particularly during peak periods) where breakdowns to the traffic flow regularly or periodically occurs. Disruptions in traffic flow greatly increase the potential for crashes and particularly rear-end crashes.

- Signalized intersections—Intersections with traffic signals where slowing and stopping traffic actions due to red lights increases the potential for more crashes and particularly rear-end crashes.

- Unsignalized intersections—Intersections without traffic signals. These locations create potential conflicts because vehicles crossing the intersection or making turning movements significantly increases the potential for crashes and particularly rear-end and right-angle crashes. The problem is related to gap acceptance by drivers on the intersecting street.

These three categories are believed to be reflective of sites where improvements in friction and texture will have a high potential for reducing both total and rear-end crashes (particularly on wet pavements). Although this selection process may have biased the data towards higher crash locations that are not necessarily representative of the network as a whole (i.e., the majority of the network is represented by free flowing freeways and other 2 or 4 lane state highways), the analysis attempted to identify the role of increased skid resistance in reducing total crashes and wet/total crash rates at critical locations.
Within each selected site category type, it was important to get data that represented a wide range of wet/total crash ratios. To address the desired need for a range of wet/total crash rates, ODOT personnel first compiled a pool of projects for each site category type. Next, each pool of projects was subjectively divided into three groups: those with low crash rates (30 percent of the sections having the lowest wet/total crash rates), those with medium (or average) crash rates (40 percent of the sections with intermediate wet/total crash rates), and those with high crash rates (30 percent of the sections with the highest wet/total). Finally, 30 sections for each of the three separate site categories (i.e., 90 sections total) were manually selected by ODOT personnel so that approximately one-third of the 30 sections represented each of the three wet/total crash rate groups. A summary of the final number of selected site locations for each category and their associated wet/total crash ratio ranges is presented in table 1.

Table 1. Summary of wet/total crash ratios ranges associated with the low, medium, and high crash rate groups for each site category.

<table>
<thead>
<tr>
<th>Site Category</th>
<th>Crash Rate Groups</th>
<th>Number of Final Site Locations</th>
<th>Wet/Total Crash Ratio Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congested Freeways</td>
<td>Low</td>
<td>11</td>
<td>0.031 to 0.143</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>9</td>
<td>0.194 to 0.348</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>10</td>
<td>0.364 to 0.465</td>
</tr>
<tr>
<td>Signalized Intersections</td>
<td>Low</td>
<td>9</td>
<td>0.000 to 0.125</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>10</td>
<td>0.150 to 0.333</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>11</td>
<td>0.350 to 0.759</td>
</tr>
<tr>
<td>Unsignalized Intersections</td>
<td>Low</td>
<td>10</td>
<td>0.056 to 0.091</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>10</td>
<td>0.143 to 0.333</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>10</td>
<td>0.353 to 0.706</td>
</tr>
</tbody>
</table>

In addition to the distribution of wet/total crash ratios, it was also desired that the sections be selected such that there was good geographic coverage of the state. To accomplish this goal, ODOT personnel also considered geographic location during the final site selection process. To illustrate the geographical coverage represented by the final data set, table 2 summarizes the final number of projects included in the twelve ODOT districts.

In addition to geographical distribution, a special attempt was made to ensure that the total sample included sections that could be expected to have the full range of performance from very poor to very good. Site locations with known skid resistance problems were included to represent very poor performance, while site locations with high skid resistance surface treatments were included to represent very good performance. Detailed summaries of the final sections chosen for the congested freeways, signalized intersections, and unsignalized intersections site categories are summarized in tables 3 through 5, respectively.
Table 2. Summary of final selected sites by site category and district.

<table>
<thead>
<tr>
<th>District</th>
<th>Congested Freeways</th>
<th>Signalized Intersections</th>
<th>Unsignalized Intersections</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>30</strong></td>
<td><strong>30</strong></td>
<td><strong>30</strong></td>
</tr>
</tbody>
</table>

Data Compilation

Compilation of Section Inventory Data

After the final list of sections was prepared, useful inventory data was retrieved from ODOT’s road inventory system and location referencing system. The final data tables provided by ODOT included the following data elements for all 90 site locations:

- District number.
- Intersection or Section ID.
- Beginning and ending section log points (BLOG and ELOG).
- Pavement type.
- Cross street name and ID.
- Average daily traffic (ADT).
- Number of lanes.
- Surface treatment information (surface treatment, material, and date of last treatment).
Table 3. Summary of final selected congested freeway site locations.

<table>
<thead>
<tr>
<th>Crash Rate Group</th>
<th>District</th>
<th>County</th>
<th>Route Number</th>
<th>Intersection ID/Section ID</th>
<th>BLOG</th>
<th>ELOG</th>
<th>Pavement Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>2</td>
<td>WOO</td>
<td>75</td>
<td>431</td>
<td>26</td>
<td>26.5</td>
<td>Composite</td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>MAH</td>
<td>80</td>
<td>17</td>
<td>5</td>
<td>5.5</td>
<td>Composite</td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>TRU</td>
<td>80</td>
<td>266</td>
<td>2.5</td>
<td>3</td>
<td>Composite</td>
</tr>
<tr>
<td>Low</td>
<td>5</td>
<td>LIC</td>
<td>70</td>
<td>336</td>
<td>1</td>
<td>1.5</td>
<td>Flexible</td>
</tr>
<tr>
<td>Low</td>
<td>5</td>
<td>LIC</td>
<td>70</td>
<td>139</td>
<td>3</td>
<td>3.5</td>
<td>Flexible</td>
</tr>
<tr>
<td>Low</td>
<td>6</td>
<td>FRA</td>
<td>70</td>
<td>178</td>
<td>9.5</td>
<td>10</td>
<td>Flexible</td>
</tr>
<tr>
<td>Low</td>
<td>6</td>
<td>FRA</td>
<td>270</td>
<td>222</td>
<td>9.5</td>
<td>10</td>
<td>Flexible</td>
</tr>
<tr>
<td>Low</td>
<td>7</td>
<td>CLA</td>
<td>70</td>
<td>70</td>
<td>15.5</td>
<td>16</td>
<td>Composite</td>
</tr>
<tr>
<td>Low</td>
<td>7</td>
<td>MOT</td>
<td>70</td>
<td>19</td>
<td>8.5</td>
<td>9</td>
<td>Composite</td>
</tr>
<tr>
<td>Low</td>
<td>8</td>
<td>BUT</td>
<td>75</td>
<td>43</td>
<td>5.5</td>
<td>6</td>
<td>Jointed Concrete</td>
</tr>
<tr>
<td>Low</td>
<td>8</td>
<td>GRE</td>
<td>675</td>
<td>276</td>
<td>9.5</td>
<td>10</td>
<td>Composite</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>LUC</td>
<td>75</td>
<td>343</td>
<td>6.5</td>
<td>7</td>
<td>Composite</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>LUC</td>
<td>475</td>
<td>13</td>
<td>14</td>
<td>14.5</td>
<td>Composite</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>STA</td>
<td>77</td>
<td>385</td>
<td>14.5</td>
<td>15</td>
<td>Composite</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>TRU</td>
<td>80</td>
<td>429</td>
<td>0.5</td>
<td>1</td>
<td>Composite</td>
</tr>
<tr>
<td>Medium</td>
<td>5</td>
<td>LIC</td>
<td>70</td>
<td>334</td>
<td>0</td>
<td>0.5</td>
<td>Flexible</td>
</tr>
<tr>
<td>Medium</td>
<td>6</td>
<td>FRA</td>
<td>71</td>
<td>212</td>
<td>23.83</td>
<td>24.33</td>
<td>Composite</td>
</tr>
<tr>
<td>Medium</td>
<td>6</td>
<td>FRA</td>
<td>270</td>
<td>253</td>
<td>35.5</td>
<td>36</td>
<td>Flexible</td>
</tr>
<tr>
<td>Medium</td>
<td>7</td>
<td>CLA</td>
<td>70</td>
<td>62</td>
<td>11.5</td>
<td>12</td>
<td>Composite</td>
</tr>
<tr>
<td>Medium</td>
<td>7</td>
<td>MOT</td>
<td>75</td>
<td>357</td>
<td>3.5</td>
<td>4</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>7</td>
<td>MOT</td>
<td>75</td>
<td>371</td>
<td>14.5</td>
<td>15</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>7</td>
<td>MOT</td>
<td>75</td>
<td>372</td>
<td>15</td>
<td>15.5</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>8</td>
<td>HAM</td>
<td>74</td>
<td>299</td>
<td>17.5</td>
<td>18</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>8</td>
<td>HAM</td>
<td>75</td>
<td>302</td>
<td>1.22</td>
<td>1.72</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>8</td>
<td>HAM</td>
<td>75</td>
<td>304</td>
<td>2.22</td>
<td>2.72</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>8</td>
<td>HAM</td>
<td>75</td>
<td>316</td>
<td>14.22</td>
<td>14.72</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>12</td>
<td>CUY</td>
<td>71</td>
<td>81</td>
<td>17.5</td>
<td>18</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>12</td>
<td>CUY</td>
<td>77</td>
<td>103</td>
<td>14</td>
<td>14.5</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>12</td>
<td>CUY</td>
<td>90</td>
<td>105</td>
<td>14</td>
<td>14.5</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>12</td>
<td>CUY</td>
<td>480</td>
<td>158</td>
<td>21</td>
<td>21.5</td>
<td>Composite</td>
</tr>
</tbody>
</table>
### Table 4. Summary of final selected signalized intersection site locations.

<table>
<thead>
<tr>
<th>Crash Rate Group</th>
<th>District</th>
<th>County</th>
<th>Route Number</th>
<th>Intersection ID/ Section ID</th>
<th>BLOG</th>
<th>ELOG</th>
<th>Pavement Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low 1</td>
<td>DEF</td>
<td>111</td>
<td>184369</td>
<td>6.88</td>
<td>N/A</td>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td>Low 1</td>
<td>VAN</td>
<td>118</td>
<td>353230</td>
<td>10.44</td>
<td>N/A</td>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td>Low 3</td>
<td>CRA</td>
<td>19</td>
<td>175309</td>
<td>2.86</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Low 4</td>
<td>ATB</td>
<td>20</td>
<td>104678</td>
<td>4.67</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Low 5</td>
<td>FAI</td>
<td>158</td>
<td>200859</td>
<td>0.37</td>
<td>N/A</td>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td>Low 6</td>
<td>DEL</td>
<td>23</td>
<td>190443</td>
<td>4.45</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Low 7</td>
<td>MIA</td>
<td>55</td>
<td>480965</td>
<td>12.07</td>
<td>N/A</td>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td>Low 10</td>
<td>GAL</td>
<td>160</td>
<td>207082</td>
<td>0.00</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Low 11</td>
<td>COL</td>
<td>164</td>
<td>167011</td>
<td>25.80</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Medium 2</td>
<td>LUC</td>
<td>51</td>
<td>325816</td>
<td>1.52</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Medium 3</td>
<td>WAY</td>
<td>30</td>
<td>373409</td>
<td>24.03</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Medium 5</td>
<td>FAI</td>
<td>188</td>
<td>200973</td>
<td>14.9</td>
<td>N/A</td>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td>Medium 5</td>
<td>KNO</td>
<td>36</td>
<td>267899</td>
<td>19.21</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Medium 6</td>
<td>FRA</td>
<td>23</td>
<td>39522</td>
<td>16</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Medium 7</td>
<td>MOT</td>
<td>741</td>
<td>515455</td>
<td>0.76</td>
<td>N/A</td>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td>Medium 8</td>
<td>HAM</td>
<td>32</td>
<td>68860</td>
<td>4.46</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Medium 9</td>
<td>HIG</td>
<td>50</td>
<td>243444</td>
<td>14.01</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Medium 9</td>
<td>SCI</td>
<td>52</td>
<td>548821</td>
<td>21.03</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Medium 12</td>
<td>CUY</td>
<td>43</td>
<td>76602</td>
<td>5.03</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>High 1</td>
<td>ALL</td>
<td>117</td>
<td>98142</td>
<td>18.01</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>High 1</td>
<td>HAN</td>
<td>224</td>
<td>230783</td>
<td>16.94</td>
<td>N/A</td>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td>High 2</td>
<td>WOO</td>
<td>795</td>
<td>385366</td>
<td>4.8</td>
<td>N/A</td>
<td>Flexible</td>
<td></td>
</tr>
<tr>
<td>High 3</td>
<td>LOR</td>
<td>57</td>
<td>302539</td>
<td>18.3</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>High 3</td>
<td>LOR</td>
<td>57</td>
<td>302544</td>
<td>18.97</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>High 4</td>
<td>ATB</td>
<td>534</td>
<td>104552</td>
<td>20.74</td>
<td>N/A</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>High 4</td>
<td>POR</td>
<td>14</td>
<td>583015</td>
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<tr>
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<td>219346</td>
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<td>77218</td>
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Table 5. Summary of final selected unsignalized intersection site locations.

<table>
<thead>
<tr>
<th>Crash Rate Group</th>
<th>District</th>
<th>County</th>
<th>Route Number</th>
<th>Intersection ID/ Section ID</th>
<th>BLOG</th>
<th>ELOG</th>
<th>Pavement Type</th>
</tr>
</thead>
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<tr>
<td>Low</td>
<td>2</td>
<td>WOO</td>
<td>23</td>
<td>385547</td>
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<td>POR</td>
<td>59</td>
<td>583362</td>
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<td>Composite</td>
</tr>
<tr>
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<td>172</td>
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<tr>
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<td>MUS</td>
<td>60</td>
<td>528306</td>
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</tr>
<tr>
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<td>MUS</td>
<td>60</td>
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<tr>
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<td>6</td>
<td>DEL</td>
<td>605</td>
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</tr>
<tr>
<td>Low</td>
<td>6</td>
<td>MRW</td>
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<td>800</td>
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</table>
• Condition information (PCR, subjective rutting indicator [none, slight, severe], and a subjective roughness indicator [low, medium, high]). In addition, actual roughness was measured and analyzed for a majority of the sections.
• Horizontal curve information (none, slight, sharp).
• Approach grade information (subjective ratings such as level, up slight, down slight, etc.)
• Posted speed limit (in mi/hr).
• Sight distance information (subjective ratings such as none, short, medium, and long).
• Superelevation information.

Compilation of Section Crash Data
In addition to the inventory data for the 90 selected site locations, ODOT personnel also compiled necessary crash data for the study from data retrieved from ODOT’s crash record system. For each individual site location, 3-year crash data totals (for the years 2003 to 2005) were provided for the following crash types:

• Total crashes (total number, rear end crashes, wet pavement crashes, wet/total ratio, and rear end crash rate [per 100 MEV for intersections; per 100 MVMT for freeways]). Note: MEV = million entering vehicles; MVMT = million vehicle miles traveled.
• Day crashes (total number, rear end crashes, and wet pavement crashes).
• Night crashes (total number, rear end crashes, and wet pavement crashes).
• Percent crashes by direction.

Field Data Collection Activities
The field testing portion of this study included the following activities:

• Friction testing at each location using different testing speeds and ribbed and smooth tires.
• Macrotexture and roughness (IRI) measurements on the majority of sections using profile data.
• Rutting measurements from profile data on a limited number of sections.
• The completion of site assessment forms and photo logs to document useful information about each site.

Each of these different field testing activities is discussed in more detail below.

Friction Testing
For this study, multiple friction tests were conducted at each selected site in order to assess: 1) which friction testing speed and tire would correlate best with crash data, and 2) to allow an evaluation of the speed gradient. Testing was conducted in only one direction at each site location. The final direction of testing was usually chosen by ODOT field personnel as the
direction with the largest percentage of crashes reported in the crash data summary. In the rare occasion where the percentages were equal for more than one direction, the logistical characteristics of the site were assessed and the testing was completed in the direction on the State Route that was deemed easiest to test. All testing was completed in the inner wheelpath of the outside lane (i.e., furthest right lane) in the selected direction of testing.

To obtain useful friction testing data for this study, friction testing was completed at each selected site using both a ribbed tire (ASTM E 501) and a smooth tire (ASTM E 524) and at two different speeds. The two selected test speeds consisted of one set of tests at 40 mi/hr (64 km/hr), and a second set of tests either at 20 mi/hr (32 km/hr) or 60 mi/hr (97 km/hr) (depending on the facility type). Congested freeways used test speeds of 40 and 60 mi/hr (64 and 97 km/hr), while all but two intersections (that were tested at 40 and 60 mi/hr [64 and 97 km/hr]) were tested at speeds of 20 and 40 mi/hr (32 and 64 km/hr). The 0.5-mi (0.8-km) long congested freeway sections were tested five times in one pass in accordance with ASTM requirements. The 500 ft (152 m) approaches to intersections generally required two passes to get a minimum of three friction tests. This was considered acceptable because these sets of tests were repeated with both ribbed and smooth tires. Friction testing was completed by ODOT personnel using two locked-wheel friction testers—one older International Cybernetics Corporation (ICC) unit and one Dynatest model 1295 unit—operating in accordance with the testing procedures outlined in ASTM E 274. The use of two trailers was required to complete the testing within the time constraints of this research study and for ODOT’s routine friction testing program. Both friction testers were calibrated within 2 months of the commencement of testing. The raw friction numbers were adjusted to reflect the calibration constants for the two different friction testers used, but the data were not adjusted to correct for the actual testing speed within the 20, 40, or 60 mi/hr (32, 64, and 97 km/hr) speed categories. Due to the relatively low actual speed gradients (typically less than 0.2 FN per mi/hr [0.12 FN per km/hr]) for most of the sections, the lack of this speed adjustment is unlikely to have a significant effect on the analysis conducted.

Texture, Profile, and Rutting Testing

ODOT recently acquired a profile van that has a texture and profile laser in left wheelpath and profile laser in right wheelpath. Under the testing program, macrotexture data were collected for 85 of 90 site locations, and IRI data were collected for 89 of 90 site locations. The macrotexture data were summarized every 1 ft (0.3 m) (for possible later use if it was determined necessary to change the sample section length) and every 20 ft (6.1 m) (to give a minimum of 25 samples on the 500 ft [152 m] intersection approaches). The IRI data were also summarized using a 20 ft (6.1 m) sliding baselength (using the ProVAL software) to subsequently analyze if short sections of roughness increased the wet/total crash ratio or the number of total and rear-end crashes. In addition, ODOT collected rutting data on 16 of the 90 site locations, but these data were not considered as part of the final analysis because of the few number of sites tested and the fact that there was very little rutting in the sections.

Because the macrotexture data for this study were collected using the profiler van, it would be very interesting to compare the collected laser MPD data to sand patch tests at the same locations. Although this comparison was not conducted during this study, ODOT is currently evaluating this relationship on the sections used to calibrate the friction testers. Also, a high resolution Ames Engineering LTS9200 Laser Texture Scanner was purchased by ODOT to assist
in this evaluation. This stationary testing device can measure both microtexture and macrotexture.

**Site Assessment Form and Photo Log Record**

For each site location, the ODOT field testing personnel completed a site assessment form that documented the general site conditions, the direction of the friction testing, and noted any special situations that might affect the crash rate. In addition, ODOT compiled photographs taken every 50 ft (15.2 m) from their video log system, so that general site conditions could also be reviewed later without returning to the field. A summary of comments on the site assessment form for each section are included in the data along with a copy of each individual site assessment form. A sample site assessment form is included in figure 1. It should be noted that the objective testing data (not the subjective ratings on the site assessment form) were used in the actual data analysis.

**Summary**

This chapter describes the field testing program that was conducted under this research project. A total of 90 sites were selected for the testing program, and these were selected based largely on the prevalence of crash data (specifically how it fit into three wet/total crash rate categories—low, medium, and high) and geographic distribution throughout the state. An overview of the field testing program is also provided, which consisted of friction testing, profile testing, macrotexture measurements, and rut measurements. The field testing program was conducted by ODOT in the summer and fall of 2007, and the resultant data serve as the basis for the data analysis work described in chapter 4.
Figure 1. Sample site assessment form.
4. DATA ANALYSIS

Introduction
This chapter describes the data analyses that were conducted using the friction, texture, and crash data collected for the 90 test sites. The overall goal was to determine if reliable correlations could be identified between friction (as measured by both ribbed and smooth tires), macrotexture, and crash rates, and to identify critical friction numbers that could be used to help locate potential problem areas.

The first part of the chapter describes the data compilation process, indicating how the various data elements were processed for use in the analysis. The next part of the chapter describes some of the data analysis activities, including the development of analysis plots and the conduct of the regression analysis. Finally, based on these results, and coupled with information from the literature, preliminary recommendations are presented.

Data Compilation
During this study, ODOT provided a number of different data tables to the project team. The first information provided by ODOT was the final summary of selected sites. Also included in this data table were the compiled inventory and crash data associated with each site location. In separate data tables, ODOT provided friction testing results, texture testing results, and IRI testing results. All of the data associated with the conducted field testing needed to be processed and matched up to each selected site location. This section of the report summarizes the process used to process each of these different types of data.

Crash Data
While the raw crash data totals were provided in the initial ODOT data offering, some manipulation of the crash data was still required in preparation for final use in the study. According to information from ODOT, the provided crash data totals represented 3-year (2003 to 2005) counts. Because it was desired to conduct the data analysis on estimated annual counts of the crashes in the friction testing direction only, the following steps were completed to compile the data:

1. Divide the total 3-year crash count by 3 to get an estimate of the total crashes per year.
2. Determine the direction of friction testing.
3. Retrieve the ODOT-reported percentage of total crashes in the direction of friction testing.
4. Multiply the total crashes per year (for all directions) by the percentage of total crashes in the friction testing direction to determine the estimated total crashes per year in the friction testing direction.

In the final analysis, the following four different crash data counts were analyzed separately versus different variables to see what would give the best correlations:
• Total 3-year crash counts.
• Estimated total crashes per year in the friction testing direction.
• Wet/total crash ratio.
• Rear end crash rate (per 100 MEV for intersections; per 100 MVMT for freeways).

Friction Testing Data

The friction testing data provided by ODOT consisted of raw testing data results associated with each site location. Within a given site location, 3 to 6 individual tests were completed for each combination of testing tire (smooth or ribbed) and target testing speed (20, 40, or 60 mi/hr [32, 64, or 97 km/hr]). Each set of raw friction testing data for a given site location included the following types of data for each individual friction test:

• Location information (county and route).
• Lane information (tests were always conducted in the inner wheelpath of the outer lane).
• Tire type (ribbed or smooth).
• Testing speed (in mi/hr).
• Time of test.
• Ambient temperature at time of test.
• Computed friction number associated with each test.

The final processing of this raw friction data consisted of 1) the compilation of friction number (FN) statistics (i.e., average, standard deviation, minimum, and maximum values), 2) the computation of average testing temperatures, 3) the computation of speed gradients associated with each tire type, and 4) the estimation of FN values at the posted speed limit. More detailed descriptions of each of these data processing steps are presented below.

Computation of Friction Number Statistics

During the processing stage of this task, all of the individual test FN values were processed together to determine an FN average, standard deviation, minimum, and maximum associated with each combination of tire type and test speed. Therefore, these FN summary statistics were computed for each of the following tire and test speed combinations at each site location:

• Tire type = Ribbed, Testing speed = 40 mi/hr (64 km/hr).
• Tire type = Smooth, Testing speed = 40 mi/hr (64 km/hr).
• Tire type = Ribbed, Testing speed = 20 or 60 mi/hr (32 or 97 km/hr) (depending on facility type).
• Tire type = Smooth, Testing speed = 20 or 60 mi/hr (32 or 97 km/hr) (depending on facility type).
Computation of Average Testing Temperatures

In addition to compiling statistics associated with the friction numbers, the average ambient testing temperature associated with the tests conducted with each tire type was also determined. These average temperatures were used in the analysis to investigate possible trends between friction number and testing temperature.

Computation of Speed Gradients

The compiled friction testing results were also used to compute ribbed and smooth speed gradients associated with site location. Speed gradients are determined by conducting friction testing at two different speeds, and then using that information to determine the slope of the FN vs. speed line. Specifically, the friction-related speed gradient is computed using equation 1.

\[
\text{Speed Gradient} = \frac{(FN_{2\text{avg}} - FN_{1\text{avg}})}{(SPD_2 - SPD_1)}
\]

(Eq. 1)

where:

\(SPD_2\) = The higher test speed (in MPH) of the two testing speeds used for a site location (i.e., 60 mi/hr [97 km/hr] if two tests were conducted at 60 and 40 mi/hr [97 and 64 km/hr], or 40 mi/hr [64 km/hr] if two tests were conducted at 40 and 20 mi/hr [64 and 32 km/hr]).

\(SPD_1\) = The lower test speed (in mi/hr) of the two testing speeds used for a site location.

\(FN_{2\text{avg}}\) = Average FN value associated with the higher testing speed (i.e., SPD2).

\(FN_{1\text{avg}}\) = Average FN value associated with the lower testing speed (i.e., SPD1).

Computation of FN at Posted Speed Limits

The final processing step for the friction testing data consisted of the estimation of FN values at the posted speed limit for each site location. These values were computed in order to investigate if there was better correlation between the FN at posted speed limit and crash data than the correlation between crash data and an arbitrarily chosen testing speed (e.g., 40 mi/hr [64 km/hr]). The FN at the posted speed limit is computed using equation 2.

\[
FN @ \text{SpdLimit} = FN_{1\text{avg}} + \text{Speed Gradient} \times (\text{SpdLimit} - SPD_1)
\]

(Eq. 2)

where:

\(FN@ \text{SpdLimit}\) = Estimated friction number at posted speed limit for a given tire type.

\(SPD_1\) = The lower test speed (in mi/hr) of the two testing speeds used for a site location (i.e., 40 mi/hr [64 km/hr] if two tests were conducted at 60 and 40 mi/hr [97 and 64 km/hr], or 20 mi/hr [32 km/hr] if two tests were conducted at 40 and 20 mi/hr [64 and 32 km/hr]).
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

FN1\textsubscript{AVG} = Average FN value associated with the lower testing speed (i.e., SPD1).

Speed Gradient = Speed gradient computed for a particular tire type (ribbed or smooth) for the site location.

SpdLimit = Posted speed limit in mi/hr.

Individual FN values at posted speed limit values were computed for both ribbed and smooth tires for each site location.

Texture Testing Data

Raw texture testing results data were provided by ODOT in individual Microsoft Excel workbook files associated with each site location. Within each workbook, average mean profile depth (MPD) values (in units of inches) were provided for every 20-ft (6.1-m) interval tested at each site location. Typically, a total of 500 ft (152 m) was tested at intersection locations and 2,640 ft (805 m) was tested on congested freeway sites. Because macrotexture values are typically reported as mean texture depth (MTD) in units of millimeters, the raw MPD data needed to be converted. This conversion was completed using the following steps:

1. Convert 20-ft (6.1 m) average MPD values from units of inches to units of millimeters using the following conversion equation:

\[
MPD(\text{mm}) = MPD(\text{in}) \times 25.4 \quad (\text{Eq. 3})
\]

where:

\[
MPD(\text{mm}) = \text{20-ft (6.1-m) average mean profile depth in units of millimeters.}
\]

\[
MPD(\text{in}) = \text{20-ft (6.1-m) average mean profile depth in units of inches.}
\]

2. Convert MPD(\text{mm}) values to MTD(\text{mm}) values. This conversion is completed using the following conversion equation (ASTM 2005):

\[
MTD(\text{mm}) = 0.79 \times MPD(\text{mm}) + 0.23 \quad (\text{Eq. 4})
\]

where:

\[
MTD(\text{mm}) = \text{Mean texture depth in units of millimeters.}
\]

\[
MPD(\text{mm}) = \text{Mean profile depth in units of millimeters.}
\]

After the 20-ft (6.1-m) average MPD(\text{in}) values had been converted to 20-ft (6.1-m) average MTD(\text{mm}) values, representative summary statistics (i.e., average, standard deviation, minimum, and maximum values) of the 20-ft (6.1-m) average MTD(\text{mm}) values were computed and stored in the primary data analysis worksheet for this study.
IRI Testing Data

Raw IRI testing results data were provided by ODOT in a series of Microsoft Excel workbooks in which one worksheet was associated with each site location. Within each site-specific workbook, individual IRI values (in units of in/mi) were computed using a 20-ft (6.1-m) sliding baselength and reported at 0.1-ft (0.03-m) intervals along the total tested length (approximately 500 ft [152 m] for intersections and 2,640 ft [805 m] for congested freeways). Because of the use of the 20-ft (6.1-m) baselength, the first reported value was at 10 ft (3.0 m) into the section (the midpoint of the 20-ft [6.1-m] baselength), and the last reported value was at 10-ft (3.0-m) before the end of the section. Summary statistics of all of the individual 20-ft (6.1-m) baselength values were also computed and presented within the provided site-specific workbooks. These summary statistics included the overall average, standard deviation, minimum, and maximum of the individual computed 20-ft (6.1-m) baselength values. The relationships between these IRI summary statistics and collected crash data were analyzed in this study.

Rutting Testing Data

Rutting data was collected as part of this study, but only on 16 of the 90 sections. Because of this relatively small sample size, and the fact that the site assessment sheets indicated that only no or only slight rutting was present on all sections, the rutting data was not included in the final analysis. It is also important to note that the literature search suggested that in general, low amounts of rutting do not significantly affect safety (Davies, Cenek, and Henderson, 2005).

Development of Analysis Plots

During the analysis portion of this project, many different data plots were produced to help identify potentially meaningful trends in the data. As a first step in this data analysis process, all three site category types were analyzed together to investigate general trends in the data between wet/total crash ratios and various pavement characteristics. Specifically, the following trends were investigated by analyzing all 90 site locations as one data set:

- Wet/total crash ratio vs. FN40.
- Wet/total crash ratio vs. friction number at posted speed limit.
- Wet/total crash ratio vs. mean texture depth (average and minimum).
- Wet/total crash ratio vs. speed gradient for both ribbed and smooth tires.
- Wet/total crash ratio vs. IRI.
- Wet/total crash ratio vs. average daily traffic.

While all of these plots are summarized in Appendix C of this report, an example plot showing the wet/total crash ratio vs. FN40 data is shown in figure 2 below. Detailed discussions of the trends and their meaning are contained later in this chapter.
On each of the data plots produced in the analysis, trend lines were fit through each logical set of data to determine a best fit equation for the data. While different equation types were tried, the logarithmic or linear equations provided the best fit in all cases (in terms of the r-squared \([R^2]\) value, which was used to assess the goodness of each data trend included in the plots). Trendline equations and \(R^2\) values were included on each plot, although the \(R^2\) values were typically less than 0.5.

A common observation from the first plots where all 90 sections were included in the same data set was that the variability of the data around the trends was very large. This was also indicated by extremely low \(R^2\) values associated with the trends. Because of this, the remainder of the analysis plots were produced with data sets specific to only one site category type (i.e., congested freeways, signalized intersections, and unsignalized intersections). Therefore, each investigated trend resulted in a group of three different analysis plots that could be viewed side-by-side to see how trends differed between site category types. An example of a group of site category-related plots is showed in figure 3. A complete collection of all of these site category-specific data plots is contained in Appendix C.

A complete summary of the data plot groups that were produced with site category type-specific data include the following:

- Wet/total crash ratio vs. various variables such as FN40, FN at posted speed limit, MTD, speed gradient, IRI, and ADT.
Figure 3. Example of a group of plots showing wet/total crash ratio vs. FN40 trends for different site categories.
• Wet/total crash ratio vs. various variables (FN40R, FN40S, MTD, location [urban vs. rural], ADT), but with data sets divided into crash ratio groups (i.e., low, medium, high).
• Total crashes per year (all directions) vs. various variables such as FN40, FN at posted speed limit, MTD, speed gradient, IRI, and ADT.
• Rear end crash rate vs. various variables such as FN40, FN at posted speed limit, MTD, speed gradient, IRI, and ADT.
• Total crashes per year in the test direction vs. various variables such as FN40, FN at posted speed limit, MTD, speed gradient, IRI, and ADT.
• FN statistics (average and minimum) for different testing speeds vs. MTD statistics (average and minimum).
• Friction statistics vs. other variables such as testing speed and temperature at time of testing.
• FN ribbed vs. FN smooth at different testing speeds.
• Total crashes in the testing direction vs. different ranges of 20, 40, 60 mi/hr (32, 64, 97 km/hr) FN values (i.e., FN = 15 to 20, 20 to 25, and so on) for different site categories. These plots contain relationships for both ribbed and smooth tires.
• Cumulative percentage of all crashes (in the testing direction) observed for a given site category vs. various FN values (i.e., FN20, FN40, and FN60). Again, these plots contain relationships for both ribbed and smooth tires.

All data plots were reviewed as part of the data analysis portion of the study to assess how well different surface characteristics correlated to crash data and other factors. A summary of some of the more noteworthy observations is presented in the following section, with the results of a detailed statistical analysis of the various data sets presented later.

Analysis of Data Plot Trends

The three site categories were sorted by wet/total crash rates so that both good and poor performing sections (30 sites in each category with 10 each in low, medium and high wet/total crash rate groups) were represented. The three site categories selected were based on the assumption that they would most directly address ODOT’s objectives to reduce both the total number of crashes, and specifically the number of rear-end crashes. Poor friction and texture on these sites are assumed to contribute to both total and rear-end crashes.

For the three site categories selected, the priority is on congested freeway sites, followed by signalized intersection sites, and then the unsignalized sites. The congested freeway sites have the most potential to reduce total crashes (and crash costs), but also significantly reduce user delay costs which are also very significant.

While the data analyses resulted in many interesting results, one general observation was that all of the trends had relatively low $R^2$ values (typically less than 0.5). While these low $R^2$ values do not necessarily invalidate the generally observed trends, they do indicate that there is considerable variability in the data which suggests that there are other factors that are not being
considered. Keeping these low R² values in mind, a summary of some of the more interesting analysis results for each individual site category are summarized below.

**Congested Freeway Sites**

Due to the high volumes of traffic and the serious impact of traffic crashes on congestion delays, these sites are assumed to warrant the highest priority. Based on the literature review and analysis of the data for these 30 sites, the following findings and recommendations are made:

1. While the high cost of traffic congestion is recognized, the high cost of traffic crashes generally is not. The American Automobile Association (AAA) estimates that traffic crash costs in urban areas are three times congestion costs and about 30 percent of congestion delays are due to traffic crashes (AAA 2008). Providing high quality, skid resistance surfaces on congested freeway sites (or ramps) with low friction and texture should provide a large benefit-to-cost ratio (Julian and Moler 2008).

2. FN40R and FN40S are highly correlated for congested freeways. The analysis found this relationship to have a linear trend with an R² = 0.68 (see figure C-47 in Appendix C). The NY SKARP criteria based in part on FN40R_min has been validated as being cost effective when sites with low friction and texture are given a surface treatment or overlaid with high quality non-carbonate aggregates. When applied to the ODOT data, the SKARP criteria identified 6 of the 30 sections where skid resistant surfaces are expected to be warranted. However, it should be noted that the FN40S vs. MTD_min relationship had the highest R² of 0.49 (see figure C-39). Thus, the friction number increases with an increase in MTD.

3. The FN60S versus MTD_min trend had an R² = 0.48 compared to the FN60R vs. MTD_min trend that had an R² = 0.23 (see figure C-40). Increasing the texture depth above 0.03 in (0.8 mm) results in a significant increase in FN60R or FN60S. There could be an advantage in testing congested freeways sections at 60 mi/hr (97 km/hr) with a smooth tire and also measuring the macrotexture.

4. The trends for wet/total crash ratios vs. FN40R or FN40S statistics (either average or minimum) all have very low R² values ranging from 0.08 to 0.13 (see figure C-7). The trends versus the minimum friction values are slightly better than the trends versus the average friction values for both tire types.

5. Total crashes per year in the test direction vs. MTD_avg or MTD_min have very low R² values (0.07 and 0.06, respectively) (see figure C-32). Total crashes are lower if MTD_avg is greater than 0.035 in (0.9 mm) and if MTD_min is over 0.028 in (0.7 mm).

6. The total crashes per year in the test direction vs. ADT trend shows a relatively low R² of 0.18 (see figure C-35).

7. A significant drop in rear-end crash rate results when FN40R > 42 and FN40S > 32 (see figure C-24). FN40R has a slightly higher correlation than FN40S.

8. A significant drop in the rear end crash rate results when the MTD_avg approaches 0.047 in (1.2 mm) or MTD_min approaches 0.03 in (0.8 mm) (see figure C-26).
For congested freeways, sections with FN40R > 42 and MTD_{avg} greater than 0.04 in (1.0 mm) have significantly lower crash rates. Sections with lower friction numbers or lower macrotexture depths should be evaluated to see if the lower friction and/or macrotexture are contributing to increased crash rates.

**Signalized Intersection Sites**

Due to frequent starting and stopping operations, signalized intersections have a high potential for aggregate polishing, and increased roughness due to localized deformations such as rutting, shoving, and corrugations. The combination of this increased roughness, aggregate polishing, and traffic stopping actions typically results in increased crash rates for these locations. Because of this, these sites are also the location of a large number of fatalities and serious injuries. Skid resistant surfaces, if placed on the approaches, should extend through the intersection. Based on the analysis of the available data at the 30 sites, the following observations are made:

1. For signalized intersections, there was no significant correlation observed between friction and texture. Of the 30 investigated sites, 7 sites had higher FN20S than FN20R (8 of 30 unsignalized intersection sites showed the same trend). This difference can not be explained by MTD as at slow speeds, the microtexture governs the friction values. It is assumed that this difference is related to asphalt mix design variables (maximum aggregate size and quality, voids, and other mix characteristics), for which site-specific data were unavailable. This higher friction may be due to the fact that the smooth tire has more surface area in contact with the pavement than the ribbed tire, and thus more microtexture interaction (or a greater adhesion) in these cases. However, it should be noted that the literature search did not identify any other studies where the FN20S values were higher than FN20R test results.

2. The trend of wet/total crash ratio vs. FN40R_{avg} (R^2 = 0.40) is slightly better than the trend for wet/total crash ratio vs. FN40S_{avg} (R^2 = 0.29) (see figure C-7); and, it is observed that the wet/total crash ratio goes down with higher friction numbers. The trends using the minimum FN values were virtually the same as the trends using the average FN values.

3. The wet/total crash ratio vs. FN at posted speed limit plot shows a significantly better trend for the ribbed tire than for the smooth tire (ribbed tire R^2 = 0.40, smooth tire R^2 = 0.13; see figure C-8).

4. The total crashes per year in the test direction vs. FN40R_{avg} trend shows a slightly better correlation (R^2 = 0.39) than the total crashes per year vs. FN40S_{avg} trend (R^2 = 0.31) (see figure C-30).

5. The total crashes per year in the test direction vs. FN at posted speed limit shows a significantly better trend for the ribbed tire than for the smooth tire (ribbed tire R^2 = 0.43, smooth tire R^2 = 0.19; see figure C-31).

6. There is a significant drop in rear-end crash rate when FN40R is greater than 40 or when FN40S is greater than 30 (see figure C-24). The trend versus FN40R_{avg} (R^2 = 0.36) is slightly better than the trend versus FN40S_{avg} (R^2 = 0.28). Also, the trends versus the FN40R_{min} (R^2 = 0.40) and FN40S_{min} (R^2 = 0.38) are better than the associated trends using the average values.
7. The rear end crash rate vs. FN at posted speed limit was significantly better for the ribbed tire ($R^2 = 0.37$) than for the smooth tire ($R^2 = 0.13$) (see figure C-25). The rear-end crash rate is significantly less when FN at the posted speed limit using the ribbed tire (FNPSR) was > 40 and when the FN at posted speed limit using the smooth tire (FNPSS) was > 32.

8. The plot of FNPSR and FNPSS vs. MTD$_\text{avg}$ showed no correlation (see figure C-41). Whether the aggregate is polished or not may be more important than MTD$_\text{avg}$.

9. There was a high correlation between FN20R and FN20S ($R^2 = 0.79$) compared to FN40R vs. FN40S ($R^2 = 0.53$) or FNPSR vs. FNPSS ($R^2 = 0.38$).

Overall, it was surprising that the analysis of the various data using FN40R$_\text{avg}$ or FN40R$_\text{min}$ had consistently higher correlations than using FN40S statistics, which gave much more variable results. For the mostly limestone aggregates, the ribbed tire appears to be a better indicator of polishing of the aggregate than the smooth tire. The relative role of microtexture and macrotexture are not well understood, but the effects of microtexture (as related to certain mix design characteristics) are more critical for slower-speed facilities. The results of this study indicate that microtexture is the more dominant characteristic at 40 mi/hr (64 km/hr).

**Unsignalized Intersection Sites**

The unsignalized intersection approaches on the major road should have the lowest friction demand of the three site categories. However, the biggest problem is for the traffic on the crossroad to identify an appropriate movement gap. This results, perhaps, in more potential for right-angle crashes which are usually more serious and perhaps more potential for unexpected rear-end collisions with slowly accelerating vehicles. Based on the analysis of the data for these 30 sites, the following observations are made:

1. Generally FN20R and FN20S increased as the MTD$_\text{min}$ approached 0.04 in (1.0 mm). However, there were some outliers at 0.06 mm (1.5 mm) that distorted the statistics (see figure C-37). However, macrotexture should not have a significant effect on friction numbers at 20 mi/hr (32.2 km/hr).

2. The trends for FN40S$_\text{avg}$ ($R^2 = 0.18$) and FN40S$_\text{min}$ ($R^2 = 0.17$) vs. MTD$_\text{avg}$ showed much better correlations than their FN40R$_\text{avg}$ ($R^2 = 0.01$) and FN40R$_\text{min}$ ($R^2 = 0.004$) vs. MTD$_\text{avg}$ counterparts (see figure C-38).

3. The FN40S$_\text{avg}$ vs. MTD$_\text{min}$ trend ($R^2 = 0.22$) had a much better correlation than the corresponding FN40R$_\text{avg}$ vs. MTD$_\text{min}$ trend ($R^2 = 0.002$).

4. The plot of FNPSR and FNPSS vs. MTD$_\text{avg}$ showed no correlation (see figure C-41). Whether the aggregate is polished or not may be more important than the MTD$_\text{avg}$. The FN was higher for MTD$_\text{avg}$ values above 0.04 in (1.0 mm), but a lot of scatter was observed in the plot.

5. No meaningful correlations were observed in all plots of wet/total crash ratios vs. friction data.

6. There was a high correlation between FN20R and FN20S ($R^2 = 0.78$) compared to FN40R vs. FN40S ($R^2 = 0.50$) or FNPSR vs. FNPSS ($R^2 = 0.30$).
7. For wet/total ratios greater than 20 percent, there were more crashes when FN40R_{min} \leq 36, FN40S_{min} \leq 30, and MTD_{avg} < 0.04 in (1.0 mm).

For unsignalized intersections, either FN20R or FN20S resulted in the highest correlations and the minimum MTD should be 0.04 in (1.0 mm). It is suggested that this category should be analyzed separately to develop the most cost-effective countermeasure to reduce crashes (and fatal and serious injuries).

**Analysis of Cumulative Percentage of All Crashes for Each Site Category vs. FN20, FN40, and FN60 for Ribbed and Smooth Tires**

The focus of this analysis approach was to determine the percentage of total crashes (for a given site category) that occur below different observed FN values (e.g., what percentage of the total observed crashes occurred on pavements with a FN value less than 35?). Within each site category, separate plots were constructed for the different applicable testing speeds (i.e., 40 and 60 mph [64 to 97 km/hr] for congested freeways and 20 and 40 mph [32 to 64 km/hr] for intersections) and on all plots, both the ribbed and smooth tires were considered. Finally, these data were used to plot the cumulative percentage of total crashes versus FN for each combination of site category and testing speed. Figure 4 shows these plots for the congested freeway, signalized intersection, and unsignalized intersection site categories versus FN at the common 40 mph (64 km/hr) testing speed. Additional plots showing the data at other testing speeds are included in Appendix C. Table 6 summarizes many of the more interesting percent of total crashes versus FN40R and S points that are observed in figure 4. This information is used to develop the guidelines presented in chapter 5.

**Table 6. Summary of observed percentages of total crashes versus FN40 values for the three chosen ODOT site categories.**

<table>
<thead>
<tr>
<th>% of Total Crashes</th>
<th>Congested Freeways</th>
<th>Signalized Intersections</th>
<th>Unsignalized Intersections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FN40S</td>
<td>FN40R</td>
<td>FN40S</td>
</tr>
<tr>
<td>90</td>
<td>&lt;30</td>
<td>&lt;42</td>
<td>&lt;29</td>
</tr>
<tr>
<td>85</td>
<td>&lt;29</td>
<td>&lt;40</td>
<td>&lt;27</td>
</tr>
<tr>
<td>50</td>
<td>&lt;26</td>
<td>&lt;34</td>
<td>&lt;21</td>
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<td>&lt;23</td>
<td>&lt;33</td>
<td>&lt;14</td>
</tr>
<tr>
<td>10</td>
<td>&lt;22</td>
<td>&lt;32</td>
<td>&lt;13</td>
</tr>
</tbody>
</table>

A review of the plots resulting from this analysis shows that the 30 samples selected for each site category provide a good estimate of total crashes versus friction numbers for both smooth and ribbed tires. It also shows that in order to maximize the cost effectiveness of corrective actions, each site category should be analyzed separately as there are significant differences between the various site categories. As noted before, the site categories were selected to represent those sites where low friction or texture are likely to contribute to higher numbers of rear end crashes. Sites with higher friction demands (particularly sharp curves or freeway ramps) or lower friction demands (straight, level freeways or rural 2-lane highways) are not represented.
Cumulative % of All Crashes (in Test Direction) Observed on Congested Freeways vs. FN40 for Ribbed and Smooth Tires

Cumulative % of All Crashes (in Test Direction) Observed on Signalized Intersections vs. FN40 for Ribbed and Smooth Tires

Cumulative % of All Crashes (in Test Direction) Observed on Unsignalized Intersections vs. FN40 for Ribbed and Smooth Tires

377 total crashes were observed in the test direction for sections included in this analysis.

83 total crashes were observed in the test direction for sections included in this analysis.

49 total crashes were observed in the test direction for sections included in this analysis.

Figure 4. Cumulative percentage of all crashes (in test direction) vs. FN40 for all three site categories.
Other Analyses

In addition to the general analyses of friction, texture, and crash rates that were described for the different site categories, two other special studies were also conducted to evaluate the impact of IRI on safety and, the impact of ambient temperature at the time of testing on friction data. The results of these special studies are briefly summarized below:

- **Evaluation of the Impact of Roughness (IRI) on Safety.** In the past, the effect of IRI on safety has largely been ignored, but it is a relationship that needs to be more adequately considered (TRB 2008). Background data for the recent highway legislation suggests that poor highway conditions contribute to 30 percent of the highway crashes. In the data analysis portion of this study, the relationship between crash data and IRI was explored to see if any strong correlations existed. An analysis of the results of this study found a low correlation ($R^2 = 0.24$) between wet/total crash ratio and average IRI for congested freeways (see figure C-11), but the correlations for the signalized and unsignalized intersection site categories were even lower. It is believed that 20-ft (6.1-m) segments (i.e., segments defined by a sliding 20-ft [6.1-m] baselength) with over 300 in/mile (4.7 m/km) of roughness should be reviewed for possible corrective actions. Some of these short sections with the highest roughness may be associated with bridge decks that were not tested for friction or macrotexture. However, the roughness on bridge decks could cause possible vehicle control issues that could result in more total crashes on or after the bridge is crossed.

- **Evaluation of the Impact of Ambient Temperature at Time of Testing on Friction.** Several Ohio-related research reports (Bazlamit and Reza 2005; Murad 2006) suggest that high temperatures may affect friction test results and a temperature adjustment may be needed. In the literature search, a report by Corsello (1993) and a more recent friction synthesis study (FHWA 2006) suggests that a temperature adjustment is not needed. In a separate study, the Maryland DOT concluded that based on annual average summer temperature changes that there was an effect on friction test results, and that further research may be needed (Chelliah et al. 2003). Because of this uncertainty, the relationship between measured friction numbers and ambient temperature at the time of testing was investigated in the current study. An analysis of the results from this study did not suggest that temperature at the time of testing was a significant factor given all the other variability (particularly for friction tests made when the temperature was over 85 °F [29 °C]). The higher temperatures did appear to have a slightly greater effect on smooth tire friction test results; however, the sample size was too small to draw a definitive conclusion. Perhaps an evaluation of friction test results versus air and pavement temperature on the Ohio friction testing calibration sections could provide more conclusive results.

Regression Analysis

In an additional attempt to develop meaningful relationships and identify significant variables affecting crash data, a statistical regression analysis was conducted. A summary of the variables examined in the regression analysis is provided in table 7. The analysis focused on the use of friction, texture, and additional variables to predict the dependent crash variables for each of the three data subsets: congested freeways, signalized intersections, and unsignalized intersections.
Table 7. Variables examined in the regression analysis.

<table>
<thead>
<tr>
<th>Dependent Crash Variables</th>
<th>Independent Variable Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Friction Variables</td>
</tr>
<tr>
<td>Wet/Total Crash Ratio</td>
<td>• Minimum, Maximum, and Average FN at 20, 40 and 60 mi/hr with Ribbed Tire*</td>
</tr>
<tr>
<td>Total Crashes</td>
<td>• Minimum, Maximum, and Average FN at 20, 40 and 60 MPH with Smooth Tire*</td>
</tr>
<tr>
<td>Rear End Crash Rate (per 100MEV for Intersections; per 100MVMT for Freeways)</td>
<td>• Estimated Average FN at Posted Speed</td>
</tr>
<tr>
<td>Estimated Number of Crashes in Test Direction</td>
<td>• Ribbed Speed Gradient</td>
</tr>
<tr>
<td></td>
<td>• Smooth Speed Gradient</td>
</tr>
</tbody>
</table>

* FN was available at 40 and 60 mi/hr (64 and 97 km/hr) testing speeds for the congested freeways and at 20 and 40 mi/hr (32 and 64 km/hr) testing speeds on the signalized and unsignalized intersections.

**Single Variable Linear Regression**

The regression analysis began with the prediction of crashes using linear least squares regression. In a linear regression model, the behavior of the independent variable (friction, texture, and additional) is used to explain the behavior of a dependent variable. The general form of the equation is shown in equation 5.

\[ y = b_0 + b_1 x_1 \]  

(Eq. 5)

where:

\[ y = \text{Dependent variable.} \]
\[ x_1 = \text{Independent variables.} \]
\[ b_0, b_1 = \text{Coefficients.} \]

The linear least squares regression involves estimating coefficients by minimizing the sum of the squared deviations between the observed and predicted values to determine the model with the best fit to the data. The analysis included the examination of the ability of each independent variable to predict each crash variable. Therefore, the 15 friction variables, 3 texture variables, and 4 additional variables were used to predict the 4 crash variables, which resulted in the creation of 88 single variable linear regressions.
The model development process began with an examination of predicting the crash rates for the congested freeway sections. To illustrate the process utilized to determine optimal regression equations, the development process is documented here using the wet/total crash ratio. The data set for the congested freeway pavement family was used to develop a linear regression equation of the ride index versus the average FN at 40 mi/hr (64 km/hr) with a ribbed tire. The results of the regression from S-Plus, a statistical analysis software tool, are provided in figure 5.

### Linear Model

```plaintext
Call: lm(formula = Wet.Total.Ratio ~ X40.MPH.Ribbed.Avg, data = ODOT.Data.CF, na.action = na.exclude)
Residuals:
  Min     1Q   Median     3Q    Max
-0.222 -0.09346 -0.01771 0.1116 0.1891
Coefficients:                Value Std. Error t value Pr(>|t|)
(Intercept)                   0.4604    0.1276     3.6085  0.0012
X40.MPH.Ribbed.Avg            -0.0055    0.0032    -1.7270  0.0952

Residual standard error: 0.1243 on 28 degrees of freedom
Multiple R-Squared: 0.09627
F-statistic: 2.983 on 1 and 28 degrees of freedom, the p-value is 0.09518
```

**Figure 5.** Regression output from S-Plus for prediction of wet/total crash ratio as a function of FN for the congested freeway pavement sections.

Within S-Plus, the general equation formula is entered as shown in figure 5 in bold italics. Using the base formula, linear regression is conducted to return coefficients for the predictor variable and the corresponding equation intercept. In this linear regression, the results (in bold) show that the predicted intercept is 0.4604 and the predicted coefficient for treatment age is –0.0055. Based upon these values, the final $R^2$ value for the equation is a very low value of 0.09627, indicating the inability to create a regression equation that was a good fit to the crash data (a perfect fit would be indicated by an $R^2$ of 1). The resulting equation is shown in equation 6.

$$\text{Wet/Total Crash Ratio} = 0.4604 - 0.0055 \times \text{FN40R}$$  \hspace{1cm} \text{(Eq. 6)}

where:

$$\text{FN40R} = \text{Friction number measured at 40 mi/hr (64 km/hr) with a ribbed tire.}$$

Additional equations were examined for the remaining twenty-one independent variables. This process of examining the predictive capability of each of the twenty-two independent variables was then repeated for the other dependent crash variables (total crashes, rear end crash rate, and estimated number of crashes in test direction).
It should be noted that, in all cases, the examined regressions resulted in equations with relatively low $R^2$ values. Some data sets did show better correlations between certain independent variables and crash variables than others. For example, the signalized intersection data set showed the best correlation between the wet/total crash rate and the average FN at 20 mi/hr (32 km/hr) with a ribbed tire (FN20R) as shown in figure 6. The result of an $R^2$ value of 0.3964 was the best correlation seen between any of the crash variables and the independent variables. These low $R^2$ values indicate a significant scatter associated with the small data sets utilized in the regression analysis, and suggest that some key factors (such as mix design variables) are not being considered.

Given the low $R^2$ values determined for the congested freeway, signalized intersection and unsignalized intersection data sets, additional data subsets were examined to determine if the data scatter could be better described. Data subsets were created for each data set (congested freeway, signalized intersection and unsignalized intersection) using the crash rate categories of low, medium, and high. The regression combinations of crash variables and independent variables were examined and results continued to show low correlation. Therefore, the next step was to examine the use of multivariate linear regressions to determine if better correlations could be developed.

**Multivariate Linear Regressions**

The independent variables that were examined as single predictors of the dependent crash variables were again considered as the potential predictors but this time in combination with one another in a multivariate linear regression. Using the three data subsets (congested freeways, signalized intersections, and unsignalized intersections), a variety of trial equations could be examined using the combination of the independent variables shown in table 7 for each of the dependent crash variables (wet/total crash rate, total crashes, rear end crash rate, and estimated...
number of crashes). Due to the colinearity of the independent variable categories, a maximum of one of each independent variable was examined in each regression model.

In this analysis, a full factorial analysis of all variables was not conducted; rather, the independent variables under each category that showed the strongest correlation to the dependent crash variable were used in combination with one another to examine the ability to better predict the dependent crash variable. For example, when examining the signalized intersections, the wet/total crash ratio was best predicted by the following variables:

- Friction Variable: FN20R.
- Texture Variable: MTD Average (mm).
- Additional Variables: IRI Average.

Therefore, these variables were examined in combination with one another to determine the best multivariate linear regression. The details of this example analysis run are provided in figures 7 and 8. The first multivariate analysis run shown in figure 7 shows the prediction of wet/total crash ratio as a function of FN20R and MTD Average. This was examined to see if the friction and texture variable would properly predict the wet/total crash ratio. The results show that the coefficient for FN20R is negative (-0.0093), which indicates that the wet/total crash ratio decreases as the FN increases. However, the coefficient for MTD average (shown as 0.1442 in bold italics) has a positive sign indicating that the wet/total crash ratio increases with an increasing MTD average value. This does not make logical engineering sense, so the overall equation is considered invalid.

The occurrence of suspect variable coefficients also occurred when the wet/total crash ratio for the signalized intersections was examined as a function of FN20R, MTD average, and IRI average. The results of the multivariate regression are shown in figure 8. Again, the FN20R had a negative coefficient (-0.088), which is logical, but the coefficient for MTD average was positive (0.2578). This positive coefficient indicates that wet/total crash ratio increases with an increase in texture, which is not logical. The coefficient for IRI average was negative (-0.0004) indicating that wet/total crash ratio increases with a decrease in roughness, which again is not logical. It should also be noted that the resulting R² values of the equations shown in figures 7 and 8 were lower than that obtained by using FN20R as a single predictor of wet/total crash ratio.

In addition to values of the coefficient, the statistical analysis also returns the statistical significance probability of each of the coefficients. The probability column (P-value) is highlighted in figure 7. Low probability values (< 0.05) signify that with a 95 percent confidence the coefficient is different than zero, and the variable coefficients are statistically significant at predicting the given crash variable. However, as shown in figure 7, the p-value for MTD average is 0.4448. In order to have 95 percent confidence in the ability of the variable (in this case MTD average) to predict the behavior of wet/total crash ratio, a p-value of 0.05 or less is desired. Therefore, the MTD average data was not shown to be an adequate predictor for the wet/total crash ratio for the signalized intersections dataset.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

### Linear Model


Residuals:

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>1Q</th>
<th>Median</th>
<th>3Q</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residuals</td>
<td>-0.2326</td>
<td>-0.09179</td>
<td>-0.001835</td>
<td>0.1127</td>
<td>0.218</td>
</tr>
</tbody>
</table>

Coefficients:

|              | Value  | Std. Error | t value | Pr(>|t|) |
|--------------|--------|------------|---------|---------|
| (Intercept)  | 0.5418 | 0.1802     | 3.0066  | 0.0063  |
| X20.MPH.Ribbed.Avg | -0.0093 | 0.0029 | -3.1766 | 0.0042  |
| MTD.Avg..mm.  | 0.1442 | 0.1855     | 0.7776  | 0.4448  |

Residual standard error: 0.133 on 23 degrees of freedom
Multiple R-Squared: 0.3168
F-statistic: 5.333 on 2 and 23 degrees of freedom, the p-value is 0.01251

Figure 7. Regression output from S-Plus for prediction of wet/total crash ratio as a function of FN20R and MTD average for the signalized intersection pavement sections.

### Linear Model

Call: lm(formula = Wet.Total.Ratio ~ X20.MPH.Ribbed.Avg + MTD.Avg..mm. + IRI.AVG, data = ODOT.Data.SI, na.action = na.exclude)

Residuals:

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>1Q</th>
<th>Median</th>
<th>3Q</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residuals</td>
<td>-0.2256</td>
<td>-0.1039</td>
<td>0.01439</td>
<td>0.09428</td>
<td>0.1928</td>
</tr>
</tbody>
</table>

Coefficients:

|              | Value  | Std. Error | t value | Pr(>|t|) |
|--------------|--------|------------|---------|---------|
| (Intercept)  | 0.4989 | 0.1845     | 2.7041  | 0.0130  |
| X20.MPH.Ribbed.Avg | -0.0088 | 0.0029 | -3.0094 | 0.0065  |
| MTD.Avg..mm.  | 0.2578 | 0.2148     | 1.2003  | 0.2428  |
| IRI.AVG      | -0.0004 | 0.0004 | -1.0429 | 0.3083  |

Residual standard error: 0.1328 on 22 degrees of freedom
Multiple R-Squared: 0.349
F-statistic: 3.931 on 3 and 22 degrees of freedom, the p-value is 0.02182

Figure 8. Regression output from S-Plus for prediction of wet/total crash ratio as a function of FN20R, MTD Average, and IRI average for the signalized intersection pavement sections.

Additional combinations of predicted variables were examined for each dataset, and low p-values and some counter-intuitive trends were obtained. The results from the regression analysis, along with the data plot trends, showed consistently low R² values with the majority of values less than 0.5. Low R² values can be the result of several different causes. First, there appears to be significant variability in the data collected for the study. Some of the variability is attributed to the nature of pavement performance and crash occurrence data. In fact, other studies have shown difficulty in directly correlating crash occurrence to skid number due to variability in collected data (e.g., Lyon and Persaud 2008; Piyatrapoomi et al. 2008). Some of the variability may also be due to the fact that the field testing data (e.g., friction and texture testing) may not have been collected in the exact same locations where crashes occurred.
Discrepancies in the linking of collected data to exact pavement locations can lead to additional variability. One additional known source of variability is due to the fact that while friction, texture, and roughness data were collected in 2007, the crash data used in the study is from the years 2003 to 2005.

Based upon results of other research efforts, another potential cause of low $R^2$ values is that some potential predictors of performance were not included in the analysis. For example, some studies have shown that variables such as asphalt mixture gradation are correlated to predicted crash rates (Chelliah et al. 2003; Flintsch et al. 2003; Luce et al. 2007). For this analysis, such data were not available, but it is believed that the inclusion of such data may have improved the results. Unfortunately, the lack of strong correlations between crash data and other investigated variables led to the disbanding of the regression analysis. Because of this, the research effort moved toward building off of the many past research studies conducted by other agencies, as outlined in the next section.

**Application of Friction and Texture Criteria from Other Studies**

The literature review located a number of previous studies conducted by other agencies where procedures were developed that tried to identify problem sections (i.e., sections with an increased potential for total and wet-pavement crashes) based on measured friction and/or texture data. Since ODOT is interested in developing similar criteria to identify potentially dangerous roadway segments, an additional exercise conducted as part of this study was to apply the criteria documented in those other studies to the ODOT data to see what type of results were indicated. The details of each of these applications are described separately below.

**New York Skid Accident Reduction Program (SKARP)**

The New York Department of Transportation (NYDOT) has implemented a highly successful skid accident reduction program, which identifies pavement sections with a high proportion of wet-road accidents, tests the friction of those locations in accordance with ASTM E-274 (and using the ASTM E-501 ribbed tire), and applies corrective treatments to those sections that exhibit both a high proportion of wet-road accidents ($\geq$ 35 percent) and low friction numbers (FN40R < 32) (Lyon and Persaud 2008). Corrective treatments typically include either a 1.5-in (38 mm) resurfacing or a 0.5-in (13 mm) microsurfacing using non-carbonate aggregates (Bray 2003).

The SKARP approach was applied to each ODOT section using the following steps:

1. **Application of SKARP criteria #1: Wet/total crash ratio > 0.35.** The SKARP approach first identifies all sections in which the wet/total crash ratio is $\geq$ 35 percent (i.e., 0.35). A total of 30 of 90 ODOT sections (33 percent) had wet/total crash ratios $\geq$ 0.35.

2. **Determine the location setting (urban or rural) for each ODOT section.** The collected video log photos were used to make a judgment on whether the location of each project was in a rural or urban setting. This designation was required for subsequent steps in this procedure.

3. **Determine the 2-year wet road accident total associated with each section.** In preparation for the second SKARP criteria, the expected number of wet road accidents over a 2-year
period was required for each ODOT section. This value was computed by taking two-thirds of the provided 3-year wet pavement accident numbers.

4. **Application of SKARP criteria #2: 2-year wet-road accident total > 6 for rural roads or > 10 for urban roads.** The next step of the SKARP approach is to compare computed 2-year wet road accident totals to SKARP criteria based on whether or not the section is in an urban or rural setting. A total of 21 of 90 ODOT sections (23 percent) had 2-year wet road accident totals that exceeded the SKARP criteria.

5. **Application of SKARP criteria #3: \( FN40R_{\text{min}} \) value < 32.** The next step of the SKARP approach is to determine if one or more friction numbers at a given location are < 32. To check these criteria, the FN40R minimum value from the data summary was analyzed and compared to the cutoff of 32. A total of 34 of 90 ODOT sections (38 percent) had a minimum FN40R value < 32.

When applying this SKARP approach, only those sections where **all** three criteria are found to be true (i.e., wet/total crash ratio > 0.35, 2-year wet-road accident total > 6 for rural roads or > 10 for urban roads, and \( FN40R_{\text{min}} < 32 \)) are triggered for corrective action. Overall, 11 of 90 sections (12 percent) of the ODOT sections met all three SKARP criteria indicating those sections as needing a treatment. Looking at these results by site category finds the following:

- **Congested freeways**—6 of the 30 sections (20 percent) exceeded all three SKARP criteria. Note: The ODOT data indicated that two of these identified sections received of micro-surfacing within the past 3 or 4 years suggesting that microsurfacing guidelines to extend service life should be considered.

- **Signalized intersections**—5 of the 30 sections (17 percent) exceeded all three SKARP criteria.

- **Unsignalized intersections**—None of the 30 unsignalized intersection sections exceeded all three SKARP criteria, but some appear borderline and would be subject to suggested Investigatory Level criteria.

The SKARP approach is considered to be a solid approach which has been shown to be very effective in New York state. This approach was recently validated under NCHRP 17-25 (Lyon and Persaud 2008). It is important to note that the specific SKARP criteria were developed with consideration of the fact that aggregates in the state of New York are typically carbonate aggregates such as limestones and dolomites. These aggregates tend to polish more readily than non-carbonate aggregates such as granites and trap rocks, and dolomite aggregates under heavier traffic volumes are particularly susceptible to polishing. The New York program was revised to identify high wet road crash locations, friction test them, and treat those high wet road crash locations that exhibit low friction scores.

For ODOT, the SKARP criteria could be adjusted based on friction demand for specific site categories. However, here it is used as the minimum criteria to identify roadway sections or intersections where some corrective action (Intervention Level) is needed without further evaluation being necessary. To maximize the cost effectiveness of any skid resistant treatment, the use of non-carbonate aggregates (which may need to be imported) will be required. In the
suggested guidelines presented in chapter 5, additional criteria based on macrotexture and roughness spikes have been added to the NY SKARP approach.

**French National Highway Administration’s Skid Resistance Criteria**

The second outside specification evaluated as part of this study is texture specification implemented by the French National Highway Administration (Dupont and Bauduin 2005). A specification is outlined in this reference that evaluates the average macrotexture depth and the minimum macrotexture depth specified on construction projects with different friction and texture demands. Microtexture cannot easily be measured in the field but it can be controlled by the mix design and aggregate quality; therefore only macrotexture is included in the construction specifications. This French specification uses a number of variables such as speed limit, type of pavement, site configuration, specified MTD, minimum measured MTD, and information on curves and slopes (for non-urban locations only) to determine if a section has adequate macrotexture for its given setting. In this specification, different site characteristics are used to determine the following two macrotexture demand values for a given project (Dupont and Bauduin 2005):

- Mean texture depth $MTD_{spe}$—This value represents the mean level to obtain (or exceed) within a project.
- Mean texture depth $MTD_{min}$—This value represents the minimum level below which no two consecutive elementary MTD values are to be encountered.

The $MTD_{spe}$ and $MTD_{min}$ texture demand values associated with each ODOT site location were determined by using site characteristics outlined in table 8. The necessary site setting information (i.e., urban and suburban vs. open country) was determined for each site location by evaluating ODOT images taken as part of the video log during testing.

Table 8. French specification texture demand values (Dupont and Bauduin 2005).

<table>
<thead>
<tr>
<th>Site</th>
<th>Speed Limit (km/hr)</th>
<th>Type of Pavement</th>
<th>Plane Alignment</th>
<th>Length Profile</th>
<th>$MTD_{spe}$, mm</th>
<th>$MTD_{min}$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban and suburban</td>
<td>V ≤ 50</td>
<td>Two-directional</td>
<td>Urban arterial</td>
<td></td>
<td>≥ 0.40</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>50 &lt; V &lt; 90</td>
<td></td>
<td></td>
<td></td>
<td>≥ 0.60</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>V ≥ 90</td>
<td>2 x 2 lanes</td>
<td>Urban expressway</td>
<td>Slope ≤ 5%</td>
<td>≥ 0.60</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 x 3 lanes</td>
<td></td>
<td></td>
<td>≥ 0.70</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>min.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open country</td>
<td>V = 90</td>
<td>Two-directional</td>
<td>All cases</td>
<td>Slope ≤ 5%</td>
<td>≥ 0.60</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slope &gt; 5%</td>
<td>≥ 0.80</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>V = 110</td>
<td>2 x 2 lanes</td>
<td>All cases</td>
<td>Slope ≤ 5%</td>
<td>≥ 0.60</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slope &gt; 5%</td>
<td>≥ 0.80</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>V = 130</td>
<td>2 x 2 lanes</td>
<td>Radius &gt; 600 m</td>
<td>Slope &lt; 5%</td>
<td>≥ 0.60</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 x 3 lanes</td>
<td></td>
<td></td>
<td>≥ 0.70</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>min.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
After determining the required average and minimum MTD values associated with each ODOT site location, the actual measured ODOT MTD average and minimum values were compared to the French criteria to see if each site location was in compliance with the specification. The results of the application of this specification to the ODOT data for the three different site category types are as follows:

- **Congested Freeways**—3 of 30 sections (10 percent) failed the MTD\text{spe} check and 3 of 30 sections (10 percent) failed the MTD\text{min} check. Note: two sections failed both MTD criteria, but had wet/total crash ratios of only 0.111 and 0.136.
- **Signalized Intersections**—7 of 30 sections (23 percent) failed the MTD\text{spe} check and 3 of 30 sections (10 percent) failed the MTD\text{min} check. Note: three sections failed both MTD criteria. The wet/total crash ratios for the three sections that failed both criteria were 0.0, 0.105, and 0.759.
- **Unsignalized Intersections**—7 of 30 sections (23 percent) failed the MTD\text{spe} check and 2 of 30 sections (7 percent) failed the MTD\text{min} check. Note: two sections failed both MTD criteria. The wet/total crash ratios for the two sections that failed both criteria were 0.083 and 0.273.

This check provides some good guidance on the minimum texture depth that should be provided (and maintained) on various pavement surfaces for urban or rural applications. It is not, however, considered an optimum texture depth recommendation. The impact of macrotexture on safety appears to be highly correlated with mix design variables and particularly with aggregate quality. In France it is noted that they have 30 quarries with polished stone values (PSV) greater than 56 (Ledee, Delalande, and Dupont 2005), whereas ODOT requires a PSV greater than 35. The *Guide for Pavement Friction* (Hall et al. 2006) suggests PSV of coarse aggregate to be greater than or equal to 30 to 35, which is a substantial difference. As observed in the cited Ohio wet/total crash ratios, there is considerable variability in performance at any individual site based only on these criteria. Therefore, to improve reliability, it is recommended that French minimum texture criteria be combined with the NY SKARP criteria. Another option for the general criteria (not the site specific criteria) is to simply require a 0.02-in (0.5-mm) minimum texture depth, which would not apply for roads or streets with posted speed limits of 30 mi/hr (48 km/hr) or less. The U.K. increases the required friction to be provided by 0.05 SR (5 FNs) when macrotexture levels are below 0.04 in (1.0 mm) (sand patch test), which is an alternate approach that could also be considered.

**Illinois Skid Number Check**

The State of Illinois uses “categorical rating guidelines” for friction testing that attempt to evaluate if surface friction is a contributing factor to wet weather accidents (IDOT 2005). The Illinois guidelines are defined in terms of the 40 mi/hr (64 km/hr) ribbed friction number (FN40R) and the 40 mi/hr (64 km/hr) smooth friction number (FN40S). The three outlined guidelines are the following:

1. If $\text{FN40R} \leq 30$ or $1 \leq \text{FN40S} \leq 15$: Friction may be a factor contributing to wet weather accidents.
2. If FN40R $> 30$ and $16 \leq FN40S \leq 25$, or if $31 \leq FN40R \leq 35$ and $FN40S > 25$: Uncertain if friction is a factor contributing to wet weather accidents.

3. If FN40R $> 35$ and FN40S $> 25$: Friction may not be a factor contributing to wet weather accidents.

The application of these criteria to the ODOT data showed the following results:

- **Congested Freeways**: 1 section where friction may be a factor, 12 sections where it is uncertain if friction is a factor, and 17 sections where friction may not be a factor.

- **Signalized Intersections**: 12 section where friction may be a factor, 10 sections where it is uncertain if friction is a factor, and 8 sections where friction may not be a factor.

- **Unsignalized Intersections**: 7 section where friction may be a factor, 8 sections where it is uncertain if friction is a factor, and 15 sections where friction may not be a factor.

One observation of this exercise is that the criteria do not seem to clearly identify sections where poor skid resistance is contributing to higher crash rates. This deduction is supported by fact that the range of wet/total crash rates is similar for all three groups identified by the Illinois criteria (i.e., friction may be a factor, uncertain if friction is a factor, and friction may be a factor).

**Indiana DOT Program**

INDOT introduced a skid accident reduction program in 1975, which was later revised in 1997 and 2003. INDOT has tested friction with a smooth tire since 1996. Testing is performed on the interstate highways (8,000 lane miles [12,875 lane km]) annually and on U.S. and state routes on a three year cycle (Li et al. 2005; Perera, Pulipaka, and Kohn 2007). Resurfacing or other surface treatments are required on roadway segments with a low skid resistance.

The Research and Development Office manages the friction testing program. The friction testing is performed using a locked wheel skid trailer equipped with a smooth tire. The standard speed for testing is 40 mi/hr (64 km/hr). However, testing is conducted at 50 mi/hr (81 km/hr) on highways with posted speeds more than 55 mi/hr (89 km/hr), or at 30 mi/hr (48 km/hr) on roadways with posted speed less than 40 mi/hr (64 km/hr) in order to ensure safe operation. If friction numbers are obtained at 30 mi/hr (48 km/hr) or 50 mi/hr (81 km/hr), they are converted into those at 40 mi/hr using the speed gradient approach described in ASTM E-274.

Friction testing performed by INDOT can be categorized into inventory testing, warranty project testing, or special project testing. Inventory testing is performed at 1-mile (1.61-km) intervals, and a friction flag value of FN40S $< 20$ is used to identify sections with low friction values. INDOT pavement performance thresholds for a 5-year warranty specification in 2002 were an average FN40S of 35, but no single FN40S value less than 25. Special project testing is typically conducted to investigate areas where low skid resistance is a concern or to evaluate the friction performance of aggregates and mixes. This special project testing is initiated by requests from the districts or the Office of Materials Management. Friction testing has been conducted on various mixes such as stone mastic asphalt pavements, porous asphalt pavements, open graded friction courses, and other treatments. If a new aggregate source is used, the polishing resistance of such material is evaluated through a skid testing program.
Pavement surface texture data are part of the data collected at the network level for pavement management purposes. However, these data have not been utilized due to the lack of models to correlate it to pavement friction or distress types (such as raveling, stripping or disintegration). Additional research in this area is underway at the North Central Superpave Center.

One general observation from the Indiana work is that their research indicates that the use of a smooth tire for friction testing offers some advantages because the smooth tire is more sensitive to both microtexture and macrotexture. The ribbed tire is more sensitive to microtexture because of the drainage provided by the tire tread, which is roughly equivalent to 0.05 in (1.25 mm) of pavement surface texture. However, given the poor understanding of the role of microtexture and macrotexture on reducing both dry and wet pavement crashes, and the greater variability in crash rates with smooth tire friction, a switch from the ribbed tire to the smooth tire for routine testing does not seem desirable at the present time. Additional research is needed in this critical area. Also, using the wet/total crash ratio as a flag value (rather than FN40S values) helps identify specific locations where low friction and texture may be contributing to crashes, and it does not require annual network friction testing. Finally, the single smooth tire flag value does not address friction demand at the specific site which can vary significantly.

United Kingdom’s Recommended Friction Investigatory Levels

The last outside procedure evaluated in this study is the U.K. application of recommended friction investigatory levels. This check identifies sections where poor friction/texture may be contributing to a higher number of crashes but further evaluation is needed. It is, however, important to note that these are Investigatory Levels based on friction demand for the various site categories (since 2004 they have identified 10 site categories) and not the Intervention Levels (Viner, Sinhal, and Parry 2005).

One critical issue still being researched is the relationship between aggregate type, maximum size, and quality (PSV from 55 to 70) for bituminous mixes. The U.K. has required a minimum texture depth of 0.05 or 0.06 in (1.2 or 1.5 mm) since 1976. Recent research suggests that the friction coefficient is maximized at a texture depth of 0.04 in (1.0 mm). Based on the Wehner Schulze laboratory test mix evaluations, the optimum texture depth would appear to be 0.04 in (1.0 mm) with further improvement achieved by decreasing the nominal aggregate size or increasing the PSV of the aggregate used (Allen et al. 2008). Note that the PSV’s being considered are much higher than those typically used in the U.S. and that blending of aggregates may reduce the need for all high PSV aggregates (which can result in a significant economical benefit and conservation of scarce high quality aggregate). However, this type of evaluation requires testing during the mix design process with laboratory type equipment similar to the German Wehner Schulze equipment, and better equipment to measure the microtexture and macrotexture to improve the quality of performance prediction models.

Another important item to note is that this method is based on SCIRIM test results (i.e., SR values). There is not currently a good method to relate SR values to locked wheel trailer friction numbers, although some research (Corsello 1993) suggests they are probably within a range of a couple of friction numbers of each other. Nevertheless, because there is not currently a good correlation between SR and FN values, the application of the U.K. procedure to ODOT data in
this study is for informational purposes only. The U.K. does have a research study underway to correlate SCRIM, locked wheel skid trailer, and Griptester friction test results.

In the U.K. method, an appropriate investigatory level value for a section is selected from table 9 based on the section’s site category and definition. Next, if the measured macrotexture MTD for the section is less than 0.03 in (0.8 mm), then 0.05 is added to the SR value requirement selected from table 9. If the final SR value after adjustment is not achieved in the field, then the section is triggered for investigation.

Table 9. Recommended site categories and investigatory levels for trunk roads in Great Britain (Viner, Sinhal, and Parry 2005).

<table>
<thead>
<tr>
<th>Site Definition</th>
<th>Investigatory Level (at 50 km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorway</td>
<td>0.35</td>
</tr>
<tr>
<td>Dual carriageway non-event</td>
<td>0.35–0.40</td>
</tr>
<tr>
<td>Single carriageway non-event</td>
<td>0.40–0.45</td>
</tr>
<tr>
<td>Dual carriageway (all purpose) – minor junctions</td>
<td>0.45–0.55</td>
</tr>
<tr>
<td>Approaches to pedestrian crossings and other high risk situations</td>
<td>0.50–0.55</td>
</tr>
<tr>
<td>Roundabout</td>
<td>0.45–0.50</td>
</tr>
<tr>
<td>Gradient 5 to 10% longer than 50 m</td>
<td>0.45–0.50</td>
</tr>
<tr>
<td>Gradient &gt;=10% longer than 50 m</td>
<td>0.50–0.55</td>
</tr>
<tr>
<td>Bend radius &lt;500 m – dual carriageway</td>
<td>0.45–0.50</td>
</tr>
<tr>
<td>Bend radius &lt;500 m – single carriageway</td>
<td>0.50–0.55</td>
</tr>
</tbody>
</table>

Note: For the purposes of investigating the ODOT data, motorways are freeways, dual carriageways are 4-lane expressways, and single carriageways are 2-lane roads.

When applying the U.K. criteria to the ODOT data, the first assumption is that SCRIM SR values are similar to FN values measured from the locked wheel friction tester (research suggests that they are not vastly different). Although there is factor of 100 difference between the SR values presented in table 9 and the ODOT FN values, the values were assumed to translate exactly (i.e., an SR value of 0.35 was assumed to equal a FN value of 35). Therefore, in the ODOT demonstration of the U.K. procedure, SR investigatory levels were selected from table 9 for each ODOT site location and then translated into FN investigatory levels by multiplying the SR values by 100 (note: the minimum SR value of the provided range was used for the ODOT demonstration). Next, the ODOT average MTD values were compared to the U.K. MTD trigger of 0.03 in (0.8 mm). If the ODOT MTD value was less than 0.03 in (0.8 mm), then 5 was added to the translated FN investigatory level (note: this is equivalent to 0.05 being added to the SR investigatory level). The last check is to compare the ODOT measured FN to the final determined required FN (i.e., the investigatory level) to determine if adequate friction exists.
The results of the application of this procedure to the ODOT data for the three different site category types are as follows:

- Congested Freeways—16 of 30 sections (53 percent) had FN values below the investigatory level.
- Signalized Intersections—25 of 30 sections (83 percent) had FN values below the investigatory level.
- Unsignalized Intersections—16 of 30 sections (53 percent) had FN values below the investigatory level.

Based on the Ohio friction data (which represents 10 low, 10 medium, and 10 high wet/total crash rates groups in each site category), these results suggest that more stringent aggregate quality and mix design requirements and minimum macrotexture depths during construction may be cost effective, but it also appears that the criteria may be higher than necessary for Ohio’s conditions.

**Summary**

This chapter presents the data analysis methods that were used to assess the effects of friction and texture on the crash rates for each of the 90 test sites. The analysis work included the development and interpretation of trend analysis charts for a number of different data sets, as well as a statistical regression analysis. While there was considerable scatter in the data shown in the trend analysis charts, and apparently some factors not fully being accounted for, there were some general overall trends that were identified and serve as the basis for the development of the recommendations presented in chapter 5. The regression analysis failed to provide any meaningful relationships, again suggesting that some key factors (such as mix design parameters) are not being considered. The use of the probability-based approach appears to be more effective in identifying critical friction levels.

An evaluation of the ODOT data against triggering protocols established by other agencies was also conducted. The criteria developed by the New York DOT, the French National Highway Administration, the Illinois DOT, the Indiana DOT, and the United Kingdom were applied to the ODOT sections to investigate the type of results indicated.
5. FINDINGS AND PRELIMINARY RECOMMENDATIONS

Introduction

In this study, a primary goal was to use the results of the analysis of real ODOT crash, friction, texture, and roughness data to find a strong relationship between crash data and one or more of these surface- or crash-related variables. In an effort to achieve this goal, two different regression analysis approaches were tried: a single variable regression analysis that looked at the influence of one variable at a time on crashes, and a more complex multivariate 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. For the single variable regression analyses, all of the analyzed trends exhibited relatively low $R^2$ values (typically much less than 0.5), and the multivariate analysis failed to show strong individual correlations for the key variables. (Note: the $R^2$ is an indicator of how well a particular trend line fits its data; for comparison, a trend line perfectly fits a data set would have an $R^2 = 1.0$). While these poor statistical correlations were not completely unexpected (many past studies noted in the literature search have found similar results) it is also important to recognize that the strong majority of observed trends were in line with the types of trends that were expected (i.e., only a few observed trends were counter-intuitive). The poor statistical correlations were primarily due to the fact that there was significant variability in the data around each trend, which indicates that there are other (potentially many other) types of factors outside of surface characteristics that are having a significant influence on crashes. Therefore, the one primary conclusion from the data analysis portion of this study is that there was not one single variable (i.e., FN40R, FN40S, 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, the preliminary recommendations from this study focus on outlining an approach that ODOT can use to help better identify pavement sections with potentially higher probability of crashes.

It is currently recommended that ODOT adopt an approach similar to the New York SKARP procedure until better predictive models can be developed that incorporate laboratory testing results of the various mix designs commonly used in ODOT’s HMA pavements. In this context, the findings from this study are organized into the following topics:

- Ribbed versus smooth tire friction testing.
- \textit{Minimum} (Intervention) and recommended \textit{desirable} (Investigatory) friction, texture, and roughness criteria for a network-level evaluation.
- Procedure for assessing friction on new construction or maintenance projects.
- Friction and texture monitoring procedures.

The chapter ends with a brief discussion of the new \textit{Guide for Pavement Friction} (currently being edited for publication by AASHTO) and its potential application in the State of Ohio. The details associated with each of these different topics are presented in the following sections.
Ribbed Versus Smooth Tire Friction Testing

One of the ODOT objectives for this study was to determine if a ribbed or smooth tire should be used for conducting the friction tests. Based on the analysis of the data for the 90 test sites, and bolstered by the information contained in the literature review, if only one type of tire and one speed is to be used, the FN40R friction test is recommended for the following reasons:

1. Overall, the FN40R$_{avg}$ or FN40R$_{min}$ resulted in better correlations with crashes than the FN40S$_{avg}$ or FN40S$_{min}$, particularly for signalized intersections.

2. The ribbed tire data at 40 mi/hr (64 km/hr) has been used routinely in the past which would allow development of performance prediction models based on both previous and future field testing.

3. The SKARP criteria (based on FN40R$_{min}$) has been validated by the NCHRP Project 17-25 Final Report 617, Appendix D, study and provides for the evaluation of a skid resistant treatment to be considered as a cost-effective countermeasure. This assumes that the surface treatment or overlay used to provide the skid resistant treatment consists of non-carbonate aggregate. This approach allows ODOT to evaluate skid resistant treatments in a similar manner to other countermeasures (based on crash reduction factors) currently being used.

Recommendations for both the ribbed and smooth tire friction testing are provided later in this chapter. There may also be some advantages to special testing at other speeds, which will be discussed in the evaluation of the three site categories.

Minimum and Desirable Friction, Texture, and Roughness Criteria for a Network-Level Evaluation

As previously stated, the primary goal of this study is to outline an approach that ODOT can use to better identify pavement sections with potentially higher probability of crashes. This section provides recommendations for monitoring existing pavements at the network level in an effort to identify locations where poor friction, texture, or roughness may be contributing to both total crashes and a high ratio of wet/total crashes.

The adoption of the SKARP approach requires the determination of wet/total crash rates, minimum average wet weather crashes based on two years of data, and minimum friction numbers (i.e., intervention levels). This recommendation of identifying minimum friction levels was recently verified by NCHRP Project 17-25 (as documented by Lyon and Persaud 2008) as an effective method for identifying sites where improved skid resistance would be a cost-effective countermeasure to reduce crashes (note: this assumes that non-carbonate aggregates would be used in the skid resistant treatment). The proposed combination of the SKARP friction criteria along with a minimum macrotexture criteria is believed to be a far more valid approach for identifying sections with high accident rates (i.e., sections with poor skid resistance that need corrective action) than any single friction or macrotexture number.

Based on an analysis of friction demand at an individual site, it may be very cost-effective to provide a surface treatment before the Intervention Level is reached (i.e., taking a pro-active approach). That is the purpose of the desirable or target (Investigatory Level) criteria. The
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

approach of using investigatory levels to identify sections that would benefit from a surface treatment has been shown to be effective in the U.K. (Viner, Sinhal, and Parry 2005; Viner and Caudwell 2008). Based on the data ODOT collected for the 90 sites, increasing the friction number and the macrotexture depth will significantly reduce total crashes and deaths and serious injuries. Also, using an available tool (sliding 20-ft [6.1-m] baselength) to identify roughness exceeding 300 in/mi (4.7 m/km), and evaluating possible corrective actions are recommended to reduce total and wet pavement crashes. The approach used to identify the Intervention Level was modified to produce an Investigatory Level to identify sites where some corrective action might be desirable (and cost-effective). This approach is also supported by the literature review where increasing the macrotexture depth was found to greatly reduce crashes (Pulugurtha, Kusam, and Patel 2008). The use of procedures to identify spikes in roughness that may contribute to an increase in total or wet pavement crashes is also a very promising procedure.

While it is possible to define one Investigatory Level friction number for all pavements, it is recommended that separate investigatory levels be developed for a small number of site categories in the future. The Guide for Pavement Friction recommends the development of investigatory levels for three to five separate site categories (Hall et al. 2006). Additional guidance on setting site categories and Investigatory levels are now available (Viner and Caudwell 2008). The analysis of the data collected under this study also shows that there is considerable merit in analyzing each of the three selected site categories separately in order to optimize the overall cost-effectiveness of safety improvements on the network. For example, the data indicates that FN20R or FN20S results could be used to evaluate friction at intersections (although this speed may not be practical from a safety standpoint), while congested freeways (and possibly other high-speed, free flowing roadways) may be better evaluated using FN60S and macrotexture. As noted previously, the FN20R and FN20S are highly correlated to each other and have a higher correlation to total crashes than FN40R or FN40S. The recognition of trends such as these supports the position that it would be more desirable to analyze each site category separately.

The issue of testing speed on congested freeways (and possibly other high speed free flowing roadways) deserves further discussion. Testing at a higher speed than 40 mi/hr on high speed roadways would be desirable. INDOT tests roads with 55 mi/hr (89 km/hr) or higher posted speeds at 50 mi/hr (80 km/hr) with a smooth tire. Texas DOT also tests high speed roadways at 50 mi/hr (80 km/hr) with a smooth tire. Their research suggests that the friction is near minimum values at 60 mi/hr (97 km/hr) (Button, Fernando and Middleton 2004). Florida has research underway to evaluate testing at higher speeds because of the safety concerns of testing at 40 mi/hr (64 km/hr). The FN60R and FN60S statistics versus mean texture depth (average or minimum) from the Ohio congested freeway sites show higher friction with higher texture depths (see figure C-40). It is important to increase macrotexture on high speed roadways to reduce the hydroplaning potential. As the smooth tire is a better indicator of both microtexture and macrotexture, and is more sensitive to hydroplaning potential, it would be the preferred tire type if only one tire type is used. Friction testing high speed roadways at 50 or 60 mi/hr (80 or 97 km/hr) rather than 40 mi/hr (64 km/hr) would have operational benefits including increased safety.
Based on the results of the data analysis conducted under this study, and the comprehensive literature review, friction, texture, and roughness guidelines were developed for ODOT conditions. To remain consistent with much of the other current research conducted on this subject, guidelines for both minimum (intervention) and desirable or target (investigatory) levels are needed. The general intervention and investigatory levels for friction, texture, and roughness criteria that were selected for ODOT network level evaluations are summarized in table 10.

Table 10. Recommended intervention (minimum) and investigatory (desirable or target) friction, texture, and roughness levels for ODOT network level evaluations.

<table>
<thead>
<tr>
<th>Check</th>
<th>Variable</th>
<th>Intervention Level</th>
<th>Investigatory Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a. If wet/total crash rate, and&lt;br&gt;b. Annual average number of wet pavement crashes (2 or 3 year average), then&lt;br&gt;c. Check minimum friction number&lt;br&gt;FN40R\text{min} &lt; 32 or&lt;br_FN40S\text{min} &lt; 23</td>
<td>≥ 35 percent&lt;br&gt;FN40R\text{min} &lt; 32 or&lt;br_FN40S\text{min} &lt; 23</td>
<td>≥ 25 percent&lt;br&gt;FN40R\text{min} &lt; 42 or&lt;br_FN40S\text{min} &lt; 32</td>
</tr>
<tr>
<td>2</td>
<td>Minimum macrotexture</td>
<td>Use the appropriate MTD\text{min} value from table 8 in chapter 4</td>
<td>&lt; 0.04 in (1.0 mm) (sand patch) (Based on U.K. criteria)</td>
</tr>
<tr>
<td>3</td>
<td>Roughness spikes based on 20-ft (6.1-m) sliding baselength</td>
<td>Use current ODOT requirements</td>
<td>&gt; 300 in/mile (4.7 m/km)</td>
</tr>
</tbody>
</table>

Notes:
1. Check 1 - Minimum wet/total crash rate, minimum annual average number of wet pavement crashes, and the ribbed tire friction numbers (FN40R\text{min}) are based on NY SKARP criteria. Sections meeting the check 1a and 1b criteria are then friction tested to determine if poor skid resistance is the likely cause of the crashes. The smooth tire criterion (FN40S\text{min}) is the corresponding minimum smooth tire friction number for those sections that failed the NY SKARP criteria based on FN40R\text{min} < 32. If all three variable criteria for check 1 are met, then a skid resistant overlay should be planned without the need for any further evaluations. A skid resistant overlay with non-carbonate aggregate will likely be very cost effective.
2. The minimum macrotexture depth is based on the French criteria in LCPC Bulletin Special Issue #255 on Skid Resistance (Dupont and Bauduin 2005). Alternatively, a 0.2 in (0.5 mm) (sand patch) minimum criteria could be used here, but it would not be appropriate for slow speed roadways.
3. Proactive approach—Desirable or Target (Investigatory Level) Criteria where low friction, texture, or spikes in roughness may be contributing to increased numbers of wet pavement and total crashes.

To apply the checks outlined in table 10, the first step is to conduct checks 1a and 1b on the data collected for a given project. If the results for both checks 1a and 1b are true (i.e., observed values exceed the defined criteria in the table), then the minimum friction check (check 1c) is required. If the result of check 1a is false, or the result of check 1b is false, then a friction problem is not indicated on the section. For sections where conducting check 1c is required and the measured minimum friction number is less than the specified criteria in the table, then an intervention or investigation is triggered (i.e., an intervention or investigation is only triggered when all three variables under check 1 have surpassed their individual defined limits). The
checks for macrotexture and roughness spikes (checks 2 and 3) are independent of check 1 and can, therefore, trigger an intervention or investigation by themselves.

While the general guidelines outlined in table 10 are customized to the ODOT data, to truly optimize the cost-effectiveness of a wet pavement program to reduce the skid accident potential, it is believed each site category should be analyzed separately (particularly at the target or desirable level [Investigatory Level]). When any site fails all three variables included in check 1 (i.e., wet/total crash rate greater than the intervention level, an annual average of wet pavement crashes exceeding the intervention level, and a field test reveals a FN less than the intervention level), there is a very high probability that a skid resistant surface treatment would be very cost effective and corrective work should be taken without delay.

However, as an added exercise under this study, recommended desirable or target (Investigatory) levels for friction, texture, and roughness were determined for the three investigated site categories (i.e., congested freeways, signalized intersections, and unsignalized intersections). These site category-specific investigatory level guidelines are summarized in table 11. Similar to table 10, check 1c is only necessary if checks 1a and 1b are true. An investigation is only triggered when checks 1a, 1b, and 1c have surpassed their individual defined limits. The checks for macrotexture and roughness spikes (checks 2 and 3) are independent of check 1 and can, therefore, trigger an investigation by themselves.

Table 11. Recommended investigatory (desirable or target) friction, texture, and roughness levels for individual ODOT site categories.

<table>
<thead>
<tr>
<th>Check</th>
<th>Variable</th>
<th>Congested Freeway</th>
<th>Signalized Intersection</th>
<th>Unsignalized Intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a. If wet/total crash rate, and ≥ 25 percent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. Annual average number of wet pavement crashes (2 or 3 year average), then &gt; 2 for rural settings &gt; 3 for urban settings</td>
<td>&gt; 4</td>
<td>&gt; 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. Check minimum friction number FN40R\text{min} &lt; 38 or FN40S\text{min} &lt; 28</td>
<td>FN40R\text{min} &lt; 40 or FN40S\text{min} &lt; 28</td>
<td>FN40R\text{min} &lt; 40 or FN40S\text{min} &lt; 30</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Minimum MTD &lt; 0.04 in (1.0 mm) sand patch test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Roughness spikes based on 20-ft (6.1-m) sliding baselength &gt; 300 in/mile (4.7 m/km)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As recommended in the draft Guide for Pavement Friction (Hall et al. 2006), it is recommended that 3 to 5 site categories be selected that reflect the friction demands on the network as a whole. This could be similar to table 12 that follows. ODOT could then adjust the Intervention and Investigatory Levels that would be expected to meet their crash reduction goals and be feasible to implement given their personnel and equipment capabilities. Desirably, this would be based on an annual network level friction testing program and annual macrotexture and IRI surveys.
Procedure for Assessing Friction on New Construction or Maintenance Projects

The previous recommendations apply to monitoring existing pavements and identifying locations where poor friction or texture may be contributing to both total crashes and a high ratio of wet/total crashes. This section applies to monitoring new construction or maintenance projects.

When corrective treatments are warranted, it is essential that the pre-surface treatment or overlay condition (surface distress, IRI, friction, and macrotexture) and the post-surface treatment condition (same variables) be documented (i.e., both the before and after conditions must be documented). Also, it should be noted that it generally takes 6 weeks to 6 months after a surface treatment for the asphalt (or the curing compound in the case of concrete pavements) to wear off before friction values “stabilize.” Perhaps the best way to address this short term issue is to ignore friction data during the year of construction. However, replacing a surface with low friction and macrotexture with a new surface with low friction and macrotexture will not be cost effective (the skid resistant treatment should contain non-carbonate aggregates); the new maintenance or construction should significantly improve the friction and macrotexture above the desirable or target (Investigatory Level) values.

One immediate issue for highway agencies is: “What minimum friction value is acceptable to open a roadway to public traffic?” Generally, macrotexture and roughness are not critical safety issues immediately after construction, and therefore, need not be considered. Again, there is no universal single friction number that is safe or unsafe; the guidance must be based on the friction demand of the specific site. A sharp curve on a roadway or freeway ramp requires a higher initial friction value than a straight, level section of rural freeway or expressway. Therefore, the following four step process is recommended when evaluating the surface friction on a new construction or maintenance project.

1. **Determine the friction demand for the specific site category.** This study selected site categories that were expected to demonstrate the effect of friction, texture, and roughness on particularly rear-end crashes which is one of ODOT’s safety objectives. Consequently, all site categories were not evaluated. Therefore, the information presented in table 12 is proposed to provide guidance on site categories, heavy commercial volumes, and Design FN based on friction demand category.

2. **Determine the friction intervention level for the specific project site category.** Select the friction demand for the site category that best matches the specific project site conditions. Note that this is the estimated friction demand not the desired minimum friction number where intervention is required. This recognizes that due to the many variables involved, most current specifications do not specify minimum friction levels during construction (but this has been included on some warranty projects). Perhaps the best approach to set the minimum intervention level where corrective action should be considered on new construction or maintenance projects, is to reduce the design FN by a set amount (e.g., 10 FN’s). This should be based on past experience with similar projects in the same location wherever possible. The U.K. guidelines (Viner and Caudwell 2008) noted earlier, can also be used as a guide.
Table 12. Site category vs. truck AADT vs. PV (Chelliah et al. 2003).

<table>
<thead>
<tr>
<th>Site Category</th>
<th>Site Description</th>
<th>PV of Aggregate Traffic in Heavy Commercial Vehicles per Lane per Day</th>
<th>Design的需求</th>
<th>Demand Category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>250</td>
<td>1000</td>
<td>1750</td>
</tr>
<tr>
<td>1</td>
<td>Approach rail road crossings, traffic lights, pedestrian crossings, roundabouts,</td>
<td>7</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Stop and Give Way controlled intersections (SH only).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Curves with radius &lt;=250 m, downhill gradients &gt; 10 percent and &gt; 50 m long,</td>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>freeway/highway on/off ramp</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Approach to intersections, downhill gradients 5 to 10%</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>Undivided highways without any other geometrical constraints which influences</td>
<td>5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>frictional demand.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Divided highways without any other geometrical constraints which influence</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>frictional demand.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Select corrective action to address critical initial conditions. As minimum friction numbers are not specified for specific project sites, the highway agency may have to conduct special testing to aid in determining the most appropriate action. The corrective actions could include speed restrictions, sanding with angular fine aggregates to increase friction, water blasting surface to improve texture, and so on. This would have to be based on a subjective evaluation of the hazard posed to the traveling public at the specific site.

4. Adjust design, construction, and maintenance guidelines to minimize a recurrence of this type of problem. As this is a very critical, undesirable situation, available guidance should be updated to minimize recurrence of this type of problem. Also, guidelines should consider providing initial friction and texture values significantly greater than the investigatory levels provided above. Where monitoring suggests that these guidelines are not being met on recently constructed projects, steps should be taken to address the issues identified to help ensure that durable, safe, and cost-effective pavement surfaces are provided.

It would be very desirable on new projects (whether construction or maintenance) to establish desirable, investigatory, and minimum friction and texture guidelines. The FAA has developed an advisory circular using this approach for airport runways (FAA 1997). Guidelines using a similar approach could be developed for highway projects with particular emphasis being placed on cost-effectiveness, which could vary at different locations within a state.
Friction and Texture Monitoring Procedures

Based on the results of this study and the literature review, the following monitoring activities are recommended:

1. Annually (within 6 months of the end of the calendar year), summarize the percent of ODOT’s network by site category, and by increments of the wet/total crash rate. This is necessary to establish the friction testing program, also. In Ohio, traffic crashes are generally entered into the database within 3 months. Monitoring these data will help evaluate the progress being made in reducing the number of sections with high wet/total pavement crash rates on the network and also help refine proactive strategies to reduce the total number of crashes and annual fatalities and injuries. Consideration should be given to friction testing all sections with wet/total crash rates of 25 percent or greater.

2. Conduct annual network level laser based macrotexture surveys and calculate the percent of the network by site category, and by various increments of macrotexture depth. This will allow an evaluation of the progress being made in increasing the macrotexture depths on the network (particularly placing emphasis on eliminating the low macrotexture depths in areas with high friction demand).

The results of the above monitoring should be reported annually. This will allow an evaluation of the progress made in improving the pavement surface condition which will reduce the wet/total crash rates. For example, the U.K. annually reports the percent of their network with friction test results below the Investigatory Level (currently about 8 percent). Monitoring the wet/total crash rates, the number of wet pavement crashes, and the macrotexture depth will be more cost effective initially than continuous friction testing of the network, which also might be considered in a future Long Term Skid Resistance monitoring program.

Possible Implementation of the Guide for Pavement Friction

The NCHRP 1-43, *Guide for Pavement Friction*, being edited for publication by AASHTO is expected to be available soon. The results of this study strongly support the recommendations in the guide. The following are recommendations that should be considered by ODOT if they proceed to implement the Guide:

- Consider the development of seasonal monitoring sites.
- Select three to five site categories based on friction demand levels and corresponding Intervention and Investigatory Levels.
- Develop laboratory mix design procedures to address friction and texture and develop safety performance prediction models.
- Develop criteria or guidance on cost effectiveness of higher quality surface treatments and use where warranted.
- Develop construction specifications and maintenance guidelines to help ensure that the friction/macrotexture provided meets or exceeds site specific friction demand and roughness does not significantly increase total crash rates.
• Develop a program to annually monitor safety performance measures involving pavement surface characteristics to ensure that significant improvements are being made to the network.

ODOT may wish to consider conducting necessary research in the next 3 to 5 years to implement these recommendations. It is important that guidelines being developed under NCHRP 17-18 and in the proposed 2009 Highway Safety Manual also be considered in implementing a Skid Accident Management Program.

Continuing with the discussion of the NCHRP 1-43 *Guide for Pavement Friction*, the guide does contain a procedure to estimate the MTD based on the FN40R and the FN40S. In this study, Microsoft Excel was used to do a multilinear regression of the Ohio MTD average data in terms of FN40R and FN40S in an attempt to compare the equation in NCHRP 1-43 report. The NCHRP equation was based on about 400 measurements from the NASA Wallops Friction Workshops data (Hall et al. 2006). The following are the 1-43 and the ODOT based regression equations so they can be compared. Note: both equations predict MTD in units of “inches.”

**NCHRP 1-43 Equation:**
\[
MTD = 0.039 - 0.0029 \times FN40R + 0.0035 \times FN40S \quad (R^2 = 0.86) \quad (Eq. 7)
\]

**Equation using ODOT data:**
\[
MTD = 0.02589 - 0.00046 \times FN40R + 0.000847 \times FN40S \quad (R^2 = 0.25) \quad (Eq. 8)
\]

It is apparent that there is a major difference in the predictive capabilities of the two equations. There appears to be a major difference in the aggregate quality and mix designs that affect the above results. Most of the ODOT data are based on limestone or gravel aggregate. This large difference also suggests caution in comparing results of friction studies in other states or countries without verifying them for Ohio conditions.

Based on observations in this study, it is particularly important to consider tests to better quantify aggregate quality (like the Micro Deval test) and friction and texture of the laboratory mixtures (using a procedure like the German Wehner Schulze Laboratory test) during the existing and planned extension of the materials testing research underway by ODOT (Luce et al. 2007; Allen et al. 2008; Dunford 2008; Woodward et al. 2008). Improved procedures to evaluate microtexture and macrotexture based on laboratory specimens or field cores using aggregate imaging systems, 3-D photographic methods, or improved laser scanners (as discussed in Appendix B) are being evaluated and should be considered for use when and if they become available. Other countries including the U.K. and France use aggregates with PSV’s greater than 50, and this should be considered for skid resistant surface treatments.
6. RECOMMENDATIONS FOR IMPLEMENTATION

Introduction

Based on the findings from this study, the implementation recommendations focus on the adoption of outlined procedures that can be used to better identify potential problem locations where wet-weather accidents are more likely to occur. Specifically, the procedures are divided into a network-level procedure used to locate problem locations within the network, and a project-level procedure used to assess if adequate friction is being provided on new construction and maintenance projects. Other implementation issues are also addressed in this chapter, including:

- Steps need to implement.
- Suggested time frame.
- Expected benefits.
- Potential risks and obstacles.
- Strategies to overcome risks and obstacles.
- Organizations that may be affected.
- Estimated costs associated with implementation.

Overall Implementation Recommendations

Procedure for Evaluating Sections at the Network Level

This research was originated by an immediate need to help the various State districts identify sections where low friction (and/or macrotexture) and roughness are contributing to total and wet pavement crashes, and particularly rear-end crashes. Based on the study findings and a review of literature, ODOT-specific intervention (minimum) and investigatory (desirable or target) levels were presented in table 10. It is believed the guidance provided in table 10 (which is based on the SKARP criteria and macrotexture depth) will allow ODOT to conduct meaningful network-level evaluations where at least 2 years of crash data are available. Some of the more detailed aspects of these network level guidelines are discussed below.

1. Ribbed Versus Smooth Tire Friction Testing—The literature review and the analysis of the ODOT data suggest that no single variable (i.e., ribbed tire friction, smooth tire friction, or macrotexture depth) correlates strongly with crashes. If a single friction test method is to be used, at this time it is recommended that the FN40R friction test remain the standard. For high speed freeways or rural two-lane highways, friction testing at 50 or 60 mi/hr (80 or 97 km/hr) with a smooth tire and evaluating available macrotexture should be considered as an option to improve safety of the data collection operation and also improve the correlation with crash data. For higher speed roadways the smooth tire is more sensitive to hydroplaning and macrotexture. Therefore, conducting friction testing at higher speeds on these roadways provides a better correlation with crashes for both FN60S and macrotexture.

2. Minimum Ribbed and Smooth Tire Friction Numbers—Because the study concluded that no single variable is highly correlated with crash data, the preliminary recommendations
from this study focused on outlining an approach that ODOT can use to help better identify pavement sections on their network with potentially higher probability of crashes. Based on the results of this study and the comprehensive literature review, intervention and investigatory friction criteria were developed for ODOT network evaluations based on the New York Skid Accident Reduction Program (SKARP) approach. These guidelines are summarized in table 10.

3. Macrotexture Data—The collected macrotexture data did not significantly help explain the difference in ribbed and smooth tire friction numbers, the speed gradient for the ribbed and smooth tire, or the total and wet/total pavement crash rates at the individual sites. This was an unexpected finding, but it should be noted that information about aggregates used in the mix design for each of the project sites was not available for analysis. However, based on the literature review and on the analysis of macrotexture data available for 85 of the 90 site locations, it is recommended that friction numbers and macrotexture depths be evaluated during the laboratory mix design process. It is also recommended that guide construction specifications be developed for HMA pavements, PCC pavements, and thin surface treatments that specify target and minimum macrotexture depths. The data show a general trend that increased macrotexture depth significantly reduces total and wet pavement crashes, particularly on high-speed roadways. Taking these results into account, minimum macrotexture intervention and investigatory levels were identified for ODOT based on French or United Kingdom (UK) criteria. These suggested macrotexture criteria are also presented in table 10.

4. Roughness (IRI) and Safety—For congested freeway sites, the data analysis showed that there appears to be a correlation between roughness and increased crash rates, particularly when IRI spikes based on a 20 ft (6 m) sliding baselength exceeded 300 in/mi (4.7 m/km). Because of this finding, this value is recommended as an investigatory level as shown in table 10.

It should be noted that the three specific site categories selected for this research were based on those sites estimated to have the most potential for reducing total and rear end crashes if adequate friction and texture are available. Table 11 shows the importance of analyzing the various site categories separately. This restricted sample (90 sites total) was necessary to reduce the friction testing required to accommodate this research effort and ODOT’s annual friction testing program. These data are not representative of the network as a whole (i.e., sections with low friction demand are not represented). The research results clearly support the importance of implementing the Guide for Pavement Friction currently being published by AASHTO. That document recommends selecting three to five site categories based on friction demand, focusing on Investigatory rather than Intervention Levels, and evaluating friction and macrotexture levels during the laboratory mix design process (and developing mix specific friction and macrotexture-based performance prediction models). In conclusion, it is recommended that ODOT develop network-level guidelines that use the procedures outlined in chapter 5, and the specific intervention and investigatory levels outlined in tables 10 or 11 depending on the approach that best meets the current ODOT needs.
Procedure for Evaluating New Construction or Maintenance Projects

The implementation recommendations in the previous section apply to monitoring existing pavements and identifying locations where poor friction or texture may be contributing to both total crashes and a high ratio of wet/total crashes based on annual monitoring of crashes on the highway network. The guidelines in this section apply to monitoring new construction or maintenance projects.

One immediate issue for highway agencies is the identification of the minimum friction value that is considered acceptable for the traveling public. Generally, macrotexture and roughness are not critical safety issues immediately after construction, and therefore, need not generally be considered. Again, there is no universal single friction number that is safe or unsafe; the guidance must be based on the friction demand of the specific site. An approach to a pedestrian crossing at an intersection, a sharp curve on a roadway, or a high-speed freeway ramp each requires a higher initial friction value than a straight, level section of rural freeway or expressway. Therefore, it is recommended that ODOT develop project-level guidelines that use the following four step process to evaluate the surface friction provided on a new construction or maintenance project.

1. **Determine the friction demand for the specific site category.** This study selected site categories that were expected to demonstrate the effect of friction, texture, and roughness on particularly rear-end crashes, which is one of ODOT’s safety objectives. Consequently, all site categories were not evaluated. Therefore, the information presented in table 12 is suggested to provide guidance on site categories, heavy commercial volumes, and Design FN based on friction demand.

2. **Determine the friction intervention level for the specific project site category.** Select the friction demand for the site category that best matches the specific project site conditions outlined in table 12. Note that this is the estimated friction demand and not the desired minimum friction number where intervention is needed. This recognizes that due to the many variables involved, most current specifications do not specify minimum friction levels during construction (but this has been included on some warranty projects) or maintenance activities. Perhaps the best approach to set the minimum intervention level where corrective action should be considered on new construction or maintenance projects is to reduce the design FN for that site category by a set amount (e.g., 10 FN’s). This should be based on past experience with similar projects in the area wherever possible. The U.K. criteria previously discussed (Viner and Caudwell 2008) provides additional guidance in this area.

3. **Select corrective action to address critical initial conditions.** It should be noted that it generally takes 6 weeks to 6 months after a new surface or surface treatment for the asphalt (or the curing compound in the case of PCC pavements) to wear off before friction values “stabilize.” Perhaps the best way to address this short term issue is to ignore friction data during the year of construction unless a significant safety issue is present. As minimum friction numbers are not currently specified for specific project sites, the highway agency may have to conduct special testing to aid in determining the most appropriate corrective action. The corrective actions could include speed restrictions, sanding with angular fine aggregates to increase friction, water blasting
surface to improve texture, and so on. This would have to be based on a subjective
evaluation of the hazard posed to the traveling public at the specific site.

4. Adjust design, construction, and maintenance guidelines to minimize a recurrence of this
type of problem. As low friction values on a recently constructed project are a highly
undesirable situation, available guidance should be updated to minimize recurrence of
this type of problem. Also, final ODOT guidelines should consider providing initial
friction and texture values greater than the investigatory levels provided above. Where
monitoring suggests that the Investigatory Level guidelines are not being met on recently
constructed projects, steps should be taken during mix design to address the issues
identified to help ensure that durable, safe, and cost-effective pavement surfaces are
provided.

On new projects (whether construction or maintenance), it may be helpful to establish desirable,
investigatory, and minimum friction and texture guidelines for the various site categories. The
FAA has developed an advisory circular using this approach for airport runways (FAA 1997).
Guidelines using a similar approach could be developed for various site categories of highway
projects with particular emphasis being placed on cost-effectiveness, which could vary at
different locations within a state.

It is also important that an annual report be developed to monitor progress being made on
increasing friction and macrotexture and decreasing roughness on the network. This would
identify the extent of the system that exceeds the Intervention Levels and the Investigatory
Levels established, and would also allow an evaluation of equipment and personnel required to
make a substantial improvement to the overall pavement surface condition, if needed.

Implementation Steps and Time Frame

In order to efficiently implement the recommendations discussed above, the following
implementation steps (and associated time frame) are recommended:

1. It is recommended that a work plan be developed within the next 9 months to implement
   the *AASHTO Guide for Pavement Friction* approach. This approach should be modified
to include additional consideration of macrotexture and IRI as recommended. This
should identify specific actions needed over the next 3 to 5 years to fully implement a
pavement condition safety management plan.

2. It is recommended that three to five site categories on the Ohio state highway network be
   selected based on friction demand, and that Investigatory Levels and minimum
Intervention Levels be assigned to each category. This step would also help implement
the new *AASHTO Guide for Pavement Friction* currently being edited for publication.
The site category selection should also consider the results of this research and currently
available guidance based on the *Highway Safety Manual* expected to be published in
2009. This effort should be completed within 6 months.

3. Friction testing should then be conducted for all sections meeting criteria 1a and 1b (in
table 10) for the Intervention Level based on calendar year 2006 and 2007 crash data and
for as many sections meeting 1a and 1b Investigatory Level criteria as ODOT equipment
and manpower limitations will allow.
4. Sections meeting the Intervention Level criteria should be programmed for corrective action as soon as possible using non-carbonate aggregates.

5. Sections not meeting the Intervention Level 1c friction criteria should be reevaluated annually.

6. Sections meeting the Investigatory Level criteria should be evaluated to determine if low friction and texture are contributing to total and wet pavement crashes. It is likely that low friction or texture and high roughness spikes are contributing to only a small but significant portion (5 to 20 percent) of the total crashes annually. The models in the 2009 Highway Safety Manual will allow an analysis of whether geometric design or other traffic operation deficiencies are likely contributing to the increased total and wet pavement crashes so appropriate countermeasures can proactively be taken before the minimum Intervention Level criteria are met. It should be noted that the NY SKARP criteria have been used to develop accident modification factors in NCHRP Project 17-25 Final Report 617, Appendix D, for skid resistant treatments as a countermeasure. This should complement ODOT’s crash reduction factor analysis and potentially assist in using the SafetyAnalyst program to identify sites where low friction/texture is contributing to increased crash rates.

7. Within 18 months, an annual report should be developed identifying the extent of the Ohio roadway network that exceed the Intervention and Investigatory Levels established. This should be used to monitor the condition of the roadways that affect safety performance and whether ODOT safety goals are being met. It can also help determine any additional equipment and personnel needed.

Expected Benefits

In the near term, the use of existing crash data (particularly wet/total crash rate and average annual number of wet pavement crashes) and network level macrotexture and roughness data to identify priority sites for friction testing will help evaluate whether low friction and macrotexture or high roughness spikes are likely contributing to the high crash rate. Combined with ODOT’s Road Safety Audit Program and the before and after evaluation of the effectiveness of skid resistant treatments at high-accident locations, the cost-effectiveness of countermeasures to correct pavement surface condition deficiencies can be documented. It can also be determined if total crashes will be reduced 10 percent by 2015. In addition, the impact of reductions in rear-end crashes can be evaluated to support ODOT’s goal of reducing rear-end crashes by 25 percent by the year 2015.

If the investigatory level approach is adopted, it will also help ODOT to proactively address sites with high-crash potential so they can either correct identified deficiencies or continue to monitor closely and take action as ultimately warranted.

In the short term, the results of this study will help justify the implementation of the recommendations provided in AASHTO’s draft Guide for Pavement Friction. It should also help justify additional personnel, equipment, and cost necessary to continue to significantly reduce annual fatalities and serious injuries in Ohio. Similar efforts in other countries have produced benefit-to-cost ratios exceeding 5 to 1 and as high as 40 to 1. New York’s implementation of the SKARP criteria in conjunction with a safety appurtenance improvement
program and a major pavement preservation program helped reduce actual annual fatalities from 2217 in 1990 to 1460 in 2000 (a 34 percent reduction) which is an outstanding accomplishment.

**Expected Risks, Obstacles, and Strategies To Overcome Them**

There is a risk that the relatively small sample size evaluated under this study (90 sites total in three site categories, and selected to accommodate the work within ODOT’s annual friction testing program) could lead to some unsupported conclusions. However, the comprehensive literature review conducted minimizes the probability of unsupported findings or recommendations.

The focus on the wet/total crash rate in selecting the sites evaluated in this research was supported by the literature review and the data analysis. However, this makes it critical that: 1) the crashes (and supporting roadway data) are accurately located; and 2) that crash data are quickly entered into the database so the wet/total crash rate and average number of wet pavement crashes can be determined within 6 months after the end of the calendar year. This is necessary so friction (or other testing) can be conducted and any corrective action needed can be evaluated, and, if necessary, implemented in a timely manner.

There is currently a significant amount of safety-related research underway. The most critical is the *Guide for Pavement Friction* currently being edited by AASHTO for publication, and the recommendations made herein are consistent and supportive of the implementation recommendations provided in that guide. Also, ODOT has underway a significant amount of related research that can directly support the suggested future implementation of the *Guide for Pavement Friction*, the expected 2009 *Highway Safety Manual*, and other related analysis tools (e.g., the *SafetyAnalyst* model which ODOT is evaluating). Advances in technology, particularly methods to better quantify microtexture and macrotexture, are currently available or are expected to be available shortly and will help identify quality aggregates, improve mix designs, and make possible the development of improved safety performance prediction models. These opportunities should be taken advantage of in existing and proposed safety related research efforts.

**Organizations That May Be Affected**

The Office of Highway Safety and the Office of Materials Management will likely be affected by some of the recommendations. In addition, the guidance provided may also affect the District Offices, helping them to address safety issues related to pavement condition in a more cost-effective manner.

**Estimated Costs Associated With Implementation**

It is estimated that the work plan to develop a short term (3 to 5 year) improved pavement condition safety management plan identified in step 1 could be done by ODOT in 9 months at a cost of about $100,000. The most significant future costs are related to improved consideration of friction and texture during the mix design stage and the development and evaluation of mix specific performance prediction models. However, the improved guidance developed should utilize local materials to the maximum extent and minimize the import of more expensive, durable aggregates. Emphasis should be placed on thin surface treatments to maximize cost
effectiveness if the existing pavement structure is adequate. The expected transportation and materials costs savings from the suggested mix design research will greatly exceed the related materials testing and evaluation costs, some of which is currently underway.

Another significant cost is related to collecting and evaluating the crash and roadway condition data. The crash data are currently collected and entered into the database usually within 3 months. It is critical that spot checks of the adequacy of the location of data reported are conducted to ensure data integrity. The crash data should be available with no significant change in current costs. Use of these data as suggested to identify locations with high accident potential can be done immediately and is much more cost effective than network-level friction surveys.

It is estimated that the costs to collect the friction data for the Intervention Level will be similar to current procedures. However, a commitment to be more proactive at identifying potential high-crash locations based on the Investigatory Level criteria suggested would significantly increase data collection and evaluation costs. It would likely require additional friction testing equipment and testing personnel, at least initially. It would also increase the number of people required to effectively process and evaluate the cost effectiveness of possible countermeasures. As noted previously, the benefit to cost ratio of similar efforts in other countries has ranged from a minimum of 5 to 1 to a maximum of 40 to 1. This research evaluated 30 sections each of three different site categories selected to evaluate conditions where improved friction and texture would likely reduce both total and rear-end crashes. It is not possible to use this limited data to project costs to address the state highway network as a whole. That is the primary purpose of the work plan proposed in step 1, which can be refined when the monitoring report proposed in step 7 is available.

The other significant cost would be to develop and prepare an annual report summarizing the condition of the network based on the Intervention Levels and Investigatory Levels developed and the Site Categories established. This critical step would allow an evaluation of the effectiveness of efforts to significantly improve the safety of the pavement surface. For example, the U.K. estimates that the benefit cost ratio of their highly effective program is 5 to 1 and that currently only 8 percent of their network is below the Investigatory Level established. Developing an annual estimate of the percent of the Ohio pavement network below the Intervention and Investigatory Levels established would help decision makers prioritize efforts to improve the condition of the pavement surface as part of their overall safety program.

ODOT’s currently available database and analysis capabilities are impressive. Combined with the Department’s on-going materials research activities, implementing the suggested improvements should result in a significant reduction in the number of total and wet pavement crashes on the state highway network.

**Disclaimer**

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.
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Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations


APPENDIX A. ANNOTATED BIBLIOGRAPHY


When American motorists talk about transportation problems, they generally key in on traffic. Snarled highways, epic commutes, and gridlocked business and commercial districts mar our suburban existence, weighting heavily upon our elected leaders, our policy-makers, and our families. Yet there’s a more costly problem to be addressed on America’s roads: motor vehicle crashes. In 2006, traffic crashes killed 42,642 people in the United States – about 117 deaths per day, and nearly 5 every hour. Most Americans would be surprised to learn the societal costs associated with motor vehicle crashes significantly exceed the costs of congestion. AAA commissioned this study to examine the costs of crashes to society. The study, along with recommendations for improvements, is designed to raise awareness of the importance of transportation investments, and provide policy-makers, departments of transportation, and the public with information on the magnitude of the safety problem.


Providing cost-effective, safe and smooth pavement surface is a priority for transportation agencies. The major challenge, however, is to provide a sustainable surface skid resistance for economy and preservation of superior safety, yet smooth enough for quiet and comfortable ride. Some advancement in smoothness indices and texturing methods has occurred as part of this balancing act between the pavement smoothness and surface friction. However, the sustainability issue of different surface textures has not yet fully addressed. There is also a need to develop comprehensive models that predict the short and long-term performances of different surface textures. This paper addresses the performance of concrete pavement surface textures using the Federal Highway Administration (FHWA) Long Term Pavement Performance Program (LTPP) data in GPS 3, 4 and 5. The analysis shows that tined/grooved textures maintain consistently higher skid resistance over time and concrete pavements surface friction is insensitive to ambient condition. Cumulative traffic passes was more sensitive to frictional performance than the cumulative axle loads. Two alternative models have also been successfully developed for prediction of concrete pavements long-term skid resistance as a function of texture type, cumulative traffic passes, speed, and concrete compressive strength. These models were shown to be statistically significant at 95% confidence levels with reasonable prediction accuracy.


No abstract available.


Skid resistance has been the most important property of a surface layer in the UK for many years. It has been provided by the use of aggregate with high polished stone value and mixes designed with high texture. However, in recent years this traditional approach has been subject to investigation and the simplistic relationship between texture depth and polished stone value questioned. The polished stone value test has been found to be a ranking method dependant on the stressing conditions imposed during the tests i.e. vary the stress during testing and different aggregates will react in different ways to achieve a new equilibrium level. The German Wehner Schulze test is now proposed within Europe as a replacement to the polished stone value test. This method subjects either laboratory prepared asphalt samples or cores extracted from the pavement surface to simulated trafficking and measures change in skidding resistance with time. The method has been accepted by German contractors to predict performance of the mix. This paper details an investigation of the Werner Shultz equipment to assess UK asphalt surfacing mixes.

Researchers at Pennsylvania State University have developed a computer-based system that uses fuzzy logic to predict the risk of accidents on wet pavement. The system can help identify high-risk roads and indicate ways to improve their safety. When compared with probabilistic and nonlinear regression models, the fuzzy logic models not only were more accurate in predicting the risk of wet pavement accidents but also had the advantage of providing specific ways to decrease risk. Researchers hope that their work will help highway departments with limited resources decide which sections of road to focus on when doing improvements.


The purpose of this project was to identify techniques for improving the drainage of multi-lane highway pavements and to develop guidelines for implementing the most promising of these techniques. The drainage of highway pavement surfaces is important in the mitigation of splash and spray and hydroplaning. This study focused on improving surface drainage to reduce the tendency for hydroplaning. The main factor affecting the propensity for hydroplaning is the thickness of the water film on the pavement surface. Three general techniques were identified for reducing the water film thickness: controlling the pavement geometry, the use of textured surfaces to include porous asphalt surfaces and grooved surfaces, and the more effective use of drainage appurtenances. The prediction of the water film thickness is based on the use of the kinematic wave equation as a model to predict the depth of flow on pavement surfaces. Data supporting the model were obtained from the literature and from studies conducted to measure Manning’s n for a brushed concrete surface and for porous asphalt surfaces. Expressions for Manning’s n as a function of Reynold’s number were developed for Portland cement concrete, asphalt concrete, and porous asphalt surfaces. Full-scale skid testing was also conducted on grooved and brushed concrete surfaces and on porous asphalt surfaces; texture measurements were obtained for all of the tested surfaces (laboratory and field). The results have been integrated into an interactive computer program, PAVDRN. This interactive program allows the pavement design engineer to select values for the critical design parameters. The program then predicts the water film thickness along the line of maximum flow and determines the hydroplaning potential along the flow path. If the predicted hydroplaning speed is less than the design speed, the designer is prompted to choose from alternative designs that reduce the thickness of the water film.


This report provides background information for designers and users of braking slip measurement devices, with emphasis on topics related to the comparison and harmonization of friction measurement devices. It describes aspects of measuring braking slip friction on traveled surfaces, especially those found during weather changes on aerodrome movement areas during winter. In practice, all types of surfaces and conditions are encompassed, ranging from bare and dry to pavements covered with precipitation deposits, thus providing a year-around context. The mechanics of various combinations of the surface interaction mechanisms are discussed and a parallel case presentation of a force measuring and a torque measuring friction device highlights the difficulties of obtaining mechanical error-free measurements of braking slip friction in action. Also, the report presents models for the interaction between a braked tire and a surface, along with several approaches to harmonization of friction measuring devices and ways in which harmonized results could be used to predict aircraft braking-wheel performance. The report suggests normalized friction measurement devices and segmented runway condition maps to monitor friction at airports.


This paper presents a 5-year evaluation of nine test sections with varying textural characteristics. Nine test sections were constructed on I-70 near Denver, Colorado with varying textural characteristics. Texture depth, skid numbers at different speeds and their noise properties were measured and compared. Review of the acquired data revealed a definite relationship between speed, types of surface texture, and the magnitude of skid numbers. As speed increased, the skid numbers declined. This relationship was clearly more pronounced and consistent using the smooth tire. Longitudinal macrotexture and microtexture were the quietest surfaces. State standard transverse tining with 1-inch uniform spacing exhibited the highest noise level among all the test sections when measured with the microphone at the rear tire position. CDOT has adopted longitudinal tining as its preferred method of texturing.
concrete pavements since 1997. The results of this study indicated that longitudinal tining, in addition to possessing adequate frictional properties, provides lower noise than the CDOT’s standard transverse tining.


This report presents a 5-year evaluation and construction details of nine test sections with varying textural characteristics. Included in the report is an overview of the methodologies used to texture concrete pavement surfaces and a discussion of frictional attributes of various textures at different speeds and their impact on noise properties. Also included in the report are descriptions of texture-measuring devices and texture-installing equipment, a description of the state-of-the-art equipment used to acquire sound pressure levels, plus a thorough discussion of data acquisition/analysis. Frictional characteristics of the individual test sections were evaluated using the ASTM E 274 skid testing procedure. Ribbed-tire and smooth-tire friction tests were conducted to acquire skid numbers at three different speeds of 40, 50, and 65 mph (64, 80, and 105 km/h). To examine the noise properties of the test sections, noise measurements were acquired to acoustically assess the impact of various surface textures at three different locations: inside the test vehicle; 25 ft (7.6 m) from the center line [3 ft (0.9 m) away from the right shoulder); and near the right rear tire of the test vehicle, away from the exhaust pipe.


The third Action Plan identifies the main issues expected to influence road trauma levels in the foreseeable future, and sets out the priority areas for action in calendar years 2005 and 2006. The Action Plan was developed jointly by all Australian jurisdictions, with input from the National Road Safety Strategy Panel, which represents a broad range of organizations with a stake in road safety. It has been endorsed by Ministers of the Australian Transport Council (ATC). This new Action Plan deliberately builds on previous work, but also recognizes that changes in the Action Plans are needed to reflect recent developments and new information, and to anticipate actions that will influence road safety beyond 2010. An important aim of the Action Plan is to highlight the Safe System concept as an overarching framework for road safety intervention. The Safe System approach emphasizes the way different elements of the road transport system combine and interact with human behavior to produce an overall effect on total road trauma. The key components of the system are safer roads and road sides (infrastructure), safer speeds and safer vehicles.


This guide provides systematic guidelines to asset managers, maintenance engineers and supervisors on the characteristics of road surfacings to assist in the process of selection of appropriate road surfacings for particular conditions. Companion Austroads publications provide detailed guides to the design and application of the various surfacings types. The guide provides detailed advice on:

- surfacing performance characteristics, which may influence the choice of pavement, and surfacings type;
- desirable performance characteristics of road surfacings and measures used for assessing the level of surface required;
- surfacing types;
- the selection of surfacings for new pavements;
- identifying and correcting deficiencies in existing pavements surfacings;
- the selection of surfacings for retreatments.

Detailed methodology is provided for the selection of surfacings for new pavements and also for pavement maintenance purposes.


These Guidelines provide information for road authorities to develop and implement a local response (throughout this document referred to as a local strategy) to manage the skid resistance of surfaced roads (i.e. both bituminous and concrete) within their network and introduces sixteen (16) key elements that need to be considered in the
development of such a strategy. The Guidelines also provide information on the basic principles of skid resistance, including surface friction, surface texture and the impact of road condition.


The Maryland State Highway Administration (SHA) owns and maintains 15,000 lane miles of mainline road network of which 98% is Hot Mix Asphalt (HMA) surfaced. The pavement friction survey includes collecting information on other roadway and pavement condition features such as traffic, location, test speed, date of testing, etc. The friction data in SHA’s database is managed by the Pavement Management Division, which is charged with receiving pavement condition data from the Exploration Division and maintaining the data. The pavement friction surveys in Maryland are conducted using the locked wheel pavement friction tester attached to a truck. The test vehicle used by SHA in the friction surveys is usually calibrated to conduct surveys at 40 mph. However due to speed limit restrictions and road usage, the test crew is sometimes forced to take readings at speeds less than prescribed by the manufacturer. Twenty percent (20%) of the friction values in SHA’s database were taken at speeds less than 38 mph. Currently at SHA, there is no correction applied to the friction numbers recorded at low speeds. The data that was used for this analysis was obtained from roadways located in six of the twenty-three counties in Maryland. The results of the analysis show that there is an inverse relationship between speed and friction values.


The results of a study aimed at investigating the effects of temperature and surface texture on the friction force developed at the tire-pavement interface during skidding are presented. Ten field sites representing a variety of asphalt pavements in the State of Ohio were selected for the study. Five laboratory briquettes made from the same materials used in the construction of the pavements were prepared for each of the sites. Skid resistance measurements were performed on the briquettes using a portable British pendulum tester. The friction force was considered to consist of two parts, namely, the wet adhesion and the hysteresis components. The adhesion and hysteresis components were measured separately using water and liquid hand soap as lubricants. To simulate the changes due to wear and aging of pavements, several cycles of mechanical polishing were conducted and the available contact area after polishing was determined using a digital image processing technique. Tests were conducted at five different temperatures. The hysteresis component of friction decreased with increasing temperature regardless of surface texture state. The adhesion component was more sensitive to surface texture effects. Hysteresis was found to account for the larger part of the total friction force. Combined friction decreased with increasing temperature on a polished surface; hence it is recommended that skid numbers obtained at any arbitrary temperature be normalized with respect to a value at a reference temperature, for example, 293 K (68°F).


The effective use of measurements of skid resistance requires that the measurements are accurately located. Traditionally linear referencing has been used to locate the measurements. The development of accurate GPS systems has offered the opportunity for more accurate referencing and this approach has been used together with GIS systems to present the measurements. However, software used to analyse the measurements and manage the data to produce maintenance treatment options associated with asset management plans, relies on linear referencing. Changes to this software would require a major investment. This paper shows how the accuracy of GPS referencing can be transferred to linear referencing thus gaining the benefits of GPS while maintaining the use of existing software systems. The paper describes the application of the approach in New Zealand and reports from pilot trials, the improvements in accuracy that can be expected. The paper concludes by describing the benefits that will accrue by implementing the approach and describing briefly the lessons learned from the trials to date.


Can the Sideways force Coefficient Resistance Investigation Machine (SCRIM) output data be utilized as a project tool? The annual SCRIM exception report for the New Zealand State Highways indicates at a network level that
specific lengths of road may have a loss of microtexture and macrotexture and thus need further investigation leading to remedial works. The Auckland region has traffic volumes of up to 200,000 vpd, as well as some topographically constrained alignments, exposes surfacing aggregate to the highest wheel tractive forces nationally. Monitoring of average Equilibrium SCRIM Coefficient results over treatment lengths of lengths 500m to 2 Km has produced credible trend information, which has lead to sustainable accident reduction.

The paper will describe how this approach has lead to timely intervention, a process of back calculation to better determine the PSV formula environmental factor and confidence with specific aggregate micro texture performance.


The purpose of NYSDOT’s Safety Appurtenance Program (SAFETAP) is to facilitate the inclusion of safety improvements in the Department’s simple resurfacing projects. The process of the implementation of SAFETAP involved explanatory discussions and negotiations, as well as some compromise with diverse agency interests before the program gained formal agency approval. The result has been the institutionalization of a major Department-wide program, which by systematically incorporating highway safety into hundreds of simple resurfacing projects will go a long way toward ensuring the continuation of sizeable accident reductions (which occurred in our state during the previous thirty-five years) into the next century.


The state of New York owns and maintains an enormous inventory of roadside appurtenances, including guide rail, signs, delineators, and drainage structures. Those roadside features exist for the convenience and safety of the motoring public. Historically, maintenance of roadside appurtenances has depended to a large degree on inclusion in the department's pavement resurfacing programs, particularly the previous resurfacing and preservation and ongoing resurfacing, restoration, and rehabilitation programs. Those resurfacing programs have been largely supplanted by the department's highly successful preventive maintenance paving (PMP) program. In fact, the share of miles of pavement being resurfaced each year under the PMP program has been increasing steadily since 1990 (from 44 to 72% of total miles resurfaced). Since the goal of the PMP program is limited largely to maintaining pavements, roadside appurtenances were not receiving the attention they required. The New York State Department of Transportation Safety Appurtenance program (an FHWA road safety audit pilot program) ensures that roadside appurtenances receive the attention they need under the PMP program in order to protect a sizable roadside investment and to ensure the safety of road users. The Offices of Engineering and Operations jointly proposed the plan that would involve maintaining existing safety features and adding appropriate, easily implementable, and low-cost safety treatments at PMP project locations either during construction or, more likely, after construction as part of a distinct but "linked" effort. Work not included in the PMP project could be undertaken by maintenance forces or under requirements type contracts (separate signing or guide rail contracts). The guiding principles behind the plan are that it not interfere with accomplishment of the primary goal of the PMP resurfacing program (pavement maintenance), that it not result in a reduction in the number of lane miles treated with PMP resurfacing, and that it not significantly delay or otherwise complicate the processing of PMP resurfacing projects. A regional road safety audit team (composed of staff from design, traffic, and maintenance areas) now reviews proposed PMP project locations for existing accident problems, based on an identified accident history or potential accident problems such as obvious, hazardous roadway features that can be readily identified during a field review, and recommends cost-effective improvements to address existing and potential accident problems. The design of the program, how it gained executive management approval, and some early program accomplishments are discussed. The initiative has proven successful not only because of its clearly defined benefits for two agency goals (highway maintenance and safety) but also because of the systematic process by which it was introduced to agency managers with sometimes conflicting needs and agendas.


New York State Department of Transportation's (NYSDOT's) Skid Accident Reduction Program (SKARP) identifies sections of pavement experiencing unusually high proportions of wet road accidents, friction tests them,
and treats those sections which are experiencing both high wet road crashes and low friction numbers. The treatment generally involves a 1 and 1/2" resurfacing, or a 1/2" microsurfacing, using non-carbonate aggregates (costing $20,000 per lane mile). Forty (40) locations treated under the Program have been evaluated. Based on the size and consistency of the differences in crash experience and friction numbers during each year before and following resurfacing at identified high wet road crash sites, it is concluded that the Program selection and treatment strategies are appropriate and effective. Percentages of wet road crashes (compared with total crashes) have remained consistently high during years before treatment, and consistently low following treatment. Particularly noteworthy, is that the percentages remained high during the before period even during years when the identified high wet road crash sites did not appear on the annual high wet road crash listing (suggesting a minimal effect of regression to the mean at identified high crash sites experiencing low friction numbers). "Before and After" accident analyses have shown that each year more than 740 annually recurring accidents are being reduced as a consequence of treatments undertaken at 40 sites between 1995 and 1997 on Long Island alone. Five hundred and forty (540) of those crashes were wet road crashes. Some simple empirically based tests for regression to the mean were undertaken (in addition to the above). A one year before/after study was performed for 20 of the test locations, which did not appear on the wet road crash listing during the one year before period. Results from that evaluation, the general consistency of percentages of wet road crashes in the before period, and previous empirically based findings regarding the effect of regression to the mean at untreated high accident sites, suggest crash modification factors for the SKARP program as follows: total crashes should be expected to decline by 20%, wet road crashes should be expected to decline by 60%, and severe (Fatal and injury) wet road crashes should be expected to decline by 70%. All but one of the 40 sites treated in this study involve intersections. Improving pavement friction at intersections experiencing high wet road crashes and low friction numbers, presents a relatively low cost improvement which should be expected to produce large crash reductions - particularly as regards severe (fatal and injury) crashes.


In March 2000, the Government announced a new set of casualty reduction targets for the year 2010 for Great Britain. A key element in the preparation of the new target was to forecast the number of casualties in 2010, taking account of any factors that might influence this number substantially. This report provides an account of progress up to 2004 and describes the casualty trends and what they suggest for the likelihood of achieving each of the targets. It updates the original analyses with data from 1999-2004 to re-assess the conclusions that were drawn about future casualty trends, and summarizes of the other investigations that have been carried out. The key target is for the number of people killed or seriously injured (KSI), with no separate target for the number killed. The number of deaths had tended to rise between 1998 and 2003, but fell by 8% in 2004. The changes in 2004 are analyzed in detail to see whether they are likely to signify a change in previously observed trends.


The purpose of this study is to provide a comparison of longitudinal diamond-ground and transverse-tined pavement surface texturing for newly constructed portland cement concrete pavement (PCCP). The study area is located along a test section of I-190 in Buffalo, New York. The two PCCP surface treatment types under evaluation are compared based on safety, noise, construction cost, service life, rideability, handling, and maintenance requirements. The initial evaluation is documented, as is the analysis of follow-up noise and skid resistance measurements conducted approximately one year later. Analysis of the initial testing indicates that the relative skid resistance of the experimental longitudinal diamond-ground surface is as good or better than that of the transverse-tined surface. The results of the noise analysis indicate that the longitudinal diamond-ground surface is 2 to 5 dB quieter depending primarily on the traffic vehicle mix. Noise and skid resistance measurements conducted one year later showed little change. Although less construction time was required for the transverse-tined pavement compared with that for the diamond-ground pavement, the actual cost difference is not quantifiable. However, a higher initial cost for longitudinal diamond grinding would likely be partially offset by an extended service life.
The objective of this research project was to produce a synthesis of available information to support specific areas related to pavements for the safe, economical development of the Trans Texas Corridor (TTC). This synthesis is divided into several sections, each of which deals with a specific topic or topics. These specific areas include (1) pavement design for heavy vehicles, (2) pavement design for light vehicles, (3) skid resistance issues on high-speed corridors, (4) issues related to traffic characterization, (5) smart pavements for high-speed corridors, (6) pavement material response to dynamic loads and performance prediction, (7) safety issues related to splash and spray, and (8) ride quality for high-speed corridors. Regarding these stated issues, this synthesis recommends state-of-the-art technology to the Texas Department of Transportation (TxDOT) for use during development of the TTC. It provides recommendations for future research to fill gaps in knowledge and to take emerging technology to the stage where it can be implemented during the design and construction of the TTC pavements. This is the first synthesis study to address issues related to the TTC. A secondary objective of this project was to determine if additional synthesis studies in other areas of transportation related to the TTC should be conducted and, if so, how the process might be improved. This synthesis recommends that future syntheses should be more focused on specific, maybe critical issues; the researcher should be instructed to present only those findings that are really new, innovative, and potentially implementable. One element of the study should pursue non-transportation related technology that might be adapted to transportation issues.


Macrotexture refers to variations in the road surface in the range 0.5 mm to 50 mm. It is generally believed to affect braking through the two mechanisms of hysteresis and the prevention of a water film. A literature review concluded that crash risk is greater at sites with low macrotexture, but studies differ as to the macrotexture values at which risk begins to increase. Limited work to date suggests that the relationship cannot be explained simply in terms of traffic flow. A pilot study of the relationship between macrotexture and crashes was undertaken by locating each crash on the macrotexture measurement record. The relationship was compared on the Great Eastern Highway, Western Australia, Princes Highway West, Victoria, and the Duke’s Highway, South Australia. In nearly all cases, there was an association between macrotexture and crashes, the exceptions being rural sites on the Princes Highway West, where the relationship was marginally significant, and urban sections on the Dukes Highway, where there was no association (but note there was very little urban road on this route). There was a significant association between low macrotexture and crashes at all rural intersection sites, but no association between low macrotexture and wet road crashes, nor between macrotexture and young driver crashes, and insufficient data to examine the relationship for heavy vehicles. The data were also examined for associations between low macrotexture and wet road crashes, and insufficient data to do formal testing for heavy vehicle involvement, but the pattern of the data suggests that low macrotexture was underrepresented at the sites of crashes involving heavy vehicles. The results agree with previous studies regarding the increase in risk with low macrotexture. The prospects for a surface management process based on macrotexture are therefore good, but further work is required before this is possible.


This paper reports an analysis of the relationship between road surface characteristics and crashes on undivided two-way roads in the state of Victoria, Australia. Surface condition data from multi-laser profilometer surveys was linked to geometry, traffic and crash data using GIS and the resulting tables analyzed to investigate the relationships. The three road surface characteristics were either uncorrelated or showed small enough correlations to disregard possible interactions among the variables. Crash rate was higher for road sections with low macrotexture; a power relationship provided a good fit to the data. Crash rate was also higher for roads where roughness was extreme, with a polynomial relationship providing a good fit to the data. No clear relationship emerged between rutting and crash rate. An economic analysis suggests that resurfacing sites with macrotexture of 1 mm SPTD or less would produce crash savings which would provide a very good return on the investment.
The frictional properties of pavement surfaces play an important role in highway safety. Pavement surfaces must ensure an adequate level of friction at the tire pavement interface to provide safe operation of vehicles. The Maryland State Highway Administration (MDSHA) routinely measures friction on State highways to assist with decision making associated with road maintenance management and to monitor network health against road condition targets detailed in the system preservation report published annually. The MDSHA uses the Friction Tester to monitor the micro-texture of the pavement aggregate during the service life of the pavement surface. Micro-texture is a measure of the degree of polishing of a road aggregate and is the main factor in determining the peak level of dry and wet friction provided by a pavement surface. Initial analysis of past friction information indicates a relationship between geometry, AADT, polish stone value and Friction Number. The MDSHA is attempting to better understand surface frictional requirements at approach to pedestrian crossing, traffic lights, etc during wet weather and to establish minimum friction levels for different types of roadways based on accident data. This paper describes the MDSHA process in developing a design policy to improve pavement surface friction.


Identification of hot spots, also known as the sites with promise, black-spots, accident prone locations, or priority investigation locations, is an important and routine activity for improving the overall safety of roadway networks. There is an extensive literature focused on methods for the identification of "hotspots" (HS1D). A subset of this considerable literature has been dedicated to conducting performance assessments of various HS1D methods. A central issue in comparing HS1D methods is the development and selection of quantitative and qualitative performance measures or criteria. It is the contention of this paper that currently employed HS1D assessment criteria—namely false positives and false negatives—are necessary but not sufficient, and additional criteria are needed to exploit the ordinal nature of site ranking data.

With the intent to equip road safety professionals and researchers with more useful tools to compare the performances of various HS1D methods and to ‘raise the bar’ with regard to HS1D assessments, this paper proposes four quantitative HS1D evaluation tests that are to the authors’ knowledge new and unique. These tests evaluate different aspects of HS1D method performance, including reliability of results, ranking consistency, and false identification consistency and reliability. It is intended that road safety professionals can apply these different evaluation tests in addition to existing tests to compare the performances of various HS1D methods and then select the most appropriate HS1D method to screen the road network to identify sites that require further analysis.

We demonstrate the five new criteria using three years of Arizona road section accident data and four commonly applied HS1D methods (Accident Frequency Ranking, Accident Rate Ranking, Accident Reduction Potential, and Empirical Bayes'-EB). The EB HS1D method reveals itself as the superior method in most of the five evaluation tests. In contrast, identifying hot spots using Accident Rate Rankings performs the poorest among the five tests. The Accident Frequency and Accident Reduction Potential methods perform similarly, with slight differences explained. We believe the four new evaluation tests offer insight into HS1D performance heretofore unavailable to analysts and researchers.


The present state-of-the-art 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 resulting data 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, the Florida Department of Transportation (FDOT) initiated the present field study to assess the level of precision of its own locked-wheel testers for field measurements. Friction measurements were acquired using four friction locked-wheel testers concurrently on a number of asphalt section sites. These test sections were randomly selected to include both open and dense graded surface mixtures. The collected friction data were first analyzed to determine the friction characteristics at each test
location, in terms of a friction number at 40 mph using a standard ribbed test tire (FN40R). The results were then used as a basis for an evaluation of the repeatability and reproducibility of the friction units. In addition, the effects of pavement surface texture on friction measurements were assessed. This report presents a description of the testing program, the data collection effort, and the subsequent analyses and findings.


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Clonch, D. 2006. “Ohio Department of Transportation Road Grip Tester Project.” Proceedings, GIS for Transportation Symposium. Columbus, OH.

The Ohio Department of Transportation (ODOT) has initiated a process to create a system that detects, records, reports, and disseminates informational data regarding low grip areas on roadway surfaces. A Road Grip Tester (RGT) system measures road surface friction by utilizing an existing hydraulic system to deploy and retract a wheel that is located in the front of the drive axle underneath the vehicle or using a wheel mounted to a tow hitch at the rear of the vehicle. In normal, dry conditions, a graphical display in the cab of the vehicle will show green lights (along with a corresponding numerical value). As the surface loses friction (e.g., wet or snowy conditions), more lights are displayed and the color changes from green to yellow; the numerical value changes (decreases) as well. As the road becomes snow covered, even more lights are displayed and the color changes to red. The numerical value decreases even further. The intent of the system is to serve as an early alert and advance notification system for road conditions before, during, and after a winter event. The RGT provides the ability to detect deteriorated pavement surface conditions associated with winter weather that are otherwise not visibly evident. The system provides information allowing ODOT maintenance forces to detect the presence of black ice on pavement surfaces and prompt immediate treatment where needed. It also provides real-time information to detect the rapidly changing conditions associated with winter maintenance activities.

Connecticut Department of Transportation (ConnDOT). “Enhancements to ConnDOT's Pavement Friction Testing Program.” (Research in Progress).

The objectives of the proposed research are to: (1) evaluate the effect of roadway geometry on friction measurements; (2) update friction number speed correction factors based upon pavement mix designs in use in Connecticut today with an upgraded friction tester (hardware and software); (3) research relationships between texture and friction; (4) evaluate the potential use of the International Friction Index in Connecticut; and, (5) implement the appropriate latest technology and procedures for pavement friction data request, collection and processing.


The skid resistance of a road is not constant and changes throughout the year, being at its highest in the late winter and at its lowest towards the end of the summer. Throughout the year the level will change depending on periods of rainfall and dry conditions. Highway Authorities must ensure that measurements of skid resistance are corrected to remove these seasonal effects so that maintenance treatments can be applied in priority regardless of when the survey work is undertaken. This paper describes the processes and procedure that Transit New Zealand have

Three locked-wheel skid trailers, International Cybernetics Corporation (ICC) Model MOR 5041 and K.J. Law Models M 1270 and M 1290, were tested at three speeds on 14 test sections located in Greenville, North Carolina. The test sections included a heavy-duty surface course, polymer-modified heavy-duty surface course, rubber-modified heavy-duty surface course, heavy-duty surface course with carbon black, stone mastic with fibers, polymer-modified stone mastic, and large-stone surface course. Multivariate regression analysis of friction number versus speed for the three test vehicles was performed. Despite having been load cell calibrated 1 day before testing, the ICC MOR 5041 results were statistically different from those of the other skid trailers on all but one test section. The two K.J. Law skid trailers were statistically different from each other, either on intercept or slope, on more than half of the test sections. Each individual skid trailer provided repeatable results with a standard deviation of about 2 when testing was done at 64 km/h, with a higher standard deviation for testing at lower speed. The frictional resistance of the test sections was compared by ranking friction number at 64 km/h and rate of decline of friction number with speed. The best frictional performance was provided by the heavy-duty surface course and the large-stone surface course, and stone mastic with fibers and stone mastic with polymer were ranked poorest. None of the test sections had an average friction number less than 40, even when tested at 80 km/h.


The Washington State Department of Transportation (WSDOT) determines wet-pavement surface friction characteristics by conducting skid-tests in accordance with applicable AASHTO and ASTM standards. The results of the skid-tests are used in conjunction with other criteria to assist in selecting pavements for resurfacing (the primary criteria is wet-pavement accident rates). The paper examines literature from the United States and abroad on friction number guidelines for highways. On the basis of an analysis of the literature, a revised friction number guideline was developed. The new guideline is similar to those developed by other highway departments and is based on research conducted over the last 25 years.


Safety data provide the key to making sound decisions on the design and operation of roadways, but deficiencies in many States’ safety databases do not allow for good decision making. The Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the National Cooperative Highway Research Program (NCHRP) sponsored a scanning study of how agencies in the Netherlands, Germany, and Australia develop and use traffic safety information systems. That scan produced a report that included recommendations for advancing safety themes in the areas of strategy, efficiency, and utility. This current report is the result of a follow-on effort to build on the scan team’s final report and draft implementation plan by reviewing in detail the strategies suggested, providing action-related details to some of the critical strategies, and adding new strategies to help reach the team’s goals. Although strategies related to both crash data and other safety data such as roadway inventory and traffic volumes are included in this paper, more emphasis is placed on the latter because more effort has traditionally been spent on improving crash data. The five critical strategies detailed here include: (1) increase support for both safety programs and safety information systems from top-level administrators in State and local transportation agencies; (2) improve safety data by defining good inventory data and institutionalizing continual improvement toward established performance measures; (3) improve safety data by making it easier to collect, store, and use; (4) improve safety data by increasing the use of critical safety analysis tools, which themselves require good data; and (5) improve and protect safety data by storage and linkage with critical non-safety data. Discussion and action items are presented for each strategy, along with recommendations concerning which government agency potentially could be responsible for implementing the recommendation and a priority ranking of the proposed recommendations based on input from a review panel.

This synthesis will be of interest to pavement engineers, safety officers, and others interested in wet-pavement safety programs. Information is provided on the programs used by a number of agencies in gathering data and correcting areas of potential wet-weather accidents. Wet-pavement accidents continue to be of concern to highway agencies. This report of the Transportation Research Board summarizes agencies' programs in areas such as accident reporting, vehicle testing, friction testing, corrective actions for problem areas, and tort liability and gives some general guidelines for the content of a wet-pavement safety program.


The friction testing of runways in Australia is not common practice as the Australian regulatory body, CASA, only requirement regarding surface characteristics relates to surface texture. The recent modifications to the Manual of Standards (MOS) require some airports to implement friction testing from 2006. Friction testers throughout the world acknowledge that the machines have poor repeatability and calibration problems, which make their value as a tool of regulatory compliance questionable. However, it is the value as a maintenance tool for airport managers to utilize to determine frequency of rubber removal, which could potentially be of most benefit. The purpose of this project was to develop a methodology for the analysis of runway friction testing data so that airport engineers can have confidence in the results that the devices produce. In addition, the project took on a larger focus to assist other Australian airports with friction management in preparation for the new regulations in 2006.


The paper presents the results of a first attempt to combine detailed information on road geometry (horizontal curvature, gradient and cross-fall), road surface condition (roughness, rut depth, texture depth and skid resistance), carriageway characteristics (region, urban/rural environment, and traffic flow) and crashes. Such a study was only made possible because of annual surveys of the entire 22,000 lane-km of New Zealand’s State Highway network made with SCRIM since 1997, which involves simultaneous measurement of road condition and road geometry. Four subsets of road crashes were investigated: all reported injury and fatal crashes; selected injury and fatal crashes covering loss of control events; reported injury and fatal crashes occurring in wet conditions; and selected injury and fatal crashes occurring in wet conditions. One and two-way tables and Poisson regression modeling were employed to identify critical variables and the form of their relationship with crash risk. Particular emphasis was placed on quantifying the effect of skid resistance and texture depth on crash risk.


Highway engineers rely upon conventional skid resistance measurements in order to evaluate the level of a road's skid resistance. In France, such measurements are carried out using smooth tires under conditions of total sliding. The skid resistance assimilated by users may differ significantly due to the distinct nature of the tires as well as to the generalized use of antilock brake systems. Road tests conducted have shown that certain techniques yield different results whether focusing on this conventional skid resistance vs. the "treaded tire" skid resistance with variable sliding rates. The values of low-speed friction and average texture depth, both of which serve to explain quite well the conventional longitudinal skid resistance measurements, prove insufficient when it comes to predicting the level of skid resistance mobilized with antilock brake systems. Other indices in the area of macrotexture, and more specifically the density and angularity of indenters, play a vital role in the frictional force generation process at the tire/pavement interface.


A summary of research work conducted at LCPC over the past ten years on pavement surface microtexture will be presented. Progress has been made over the years in both measuring and characterizing such microtexture. The most recent microtexture descriptors have been integrated into a contact model for the purpose of computing a low-speed...
friction coefficient. The contribution of the relationship between microtexture and low-speed friction in predicting skid resistance will then be approached. The variation in skid resistance with respect to speed will be displayed using a so-called "Stribeck" curve. The descriptive model of this curve clearly reveals the microtexture contribution. A validation procedure has been performed on a set of surfacing materials that spans use on roads exposed to traffic loads as well as test tracks. In conclusion, an assessment of the research to date on microtexture will be drawn and the avenues of subsequent research identified.

The Highways Agency has established 39 benchmark sites for long term study. The principal use of the benchmark sites is to provide a cost effective source of historical measurements of skid resistance across the network from which trends can be established to provide early warning of changes that may be required in policy. These sites have been surveyed by SCRIM three times a year, once in each of the three SCRIM periods (early mid and late) between May and September from 2002 up until 2005.

As expected the highest skid resistance for each site was given by the early runs in May/June, however, it was found that the skid resistance for the final run in the late period August/September had not recovered back to those of the early run and was often as low as or lower than the mid reading. This indicates that the August/September period is dryer than the May/June period whereas historically they have been considered similar. Therefore, in 2006, an additional survey run was included in late October and this was continued in 2007. It was found that the skid resistance for the addition very late run had recovered back to the values shown by the early survey.

It has also been found that the skid resistance for the 2006 and 2007 results are significantly lower than those from years 2002 to 2005; this suggests that the summer periods for 2006 and 2007 are dryer than they have been in the previous 4 years. These results may be indicating the effects of climate change on the skid resistance on the English road network. Although sites were selected that were not likely to be resurfaced for at least the first few years inevitably surface treatments have taken place and this has shown that the time for sites to reach a plateau skid resistance after being resurfaced is between 6 weeks and 6 months. Another interesting finding is that not all sites are affected by seasonal variation to the same extent; some sites are affected to a much greater degree than others are.

The Wehner Schulze (W/S) procedure, similarly to the Polished Stone Value (PSV) test, is designed to simulate accelerated wear on road surfacing materials and test the friction provided by the specimen before and after that wear. An important difference between the PSV test and the W/S procedure, however, is that the latter uses large, flat specimens that can be obtained from actual road surfaces, made in the laboratory from mixed materials or made in the laboratory as plates using aggregate alone. The test is carried out using a purpose-designed machine that is now available commercially. TRL Ltd operates one such machine on behalf of the Highways Agency who procured the device in 2005. The ability of the machine to test the skid resistance offered by a sample of the whole mixture used in a surface course rather than just its aggregate components is a major advantage. In some cases there is opinion that the performance of aggregate in roads is not sufficiently characterized by the PSV test, and this has led to the requirement for in situ trials to be carried out before an aggregate can be used extensively in a road network. TRL Ltd was commissioned by Tarmac Group to carry out initial investigations comparing aggregates with similar PSV, made into asphalt specimens, in the W/S machine. The work was carried out on an experimental basis, with the goal as much to expand understanding of the machine’s abilities when used with UK materials, as to define the performance of the range of asphalt samples used. Nevertheless, the results are interesting and similar experiments may eventually prove to be useful in determining expected in situ performance of new asphalt mixtures thus informing maintenance requirements on existing roads. This paper will describe the basic operation and principles of the W/S machine, and present some of the results and conclusions from the Tarmac experiment.

The French national road-building policy as regards skid resistance will be presented herein. The various circulars previously published and the primary rationale behind their successive replacement will also be recalled. The last circular issued, which dates from 2002, will be analyzed in detail; its adoption resulted from the research completed by a subgroup assembled as part of the National Surface Characteristics Working Group, which was created in 1991 by the French Highway Administration. This circular serves to establish specifications in terms of average texture depth with respect to the authorized speed for each type of pavement, pavement geometry and site layout. The general principles provided from this regulatory document are intended to successfully adapt, by means of choosing the appropriate wearing course, the skid resistance potential "supplied" with a demand based on the trio of variables: speed - site layout - pavement type.


This paper examines the effect of wavelength range on estimating macrotexture indicators from a three-dimensional surface model. Macrotecture indicators computed from the two-dimensional profiles are compared to power spectrum energy computed from the three-dimensional surface heights in the frequency domain. Pavement samples with different types of surface conditions are evaluated using a non-contact photometric stereo system. For each pavement sample, surface heights are recovered in three-dimensions. Surface profiles are also measured manually by using a dial gauge. The surface heights in frequency domain are divided into ten wavelength ranges and power spectrum energy is computed for each wavelength range. The correlation between the two-dimensional indicators (mean profile depth and root mean square roughness) and the power spectrum energy is examined. Results show that the texture indicators computed from the three-dimensional recovered surface could represent the two-dimensional indicators. Moreover, the power spectrum energy provides a good estimation of the two-dimensional indicators when it is computed from wavelength ranges of 13 times the range of two-dimensional indicators.


This report was prepared by the OECD/ECMT Working Group on Achieving Ambitious Road Safety Targets. At its first meeting held on 9-10 March 2005, the Working Group discussed the importance of cross-country comparisons and targeted performance assessment in identifying the priority areas for implementation of effective measures and areas for possible improvements.

It was decided to present and publish an overview of the safety evolution of individual countries, based on information collected through a survey. The survey was sent to all 50 OECD/ECMT countries to collect information on road safety trends, recent road safety measures implemented; key road safety issues, measures planned to address these issues, targets set, and current results towards these targets. The responses to the survey are completed by other relevant data from other sources (e.g. IRTAD, ECMT statistics, and recent reports of the JTRC). This report includes a summary of road safety performance in OECD/ECMT countries. It presents an overview of road safety targets in OECD/ECMT countries, highlights the main road safety problems identified by member countries and provides some country comparisons.


This paper compares five techniques for identifying hazardous road locations. The five techniques embody different degrees of control for randomness in accident counts. They are tested by means of data for Norwegian roads. As a basis for the comparison, a hazardous road location is defined as any road location that has a higher expected number of accidents than similar locations due to local risk factors present at the location. The following five techniques for identifying hazardous road locations were compared:

1. Hazardous road locations are identified in terms of the recorded number of accidents during a specific period.
2. Hazardous road locations are identified in terms the observed accident rate (accidents per million vehicle kilometers) during a specific period.
3. Hazardous road locations are identified in terms of the combination of a critical count of accidents and an accident rate above normal during a specific period.
4. Hazardous road locations are identified in terms of the empirical Bayes estimate of the expected number of accidents at each location.
5. Hazardous road locations are identified in terms of the size of the contribution of presumably local risk factors to the empirical Bayes estimate of the expected number of accidents at each location.

Each of the criteria were applied to the upper 1%, upper 2.5% and upper 5% of the distribution of sites according to the criterion (accident count, accident rate, etc). The diagnostic performance of the five techniques was assessed in terms of epidemiological criteria (sensitivity and specificity). The empirical Bayes technique was found to perform best according to the epidemiological criteria. It is concluded that hazardous road locations are most reliably identified by applying the empirical Bayes technique.


Until the mid-1960s, the United States was the world leader in traffic safety, but by 2002, the nation's ranking had dropped from 1st to 16th place in terms of deaths per registered vehicle. The author of this article, who is both a researcher and safety expert, argues that, if the focus of U.S. traffic safety policy would shift from vehicle factors to such road-user behaviors as speed, alcohol consumption, traffic law violation, and seat belt wearing, the number of fatalities could be reduced by half.


The ultimate objective of research in this problem area, dealing with the frictional coupling of the vehicle tire and the pavement surface, were to (1) determine pavement skid resistance requirements, (2) improve the reliability of skid resistance measurements, and (3) improve the ability to build and maintain highly skid resistant pavements. The specific objective of this project was the development of procedures for determining pavement skid resistance requirements for various classes of highways, taking into consideration such factors as driver and vehicle characteristics, traffic, weather, and highway geometry.


The determination of skid resistance requirements for any given set of roadway and traffic conditions is reported. The study focuses on wet pavement skidding accidents at intersections and curves. The feasibility of implementing these procedures was demonstrated in the field. A simplified version of the procedures was also developed. The three steps involved in the procedure for determination of skid resistance requirements are outlined. The system developed for measurement of longitudinal acceleration at intersections is based on the use of a series of event detectors to determine the time-position signature of a vehicle over some known distance, from which acceleration values can be computed. Data was collected for an average of 350 vehicles at each of 12 intersections. Controlled skid studies were conducted to determine the relationship between longitudinal acceleration and skid resistance requirements. A simplified intersection demand model (idm) for estimating skid resistance is desired. This is based on the apparent normality of distribution of observed deceleration values at the various distance intervals from the stop line of the 12 sites studied. The findings indicate a strong relationship between pavement skid resistance and locked wheel braking deceleration. Accelerations and speeds of vehicles braking at intersection are normally distributed and exhibit stable standard deviations. A relationship exists between average approach speed and skid resistance requirements. Considerably more extensive field evaluations are necessary to verify the applicability of the procedures.

This paper reports the results of reviewing the current information on pavement texture and its relationship to the skid resistance-speed gradient and to the available friction at selected speeds. The report discusses different methods of modeling the skid resistance and predicting it based on friction and texture measurements.


The purpose of this document is to provide guidance for State and local highway agencies in conducting skid accident reduction programs. This program shall provide that "there are standards for pavement design and construction with specific provisions for high skid resistance qualities." The HSPS No. 12 requires that each State have a "program for resurfacing or other surface treatment with emphasis on correction of locations or sections of streets and highways with low skid resistance and high or potentially high accident rates susceptible to reduction by providing improved surfaces." In discharging the responsibilities of FHWA, the Division Administrator should determine the acceptability of specification requirements and construction practices for placing, consolidating, and finishing both asphalt concrete and portland cement concrete pavements. Such determinations will rely on the highway agency to research, evaluate, and document the performance of the various aggregates, mix designs, and construction practices used.


A Road Safety Audit (RSA) is a formal safety performance examination of an existing or future road or intersection by an independent audit team. It qualitatively estimates and reports on potential road safety issues and identifies opportunities for improvements in safety for all road users. RSAs represent an additional tool within the suite of tools that currently make up a multidisciplinary safety management system aimed at improving safety.

The primary purpose of this guideline is to provide a foundation for public agencies to draw upon when developing their own RSA policies and procedures and when conducting RSAs within their jurisdiction. The availability of a consistent guideline is anticipated to lead to a better understanding of the core concepts of RSAs and to promote their use. These guidelines were developed by building upon experiences gained in the United States and in other countries. They are meant to present basic RSA principles, to encourage public agencies to implement RSAs, and to embrace them as part of their everyday practice. When used they should be tailored to suit local conditions.

The guidelines are divided into three main sections. Part A provides general information on RSA, information how to implement an RSA program and an overview of the RSA process. Part B describes the stages of an RSA, and different types of audits, including preliminary design, detailed design, construction, pre-opening, and RSA of existing roads. Part C describes RSA tools, namely prompt lists, and when and how to use them. Following the body of the guidelines, appendices that discuss approaches to road safety and the evolution of RSA are provided. Several case studies are also provided and a bibliography is included.


A State Department of Transportation (DOT) developed Strategic Highway Safety Plan (SHSP) is a new Federal requirement of SAFETEA-LU, 23 USC 148, and is a major part of the core Highway Safety Improvement Program (HSIP). This preview document has two purposes:

– To promote best practices and serve as interim guidance to State DOTs and their safety partners for the development and implementation of the State SHSP.
– To assist State DOTs in creating an SHSP that meets the requirements of SAFETEA-LU with the ultimate goal of reducing the number of highway fatalities and serious injuries on all public roads.

The purpose of this interim guidance in the format of this “Preview Document” is to provide the best available information in a timely manner. The US DOT is still analyzing and interpreting legislation and crafting additional guidance material to further enhance this guidance, particularly the sections on Implementing and Evaluating...
SHSPs. In addition, FHWA is developing guidance on the HSIP reporting requirements of Section 1401 of SAFETEA-LU.


This Technical Advisory (1) issues information on state-of-the-practice for providing surface texture/friction on pavements and (2) issues guidance for selecting techniques that will provide adequate wet pavement friction and low-tire/surface noise characteristics. Specifically, the advisory provides answers to the following questions:

– What are the surface texture components that influence wet-weather friction?
– What is the background on pavement surface texture/friction?
– How is tire/pavement noise impacted by surface texture?
– What is the recommended level of surface texture on high-speed (50 miles per hour or greater) facilities?
– What techniques will provide surface texture for concrete and asphalt pavements?
– How is adequate texture provided on concrete pavements over the performance life of the pavement?
– What techniques will restore desired surface texture to in-service pavement surfaces?
– What factors should be considered when selecting pavement surface techniques or thresholds?
– What factors should be considered when evaluating new or innovative texturing methods for concrete pavement?


The objective of this project was not to develop a Guide for Pavement Friction, that would identify technologies, processes, and practices suited for designing, constructing, monitoring and maintaining pavements with good frictional characteristics. The objective of this project was to compile the current methods (procedures and acceptability criteria) and related regulations that are currently implemented and used by state and local jurisdictions to not only characterize pavement friction but also to qualify pavement condition.


Since 1980, Australia has gone from nearly 4.5 to 1.5 deaths per 10,000 registered motor vehicles. This compares to a change of 3.5 to 2.3 deaths per 10,000 registered motor vehicles in the United States over the same time period. In terms of traffic deaths as a function of population, Australia went from 22.5 deaths per 100,000 population in 1980 to fewer than 9 deaths per 100,000 population in 2003. From nearly identical rates in 1980, the Australian rate has fallen to a point where it is now a little more than half the U.S. rate. This report, which was undertaken through Austroads by Professor Ian Johnston, director of the Monash University Accident Research Centre, reviews Australia’s accomplishments in highway safety. It not only discusses the performance measures established, but also goes beyond the public data. It draws from interviews with politicians, senior agency staff, and others with firsthand knowledge of how the traffic safety strategies were put together and, above all, how they were implemented, often amid public controversy but with majority community support.


The Ohio Enhanced Crash Location Identification System (OECLIS) is a flexible crash analysis software system for identifying high hazard locations combining analysis factors such as crash frequency, rate, severity, the change in the crashes occurring at a location over time, etc. allowing for a comprehensive methodology to determine hazardous locations. OECLIS also allows the user to specify minimum crash thresholds, weighting factors, and other input criteria. Three years of crash data are used in conjunction with current signal, volume, and road inventory data files associating each location with its specific operating characteristics. Intersection and intersection-related crashes are examined to ensure each crash is identified with the correct priority roadway, cross-road name and log point. OECLIS first reduces the number of locations by comparing the number of crashes occurring at both intersection and section locations with pre-defined threshold values for frequency, creating pre-candidate locations. The intersection threshold is currently specified at 14 and the section threshold is currently specified at 20 crashes. OECLIS calculates the following values for each pre-candidate location:
– Crash frequency – The number of crashes occurring at a location - (intersection).
– Crash density – The number of crashes per mile occurring along a section of roadway.
– Crash rate – The number of crashes occurring per million vehicle miles of traveled for a location.
– Delta-change – The change in the number of crashes over time using the slope of the regression line to determine whether crashes are increasing or decreasing for a location over time.
– Equivalent property damage only (EPDO) – The cost to society of a fatal crash, injury crash, and PDO crash normalized to a base of 1.0 for a PDO crash. The number of crashes by severity are multiplied by their respective values and then summed to determine a location's EPDO value.
– Equivalent property damage only rate (EPDO rate) – Uses the standard rate equation with a base of 1 million and substitutes the EPDO value for the number of crashes in the equation.
– Relative severity index (RSI) – The Relative Severity Index (RSI) represents the relative cost to society of a specific type of crash (head on, rear end, angle accident, etc.). The RSI for a location is the sum of the relative costs per crash divided by the total number of crashes for a location.

At least one of these calculated values must meet or exceed the threshold applicable for its matching criteria in order to remain as a candidate location. OECLIS then determines each location's rank with respect to each categorical value. OECLIS uses the hazard index method to determine overall ranking. A high hazard location list is developed for freeway and non–freeway locations separately. OECLIS calculates a priority index value for each location. ODOT specifies the weight given to the six categories to be included as factors for the final priority index calculations. The values for each location and method selected are multiplied by their corresponding weight value. Those products are then summed, giving the priority index value for that location. The resulting priority index values of all locations are then sorted to determine the priority hazard index rank for all location candidates.

From the 250 location high crash listing, the intersections and sections were then ranked based on fatalities and incapacitating injuries (freeways and non–freeway locations were ranked separately). An equation was developed for the combination of the fatalities and incapacitating injuries = \(2^*\text{(of fatalities)} + \text{(of incapacitating injuries)}\). Since Ohio's Strategic Highway Safety Plan has a goal of reaching 1.0 fatality per 100 million vehicle miles of travel, the fatalities were given a weighting of two times that of an incapacitating injuries. From this ranked list (>) the top 5% most severe safety needs were reported.


Take the proactive, cost-saving approach to improving roadway safety by implementing road safety audits (RSA). An RSA is the formal safety performance examination of an existing or future road or intersection by an independent multidisciplinary team. RSAs can be used in any phase of project development, from planning to construction, and on initiatives ranging from minor maintenance activities to mega projects. The Federal Highway Administration (FHWA) recently launched a new RSA Implementation Team that will be working with State and local transportation departments, tribal governments, and Federal land management agencies to provide guidance and assistance in implementing RSAs.

Under the 2005 Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), States are required to report at least 5 percent of the locations on their public roads that are exhibiting the most severe safety needs. This report must also include remedies, costs, and impediments to implementing improvements at each of these locations.


The lack of quality data that relates tire-pavement noise to the texture of concrete pavements has hindered the pavement community in both understanding the phenomena and finding ways to minimize its impact. The National Concrete Pavement Technology Center (USA), the US Department of Transportation Federal Highway Administration, and the American Concrete Pavement Association have formed a coalition to address this problem. Work to date includes the simultaneous measure of noise, profile (unevenness), friction, and texture from active roadways across the U.S. The intent is to first link tire-pavement noise to texture to friction, then attempt to measure the rate of change of these properties over time.
The data collection process has been categorized hierarchically. At the top are new construction sites employing conventional texture variations (e.g., tining, burlap drag) termed Type 1 New Construction. There are also sites including diamond grinding variations (Type 1 Grinding). For each of the Type 1 sites, full control is maintained over the types of textures, including their construction techniques. Extensive information is collected on the design, materials, construction, and climate during placement or grinding. A second level of experiments termed Type 2 includes existing projects with various types of surface texture, tested comprehensively for all surface characteristics over time. Finally, a third type of experiment includes an inventory of numerous sites, measured with noise and texture only (Type 3).

The fieldwork of this effort is well underway, with monitoring expected to continue for at least five years on an annual basis. The findings to date have been very significant, and have the potential to alter how concrete pavement surfaces are specified in the future.


Highway noise is one of the most pressing of the surface characteristics issues facing the concrete paving industry. This is particularly true in urban areas, where not only is there a higher population density near major thoroughfares, but also a greater volume of commuter traffic.

In 2004 and 2005, the Federal Highway Administration, Iowa State University, and the American Concrete Pavement Association initiated a five-year, multi-million dollar Portland Cement concrete Surface Characteristics Program. This program is administered through the National Concrete Pavement Technology Center located at Iowa State University. The purpose of the program is to determine the interrelationship among noise, friction, smoothness, and texture properties of concrete pavements.

This report addresses work conducted under Part 2 of the program. In Part 2, data were collected on 1,012 test sections totaling 240,000 ft., representing 395 unique pavement textures. This is the most comprehensive inventory of concrete pavement surface textures ever compiled. The inventory includes transverse and longitudinal tining, diamond grinding, various drag textures, grooving, exposed aggregate, shot peening, cold milling, and some asphalt pavements and surface treatments.

A preliminary analysis of the data has revealed a number of important findings. For example, relationships between texture and noise are beginning to emerge. These are not based on nominal texture dimensions, however, since a second finding is that nominal dimensions are rarely observed to be found in place. Friction and noise are also found to have no relationship, demonstrating that quieter concrete pavements can be achieved without compromising this important characteristic.


Skid resistance of a pavement surface is important for safety. Therefore the surface of a concrete pavement must have a roughness suitable for a high skid resistance but also for a low noise emission. These surface properties must be as durable as possible. In Germany there are various possible ways for producing surface textures in fresh and hardened concrete surfaces with high skid resistance. For noise-sensitive areas good results can be achieved by dragging a burlap or an artificial turf over the fresh concrete in the longitudinal direction. Also, good and durable skid resistance and low noise emission can be achieved on an exposed concrete surface. Surface grinding a hardened concrete can provide high skid resistance. The practical experiences in Germany for producing a concrete pavement surface with high skid resistance are described in the paper.


Variation in skid resistance and surface macrotexture measurements due to testing conditions such as tire, test vehicle speed, pavement grade, and hot-mix asphalt (HMA) design characteristics were analyzed in detail for different HMA surface mixtures at the Virginia Smart Road. The seven HMA wearing surface mixtures studied
include five different SuperPave™ mixtures, a stone mastic asphalt (SMA), and an open-graded friction course (OGFC). Mixture properties were measured from samples taken from each test section and compacted in the laboratory. The evaluation of the surface characteristics was based on measurements conducted using a locked-wheel trailer with the ASTM-specified ribbed and smooth tires. Macrotexture measurements were conducted using a laser profile measurement device. Statistical tests indicate that, for the mixes studied, the roadway slope has insignificant effect on skid number measurements. Friction measurements are dependent on the tire used, surface texture, age in service, and temperature of the surface. The dependence of skid numbers on the measurement speed also varies with the type of tire used and surface conditions during testing. The relationship between SN and speed can be appropriately modeled using both exponential (Penn State model) and linear models. Regression analysis was performed on specific mixture properties, including voids in the mineral aggregate, total voids in the mixture, percentage passing the number 200 sieve, and binder type and content. The analysis indicated that there is a significant influence of these parameters on the ribbed tire skid resistance measurements and laser profile mean texture depth. These properties, however, were not sufficient to develop accurate models as to their effect on the smooth tire skid resistance measurements.


This paper discusses an extensive investigation conducted to evaluate the texture and skid resistance properties of seven wearing surfaces used at the Virginia Smart Road. Variation in skid resistance and surface macrotexture measurements due to HMA design characteristics and testing conditions (tire, test vehicle speed, and grade) were analyzed. The mixtures studied include five different SuperPave™ mixes, a stone mastic asphalt (SMA), and an open-graded friction course (OGFC). The evaluation of the surface skid characteristics was based on measurements conducted using a locked-wheel trailer utilizing ASTM-specified ribbed and smooth tires. The macrotexture measurements were conducted using mainly a laser profiler. Statistical results indicated that, for the mixes studied, the roadway slope had insignificant effect on skid number (SN) measurements. Friction measurements, however, are dependent on the tire used, surface texture, age in service, and surface temperature. It was found that HMA design parameters affect pavement surface friction and texture. For the range of mixes studied, the mean profile depth (MPD) can be closely predicted based on the nominal maximum size (NMS) and VMA. Furthermore, the SN measured at 64 km/hr using the ribbed tire (SN(64)R) is mostly influenced by the NMS and VTM. The greater the NMS, the lower the ribbed tire skid number. On the other hand, other aggregate parameters and mixture properties have to be considered to accurately predict SN measured at 64 km/hr using the smooth tire (SN(64)S).


The main objective of the project is to establish a research program focused on enhancing the level of service provided by the roadway transportation system by optimizing pavement surface texture characteristics.


Different techniques for measuring pavement surface macrotexture and their application in pavement management are discussed. The main applications of surface macrotexture are to measure the frictional properties of the pavement surface and to detect hot-mix asphalt (HMA) construction segregation or nonuniformity. Since surface macrotexture can be measured quite efficiently using noncontact technologies and provides important information regarding pavement safety and HMA construction quality, this parameter may be included in the quality assurance or control procedures. Correlations between different measuring devices were investigated utilizing different HMA wearing surfaces. Excellent correlation was found between the circular track meter and sand patch measurements. In addition, the macrotexture determined using a laser profiler correlates well with that determined with sand patch measurements. Consistent with previous studies, it was found that the skid number gradient with speed is inversely proportional to the pavement macrotexture. However, there was a noticeable difference in speed dependency when smooth and ribbed tires were used. Oscillations in the percent normalized gradient with time due to seasonal variations were also observed. Macrotexture measurements hold great promise as tools to detect and quantify segregation for quality assurance purposes. A standard construction specification was proposed in a recent NCHRP study. However, the equation proposed for computing the nonsegregated estimated (mean) texture depth could not
be applied to the mixes studied. An alternative equation has been proposed, which estimates the surface macrotexture using the mix nominal maximum size and voids in the mineral aggregate. The study was based on the mixes used at the Virginia Smart Road. Further investigation using other mixes is recommended.

**Florida Department of Transportation. “Feasibility of Measuring Pavement Friction Characteristics at Higher Speeds for Added Safety.” (Research in Progress)**

The Florida Department of Transportation (FDOT) currently owns and operates four Pavement Friction Testing Units. Each consists of a tow vehicle, water tank, friction trailer, and mobile data processor. Friction measurements are obtained from the force induced on a locked test wheel as it is dragged over a wetted pavement surface. The mean friction number of the pavement section being tested is obtained from this test. Although the current FDOT friction testing program is fully functional, there are several areas that need to be addressed, most importantly safety while conducting the test. The current specified test speed of 40 mph is used on all state roadways, including primary, secondary, interstates, and toll roads. To maximize safety and minimize traffic disruption, friction testing is typically conducted on weekdays and sometimes at night. Nevertheless, there are still safety concerns related to potential conflicts with the motoring public on high-speed facilities. In order to properly address these safety concerns, it may be necessary to modify the current FDOT friction testing program to accommodate both advanced technologies and elevated testing speeds, comparable to the speed limit of the facility being tested. The objective of this project is to modify the existing standard test methods to allow for elevated test speeds.


This research investigates the feasibility of applying simple statistical models for forecasting road surface temperature at locations where RWIS data are available. Three commonly used modeling techniques are considered and those are time-series analysis, linear regression and artificial neural networks (ANN). A data set from a RWIS station is used for model calibration and validation. This paper describes the major findings with a specific focus on the generalization capability of the models. The analysis indicates that multi-variable and ANN are the most competitive technique with lowest forecasting errors.


This paper presents two statistical models for discriminating different types of road surface contaminants based on friction measurements and other road condition data. The first model is a disaggregate logit model which can be used to predict the probability that a road surface is covered by snow or in bare condition based on direct friction measurements and other available road weather data. The second model is an aggregate logit regression model that uses aggregated measures over a section of road as input to distinguish two sub snow cover states, namely, full snow cover and partial snow cover. The proposed models are calibrated using field data collected from a maintenance route in Ontario, Canada and show high discrimination power based on holdout data sets.


Traffic engineers continue to lay emphasis on the identification of crash causal factors on different functional classes of highways, in order to improve safety. The purpose of this study was to identify crash causal factors on two-lane highways and select countermeasures that could significantly reduce these crashes. The scope of the research was limited to two-lane highways in Virginia for the years 2001 to 2004.

The researchers identified 143 sites of five- to ten-miles highway segments, including proportional representatives from primary, secondary, rural and urban highways in each of the counties in Virginia, resulting in 10,000 crashes and over thirty variables. Police reports for all crashes along each site were extracted from VDOT’s crash database and relevant crash variables obtained. Traffic volumes and speed data along each site were obtained from VDOT publications. GPS data collected by the researchers for each site provided information on grading and curvature of the sites. The researchers also collected signing and speed limit data for each site.
The data were analyzed by highway classification (urban primary, urban secondary, rural primary, rural secondary) and collision type (rear-end, angle, head-on, sideswipe, run-off-the-road, deer, and other). Fault-Tree analysis was used to determine the critical fault path for each crash type and highway category to identify the causal factors and to quantify the probability of occurrence of those causal factors. Generalized linear models were then developed to predict crashes from the causal factors using the Negative Binomial distribution and then appropriate countermeasures selected.


Changes in pavement texture because of temperature, moisture, and polishing reduce the available friction for vehicles to perform routine maneuvers under normal operating conditions and thereby increase the potential for skid-related accidents. Optimization of texture and frictional properties at the mix design stage requires that specimens prepared in the laboratory accurately represent the pavement surface in the field. Initial findings from an investigation of the texture and frictional properties of specimens prepared in the Superpave gyratory compactor compared with field measurements are presented. In addition, the mix design properties that may be altered for increased friction are presented. The surfaces of the field specimens were different from their respective gyratory surfaces but were well correlated in the case of macrotexture measurements from the sand patch test. High correlation also was observed between field macrotexture and select mix properties, including the fineness modulus, voids in the mineral aggregate, percentage passing the 4.75-mm sieve, and bulk relative density. Poor correlation was observed between the British pendulum numbers recorded on unpolished field specimens and gyratory specimens, although the bottom gyratory surfaces best matched with field values. Preliminary results suggest the gyratory compactor orients the aggregate particles in a different manner from field compaction equipment. Further, the aggregate breakdown imposed by the gyratory compactor results in additional microtexture exposure not observed on newly compacted pavements in the field until trafficking removes the upper layer of asphalt cement from the coarse aggregate particles.


This paper presents results of an analysis of crashes on U.S. highways in poor road weather conditions. Dan Cohen provided crash tabulations for the seven-year period from 1995 to 2001 from National Highway Traffic Safety Administration (NHTSA) databases. The objectives of the analysis were to update a March 2001 report titled “A Preliminary Analysis of U.S. Highway Crashes Against an Exposure Index”, and to identify trends in the frequency of weather-related crashes.


The equipment and methods currently employed in France to evaluate the skid resistance characteristics of a pavement will be described. These characteristics are obtained by means of investigating both the microtexture and macrotexture of the pavement's wearing courses. The methods introduced along with associated instrumentation fully satisfy the needs of road infrastructure managers. The two international studies performed, i.e. PIARC (1992) and HERMES (2004) whose main results are summarized herein, enable understanding the relationships existing between the values output by these various instruments and have led to proposing a single index. Such an index would be beneficial, yet still not allow attaining adequate levels of repeatability and reproducibility. The primary rules when interpreting skid resistance measurements will be recalled, and the preferential fields of application for friction and texture measurements provided. The impacts of the European context on these devices will also be discussed.


For some years it has been suspected that new asphalt surfacings may have different skid resistance properties to surfaces that have been in service for some time. This is thought to be due to the presence of a film of bitumen binder on the new surface that is eventually removed by weathering and traffic. New types of surfacing introduced in the mid 1990s have led to concerns that the risk of early-life skid resistance problems, and the time that any effects last, may have increased. Research has identified physical phenomena that might lead to an increase in accident risk in some circumstances.
This paper summarizes the methodology and results of a study to investigate if a link could be observed between new surfacings and accident risk. The study used a combination of an analysis of accidents before and after resurfacing on the Highways Agency (HA) network, and collation and review of anecdotal comment from the HA’s Area Teams and Service Providers, and from other Highway Authorities. The findings from this study are generally consistent with the physical phenomena that have been measured on new asphalt surfacings. Neither of the approaches used in the study identified widespread problems with modern asphalt surfacings in their early life but there is evidence of a small increased accident risk in some circumstances.


This report documents the research performed under NCHRP Project 1-43. It describes the work activities undertaken in the study and presents the results of those activities toward the development of the Guide for Pavement Friction. The information provided in this report serves as the basis for many of the guidelines and recommendations contained in the Guide. The information will be of interest to highway materials, construction, pavement management, safety, design, and research engineers, as well as others concerned with the friction and related surface characteristics of highway pavements.

Using information collected through detailed literature reviews and survey/interviews with state highway agencies, this report discusses a variety of aspects regarding pavement friction. It describes and illustrates the importance of friction in highway safety, as well as the principles of friction, as defined by micro-texture and macro-texture. It identifies the factors affecting friction and examines the ways that friction can be measured (equipment and procedures) and expressed (Reporting indices). Most importantly, it presents valuable information on (a) the management of friction on existing highway pavements and (b) the design of new highway surfaces with adequate friction. This information focuses on techniques for monitoring friction and crashes and determining the need for remedial action, as well as identifying combinations of aggregate (micro-texture) and mix types/surface texturing methods (macro-texture) that satisfy friction design requirements.

The report includes various conclusions and recommendations based on the results of the study, and it features five appendixes containing supplemental information on friction.


This document provides guidance on the management of friction on existing pavements and on the design of new pavement surfaces with adequate friction. The overview of pavement friction includes discussion on importance and basic principles of pavement friction. The recommendations on developing the policies of the pavement friction management are provided, as well as the steps that should be taken in establishing the pavement friction management program by the state highway agencies. The friction design considerations include guidance on developing friction design policies and the project-level design guidelines.


Long-life concrete pavements require less frequent repair and rehabilitation and contribute to highway safety and congestion mitigation. The Federal Highway Administration, American Association of State Highway and Transportation Officials, and National Cooperative Highway Research Program sponsored a scanning study to identify design philosophies, materials requirements, construction procedures, and maintenance strategies used in Europe and Canada to build long-life concrete pavements. The scan team observed that concrete pavements in the countries visited are designed for 30 or more years of low-maintenance service life. The countries are responding to pavement-tire noise issues in urban areas by using exposed aggregate surface. Some use catalog designs for pavements and geotextiles as a separator layer between the cement-treated base and concrete pavement. Team recommendations for U.S. implementation include using two-lift construction to build pavements, developing pavement design catalogs, using better-quality materials in pavement subbases, paying greater attention to cement and concrete mixture properties, using a geotextile interlayer to prevent concrete slabs from bonding to the cement-treated base, and using exposed aggregate surfaces to reduce noise.

The Circular Texture Meter (CT Meter) is a laser-based device for measuring the mean profile depth (MPD) of a pavement at a static location. Both MPD measurements from the CT Meter and mean texture depth (MTD) measurements from the sand patch test were obtained in five random locations in each of 45 section of the 2000 National Center for Asphalt Technology (NCAT) Test Track. The NCAT Test Track provides a wide range of surface types including: coarse and fine dense graded Superpave mixes, Open Graded Friction Course (OGFC), Hveem mixes, Stone Mastic Asphalt (SMA) and Novachip. Testing indicated that CT Meter produced comparable results to the ASTM E965 Sand Patch Test. When open-graded mixtures were excluded, this study indicated that the offset was non-significant between CT Meter and sand patch test results.

Previously developed equations to predict macrotexture were found to be inadequate for the wide range of mix types and aggregate types found at the NCAT Test Track. An equation was developed to relate fineness modulus to macrotexture. This equation was validated with independent data collected by Virginia Transportation Research Council. Testing conducted as part of a mini round robin indicated that two readings should be averaged to represent a single CT Meter measurement. The within-lab coefficient of variation for the CT Meter is estimated to be 2.3 percent. The between-lab coefficient of variation for the CT Meter is estimated to be 4.2 percent. Both estimates are based on the average of two tests being reported as a single measurement. This indicates that the CT Meter is more variable than the sand patch test. However, less technician skill is required to operate the CT Meter.


Works Infrastructure Ltd manages the state highway network for Transit New Zealand in the Northland Region of New Zealand. The network is managed on a performance basis, using key performance measures to manage the delivery standards specified in the contract. Providing and maintaining an appropriate level of skid resistance is an important priority for network management. The Northland network is some 750 km in length and passes through a wide variety of terrain types and degrees of geometric difficulty. Heavy goods vehicle traffic levels are high in some sections, leading to rapid polishing of surface aggregates and a consequent rapid loss of skidding resistance, particularly in sections of terrain with corners of low radii. Experience has indicated that skid resistance levels on the network can not be assumed adequate simply based on a network survey performed once a year as the skid resistance, as measured by the SCRIM machine changes rapidly, depending on weather conditions and traffic loading. The recorded skid resistance is also affected by uncertainty associated with spatial referencing issues and the precision limits of measurement. This paper is a review of some of the various issues facing a network manager, such as:

- The background and development of test procedures.
- Aggregate quality and its polished stone value (PSV).
- The precision (repeatability and reproducibility) of the data.
- The uncertainty and interpretation of data used to interpret key performance measures.
- The locational accuracy of data collection.

The review described investigation and work, previously published and unpublished, relating to the network and illustrates the issues to be considered by a highway network manager when using key performance measure assessment techniques.


The measurement and assessment of skid resistance is routine on New Zealand’s state highway network. Some Local Authorities are now also investigating and implementing policies with respect to the skid resistance of their networks. Skid resistance is generally accepted to be a function of:

- The traffic volume and heavy goods vehicles over the life of the surfacing.
- The quality of the aggregate, determined by its polished stone value (PSV).
- The surface texture.
Texture, combined with the PSV, is desirable for high-speed skid resistance, however, within an urban environment, it is not so critical as suitable skid resistance can be achieved by specifying an appropriate aggregate PSV and selection of the surfacing type. Auckland City has recently investigated this approach, with respect to the PSV of aggregates used for asphalt and chip seal on its networks. The closure of a major quarry has necessitated recent changes in the sources of aggregate used in the region. The purpose of the investigation was to ensure network safety would not be compromised if materials from alternative sources, but potentially having a slightly lower PSV, were used. This paper describes an approach used to investigate potential issues related to the use of an alternative aggregate source. An assessment was undertaken using the AS/NZS 4360 “Risk Management” approach and an innovative method to develop a risk matrix table and assign hazard levels and scores to prioritise and identify high-risk sites.


This synthesis report will be of interest to pavement design, construction, management, and research engineers, highway safety officials, and others concerned with pavement friction characteristics. It describes the current state of the practice and discusses the methods used for evaluating wet pavement friction characteristics of new and restored pavements. This synthesis reviews models used for measuring and evaluating friction and texture, causes for friction changes over time, and aggregate and mix design to provide adequate friction. Also presented are construction and surface restoration practices for providing good pavement surface characteristics. In addition, considerations of noise and ride quality are discussed when compromise may be required.


The annoying noise frequencies produced from the tire/pavement interaction on some (usually transversely tined) Portland Cement Concrete (PCC) pavements have concerned both residents living nearby and motorists traveling over them. A Technical Working Group (TWG) was formed to investigate the problem by conducting a review of previous research and by evaluating the results of ongoing research in the United States. The goal of the TWG was to recommend PCC pavement surface textures that will reduce the annoying noise frequencies without compromising safety. Previous research determined that PCC surfaces constructed for speeds under 80 km/h need only a good microtexture for wet weather stopping. For speeds of 80 km/h or greater, a macrotexture is also needed to reduce the water film thickness and prevent hydroplaning. The exposed aggregate surfaced PCC pavements and the open-graded asphalt friction course pavements combine for the quietest and safest rides where premium textures are desired. Smoother pavements also result in a quieter ride. Wisconsin researchers, using narrow band frequency analysis techniques, have recently discovered how to objectively measure and analyze the annoying pure tones that create tire/pavement whining or lower frequency rumbling. Noise-reducing construction methods that work most effectively for new pavements are to randomly space (10 to 40 mm) the transverse tines/grooves, construct longitudinal tines/grooves (either according to AASHTO guidelines or to the Spanish plastic brushing method), or construct an exposed aggregate surface. Existing PCC pavements that produce an annoying noise should be retextured (diamond grooving, diamond or carbide grinding, or shotblasting) or resurfaced (PCC overlay or surface laminate, microsurfacing, or a dense- or open-graded asphalt concrete overlay). Further research needs to determine the relationship between friction numbers and wet weather accident rates and develop improved construction guide.


This interim advice note provides guidance to facilitate the effective application of the Skid Resistance Policy (HD28/04) by the Highways Agency and its Service Providers. It provides specific instructions and additional guidance about how to implement the Standard on trunk roads in England as well as introduces several changes to the standard itself. This advice is based on the results of consultation process and feedback provided by Service Providers and external consultants.


A three-year research program was initiated in 1978 at the Pennsylvania Transportation Institute by the U.S. Department of Transportation to investigate possible causes for seasonal and short-term skid resistance variations.
The primary objective is to determine the parameters that can be used to predict the influence of seasonal and short-term effects. Results concerning short-term, weather-related skid resistance variations are presented and discussed. Twenty-one test surfaces in State College, Pennsylvania, were selected for testing. The testing program includes daily skid measurements according to ASTM test method E274 and the collection of daily weather data. After the data are adjusted for long-term variations, the short-term residuals are regressed against rainfall and temperature parameters. The number of days since the last significant rainfall and the test pavement temperature are both found to be significant causes of short-term skid resistance variations. Further unexplained variations are attributable to measurement errors, particularly the lateral placement of the skid test trailer. The Pennsylvania results are supported by data collected in a similar study of 10 sites located in North Carolina and Tennessee (Federal Highway Administration Region 15).


The importance of surface texture characteristics to roadway safety was first recognized during the late 1940s and early 1950s when increases in traffic volumes and vehicle speeds resulted in increases in wet-weather crashes and fatalities. As a result, agencies conducted extensive research (including experimental projects around the country) to better understand and improve the surface conditions of Portland cement concrete pavement in wet weather conditions. As new surface texturing methods were tried and evaluated, pavement engineers recognized the corresponding influence of the texture (type, characteristics and quality) on tire-pavement interaction noise. Specifically, it was recognized that a general trade-off existed between friction and noise; i.e., surface textures with higher friction also tended to have greater tire-pavement noise. The noise associated with tire-pavement interactions has been a concern of pavement engineers for nearly 50 years, but it has received particular attention over the past decade. Although considerable information exists on the influence of surface friction characteristics on safety (surface friction and splash and spray) and tire-pavement noise, it is dispersed among numerous sources. This document identifies and summarizes key texture-related information and recommendations based on the current state of the practice. Specifically, this document provides a brief summary of texture-related research; introduces pavement texture nomenclature; discusses the measurement of texture, surface friction and tire-pavement noise; describes traditional and innovative texturing methods/techniques; summarizes respective conclusions pertaining to the influence of texture characteristics on surface friction, tire-pavement noise, and surface durability; and provides current state-of-the-art texture-related recommendations.


Crash reduction factors are used to identify and prioritize the most effective safety improvement measures, and prioritize and allocate available resources optimally for a highway safety improvement project. Simple before and after analysis accounts for the regression-to-the-mean bias. This research employs an Empirical Bias (EB) methodology that overcomes the regression-to-the-mean property that is encountered in traditional before and after analysis. Traffic, geometric and crash data for both the treatment and comparison sites were collected from Ohio in developing the crash reduction factors. Using data collected from Ohio, the EB methodology was applied in developing crash reduction factors for the following improvement categories: add a two-way left turn lane, install a median barrier, flatten slope and remove guardrail, remove or relocate a fixed object, flatten vertical curve, providing highway lighting and close median opening.


Statistics indicate that rain and wet pavement have more significant impacts on road safety than snow and ice. The effect of Wet Percent Time was found to be an important variable in wet accidents. Caltrans sponsored a two-year research project in 2006 to develop an updated Wet Percent Time table, as the current table was developed with data more than 30 years old. Historical hourly precipitation data of California reported by rain gauges were obtained from the five network data sources including CDEC, CIMIS, MESOWEST, NCDC, and the National Weather Service. Based on the density and distribution of available hourly precipitation data stations, an 11-year period (01/01/1995-09/30/2005) was chosen for this project. When available archived precipitation data were downloaded from various upstream weather data providers and uploaded to the WTI database, we followed three processes to check and improve the quality of the data: Reprocessing, Quality Control, and Missing data In-filling. To assure and
quantify the quality of the data used in this study, the statistical summaries were generated and the results were reviewed. Overall there were 1296 out of 1718 stations available from CDEC, CIMIS and MESOWEST for constructing the California Wet Percent Time table from 1995 to 2005, whereas 422 problematic stations were removed from the WTI database for either short duration of available data or large percent of erroneous and missing data. An improved method using the Zonal Statistics provided in the ArcGIS Spatial Analyst was tested and chosen for this project to produce a more accurate County-Average Wet Percent Time table.


This report provides information on best practices used in five areas in the country to enhance intersection safety. These practices focus on key elements of highway safety: safety management and comprehensive safety processes; traffic control devices for motorists, pedestrians and bicyclists; traffic operational practices; geometric design treatments; and enforcement practices and educational programs. The purpose of this document is to serve as an information and technology transfer tool on intersection safety practices used by State, regional and local transportation officials for the benefit of motorists, pedestrians and bicyclists.


The Illinois Department of Transportation (IDOT) uses two-wheeled friction testers to obtain a standard measurement of pavement surface friction under wetted conditions. A standard test is made at 40 mph in the left wheel path with a treaded tire. The test takes about 3 seconds. Torque on the trailer axle is measured for a 1-second interval. IDOT also performs a test in the right wheelpath with a smooth (treadless) tire. Treaded tire friction numbers are referred to as FNt and smooth tire numbers as FNs. Tests are made by alternating wheels as the trailer is towed along the roadway.


It’s true that US motor vehicle death rates have been trending downward for decades. Since the mid-1980s, the rate per registered vehicle has declined 43 percent. Traffic safety policies aimed at improving drivers and roadways have influenced this trend, but it’s a mistake to attribute all of the death rate reductions to such policies. More sophisticated analyses are required to get a clearer idea of what is behind the reductions, and new Institute research helps to identify the reasons.

The researchers focused on two factors that have influenced the driver death rate per registered vehicle over 20 years (1985-2004). One is how vehicle use patterns change as vehicles age. The other is vehicle design changes—the introduction over time of different types of vehicles and more crashworthy ones to replace vehicles that weren’t doing as good a job of protecting their occupants.


In Minnesota, concrete pavements are finished by dragging an inverted turf or a stiff-bristled broom longitudinally on the surface of freshly placed concrete pavements, right behind the paving machine. Prior to 1998, most concrete pavements were finished with a combination of the burlap-drag and transverse-tining. Subsequently those pavements were reconstructed and finished with current broom or turf drag. The study sought to ascertain if current texturing techniques resulted in higher wet weather accident events. A Minnesota Department of Transportation (Mn/DOT) study selected segments in the network where current texturing techniques replaced previous textures. Annual wet weather accidents data from the Mn/DOT database were analyzed. By examining annual wet weather accident counts, total accident counts and crash rates for a ten year period, current textures were compared to previous textures. The paper discusses how three statistical tools were used to compare wet weather accident data from previous texturing to data from current texturing. Statistical tools showed that current texturing practices did not cause an increase in the annual wet weather accidents and crash rates, as well as ratio of wet to dry weather accidents, in the chosen test sections.

Pavement friction testing is frequently conducted in accordance with the provisions outlined in ASTM E 274, "Standard Test method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire." The standard speed of testing in Florida is 40 mph (64.4 km/h). However, due to safety concerns related to testing on high-speed facilities, considerable attention has been focused in recent years on height-sensor based (non-contact) technology. Such sensors are potentially well suited for surveying the surface texture characteristics of pavement sections while operating at highway speeds. Although the height-sensor based technology has been available since the 1960s, it continues to mature. A considerable amount of research has been conducted to gain further understanding on the factors affecting high-speed pavement surface surveying from both the analytical and experimental points of view. Still some problems have not fully been resolved, particularly in the interpretation of the measured data and selection of adequate sensing technology (or sensor designs). The Florida Department of Transportation (FDOT) initiated the present study to assess the feasibility of using high-speed, laser-based sensors to quantify the texture and friction characteristics of asphalt pavements. The main objective of this study is to provide for a safer, faster and more appropriate method of estimating pavement friction characteristics on high-speed facilities, ramps, and at other potentially hazardous sites. Further, it is also intended to provide for a means to obtain a measure of International Friction Index (IFI) in accordance with ASTM E 1960. This report presents a description of the FDOT testing program, the data collection effort as well as the subsequent analyses and findings.


Findings are presented from a research study conducted in Texas to determine the significance of seasonal variation in skid measurements. Six bituminous highway pavement sections, two each from three different climatic regions, were monitored over a period of more than 18 months. Monitoring included collection of wet pavement skid resistance data using a locked-wheel skid trailer that met the specifications of ASTM E 274. These measurements were made at biweekly intervals in two of the three climatic regions and at monthly intervals in the remaining climatic region. The necessary climatic data were obtained from nearby National Climatic Data Centers. The data obtained indicated that significant variation in skid numbers occurs from one day of measurement to another. The maximum variations observed were on the order of 10 to 12 skid numbers. Furthermore, there were strong indications that the variations occurred in response to changes in temperature and precipitation. Finally, three methods of normalizing the skid data to obtain the true mean skid number of the pavement were evaluated. The first of these was a linear regression model based on rainfall, temperature, and other variables. The second was a nonlinear regression model based on Julian calendar day only. The third approach examined the possibility of using multiple skid measurements to achieve a desired level of accuracy. The advantages and disadvantages of each method are discussed.


It has been acknowledged recently in the UK and New Zealand that setting single investigatory levels (IL’s) for each site category may not be the optimum management of risk since each site category is quite broad and individual sites, within a site category, can have very different conditions. Therefore, a range of IL’s has been recommended for each site category; the advantage of setting a range is that levels can be more closely aligned with particular risk for each individual site. Also, since the range is set out in the policy it removes the perceived risk to the Site Investigation Engineer, to move the IL away from the tabulated value in the specification. However, fundamental to this new approach is the correct assessment of the risk through the use of a site investigation process. In this paper, a risk assessment has been carried out on 35 category 2 or 3 sites situated in the Northland region. The assessment includes the results from the SCRM survey, the effect of rain fall on the skid resistance, the results of a curve deficiency procedure, a full site investigation for each site and the wet crash data for the sites. Using all the information a comparative analysis of risk for each of the sites has been determined. The risk assessment has been used to assign individual investigatory levels and, using information from previous studies, an estimate in the benefits arising from crash reduction has been made. Using the cost associated with the crash reduction a benefit-cost analysis has been carried out taking into account the benefits obtained by crash reduction on one hand and the
cost of achieving the recommended IL on the other. Finally, the implications to local key performance measures have been discussed, along with the implications if the approach was adopted on a national basis.

Khattak, A. 2006. *Feasibility of Using Existing Crash Databases for Comparison of Crash Frequency, Rates, and Injury Severity on Concrete and Asphalt Pavements.* American Concrete Pavement Association, Skokie, IL.

Properly tined concrete pavements generally provide superior skid resistance compared to asphalt pavements. Skid resistance is a critical factor in many highway crash situations. However, no published studies exist that statistically compare the safety of concrete and asphalt pavement surfaces. The American Concrete Pavement Association (ACPA) is interested in exploring existing crash data sources that may be used in a statistically valid evaluation of concrete and asphalt pavement surface safety. This study was undertaken to assess the feasibility of using data contained in two publicly available datasets: the Highway Safety Information System (HSIS) and the Fatality Analysis and Reporting System (FARS). The assessment was based on the ability to compare crash frequency, crash rate, and crash injury severity as safety metrics. The HSIS contains crash and other relevant data from nine states: California, Illinois, Maine, Michigan, Minnesota, North Carolina, Ohio, Utah, and Washington. For each state, HSIS data consistently provides crash, vehicle, occupant, and roadlog files. Data from each state was assessed for its potential usage in a comparative study of concrete and asphalt pavement surface safety. The assessment indicated that data from all nine states can potentially be used for analysis of crash frequency and crash rates, after the necessary file merging operations. Injury severity analysis is possible, albeit with some limitations – either restricting it to injuries of drivers involved in single-vehicle crashes or relying on the characteristics of most severely injured occupant and the respective vehicle in the analysis. Alternatively, an indicator variable for injury/non-injury crashes may be used in the crash frequency models. Although FARS data initially appeared to have potential for use in a comparative study of concrete and asphalt pavement surfaces, its assessment showed that it is unlikely to be useful for an “apples-to-apples” safety comparison. The non-usefulness of FARS data for this study is due to absence of specific crash locations in the dataset and non-availability of crash exposure information on concrete and asphalt pavement surfaces. The following recommendations have emerged based on the assessment of HSIS and FARS data:

- Conduct crash frequency analysis of each of the nine states contained in the HSIS by using appropriate count data models (Poisson, Negative Binomial, Gamma, etc.).
- Using HSIS data for the nine states, conduct simple comparisons of crash rates as well as regression analysis of crash rates to obtain insights beyond those obtained by frequency analysis.
- Conduct injury severity analysis using the HSIS data with the understanding that findings from the analysis may be limited in scope.
- North Carolina, Minnesota, Ohio, and Maine databases in the HSIS appear to be good candidates if analyses are limited to only a few states.
- FARS data may not be pursued further for the purpose of comparing the safety of concrete and asphalt pavement surfaces because of non-availability of crash location and exposure information.

Data from only two states in the HSIS contain information on pavement roughness: North Carolina and Ohio. While the analyses of data from all states can reveal safety differences between concrete and asphalt pavement surfaces, the analyses of data from only these two states can potentially link the difference in safety to pavement roughness.


This report represents the second phase of a project sponsored by the Wisconsin DOT and the FHWA researching the texture and noise characteristics of Portland cement concrete (PCC) pavements. The team of Marquette University and the HNTB Corporation measured noise, texture and friction of 57 test sites in Colorado, Iowa, Michigan, Minnesota, North Dakota and Wisconsin. During 1997, new test sections were constructed in Wisconsin, including random transverse, skewed and longitudinally tined PCC pavements. Interior and exterior noise was measured on all 57 sites using the Fast Fourier Transform method with a Larson-Davis two channel real time acoustical analyzer. Subjective testing of interior noise was measured on 21 selected sections with 24 subjects with good hearing in a closed acoustical environment. Texture on all test sites was measured with the Road Surface Analyzer (ROSAN). Sand patch tests, a measure of surface texture, were also performed on most of the 22 test sections in Wisconsin. Highway noise cannot be characterized by one single type of noise measurement. For this
reason, conclusions were drawn using the data acquired from all of the different measurements. These include:

exterior, interior, subjective, and prominent frequency noise analysis as well as texture characteristics. Some
pavement textures exhibit a definite distinctive noise that is often described as “a whine”, and is exhibited as a
prominent tone or discrete frequency also described as a “spike”. Generally, the longitudinal tined PCC and the
Asphaltic concrete (AC) pavements exhibited the lowest exterior noise levels. The AC pavements and the
longitudinally tined and random skewed PCC pavements and the European texture exhibit the lowest interior noise
levels. ROSAN texture measurements were relied upon and proved invaluable in analyzing the reason why different
textures exhibited different noise characteristics. The ROSAN mean profile depth (MPD) and estimated texture
depth (ETD) correlated very closely with sand patch. There was good correlation between tining depth and width,
using the ROSAN data, and some of the loudest transverse tined pavements had both greater depth and widths, but it
could not be determined which was responsible for the greater noise. Spectral analysis of the ROSAN outputs was
utilized to recommend the proper random pattern for transverse tining. The patterns were tested in 1999 and both
subjective and objective analyses confirmed the lack of discrete frequencies.

Conclusions include that tining depths vary tremendously among the pavements constructed, even within a single
test section, uniform tined pavements exhibit a discrete frequency or whine and should be avoided, transverse tined
pavements with the deepest and widest textures were often the noisiest, longitudinal and random skewed tining (1:6
skew) can be easily built, eliminate discrete frequencies while substantially reducing noise levels, and random
transverse tining must be carefully designed to eliminate discrete frequencies, but may not substantially reduce
overall noise levels. When comparing different pavement textures with the same mean texture depth (approximately
0.7 mm) to that of uniform 25 mm, transverse tined PCC pavements, a well randomized transverse will result in a 1
to 3 dBA exterior noise reduction, a random skew 4 dBA, a longitudinal tined 4 to 7 dBA and an opened textured
AC pavement 5 dBA, based on this study. Interior noise reduction were approximately half of the exterior
reductions. Recommendations include improving the quality control over tine spacing depth and width, future
research on wet pavement accidents and longitudinal tining and the relative affects of tining depth and width on tire
pavement noise, and specific recommendation on when to use longitudinal, random skewed and random transverse
tining. Long term monitoring of noise differences of these 57 test sections is recommended in order to determine if
surface texture differences can be reflected in FHWA noise models.

Kuttesch, J. S. 2004. Quantifying the Relationship Between Skid Resistance and Wet Weather Accidents for
Virginia Data. Master of Science Thesis. Virginia Polytechnic Institute and State University. Blacksburg,
VA.

One of the factors contributing to motor vehicle crashes is lack of sufficient friction at the tire-pavement interface.
Although the relationship between surface friction and roadway safety has long been recognized, attempts to
quantify the effect of pavement skid resistance on wet accident rates have produced inconsistent results. This thesis
analyzes the relationships between skid resistance, accident, and traffic data for the state of Virginia. The
relation between wet skid resistance measured with a locked-wheel trailer using a smooth tire and wet accident
rates is examined. Additionally, the influence of traffic volumes on accident rates is considered. The research used
accident and skid data from the Virginia wet accident reduction program as well as from sections without pre-
identified accident or skid problems. The wet accident data was aggregated in 1.6 km (1 mi) sections and divided by
the annual traffic to obtain wet accident rates. The minimum skid number measured on each of these sections was
then obtained and added to the database. Regression analyses indicated that there is statistically significant effect of
skid resistance on wet accident rate; the wet accident rate increases with decreasing skid numbers. However, as
expected, skid resistance alone does a poor job of modeling the variability in the wet accident rates. In addition, the
wet accident rate also decreases with increasing traffic volume. Based on the data studied, a target skid number
(SN(64))-S of 25 to 30 appears to be justified.

Annual Meeting Compendium of Papers DVD. Transportation Research Board. Washington, DC.

Municipal, state, and federal agencies in the United States that are responsible for traffic safety have used crash rates
such as fatalities per 100 million vehicle miles traveled (VMT) as traffic safety performance measures. However, the
appropriateness of using such rates as performance measures has not been examined empirically, although the rates
have been made public.
This study examined 20 candidate crash rates (e.g., fatalities per million population and injury crashes per million registered vehicles) for an annual safety performance measure for Virginia using autoregressive error models and empirical data from 1971 through 2006. The study found that the injury rate per driver and the crash rate per VMT seem appropriate as long-term (1971-2006) and short-term (1995-2006) safety performance measures, respectively, for Virginia. Statistical uncertainty should be considered when these rates are used to measure safety performance.


This book presents a thoroughly scientific and practical approach to designing highways for maximum safety. Based on original research plus scrupulously collected data amassed over more than two decades in different continents by the main author, this important book originates vital criteria for safe design and shows you how best to achieve roads with the lowest possible accident risk and severity rates. In addition, this valuable and necessary resource gives you serious help coordinating safety concerns with important economic, environmental, and aesthetic considerations. Overall the book is an invaluable source of information for educators, students, scientists, highway agencies, and consultants in the field of highway design and traffic safety engineering.


This paper provides background information on pavement texture and its relationship to the skid resistance from period between late 60s and early 90s. It also discusses existing guidance regarding pavement friction/texture. The author emphasizes current friction/texture vs. accident research and implementation activities, providing comprehensive list of references on the issue. The following actions are recommended:

1. Develop a one day workshop to summarize the portland cement concrete (PCC) surface texturing research currently being completed in Wisconsin. This would emphasize efforts to reduce annoying tonal frequencies and total noise on PCC pavements for both the user and the adjacent residences. This would include implementation guides or aids to facilitate early technology transfer.

Attachment to the paper discusses effect of friction/texture on crash rates. While the direct relationship between skid numbers measured on the surface and wet-pavement crashes is questionable, the effect of texture depth on the crash rate has been proved to be significant by many studies both in the U.S. and overseas (U.K., Australia, New Zealand).


In the United States, it has been estimated that inadequate highway pavement conditions contribute to 13,000 of the 43,000 annual highway fatalities. Poor pavement friction or surface texture increases total crashes and also contributes to wet-weather crashes, resulting in increased fatalities, more serious personal injuries, and significant traffic delays. This issue is especially critical on two-lane roadways, because of generally lower geometric standards and more potential conflicting movements, particularly at curves, intersections, and steeper grades. Also, work zone crashes result in 1,300 fatalities annually, and transition areas are particularly critical. Ramps on freeways are also potential high accident locations. Thus it is important to compare the friction demand assumed during design with the friction/texture actually provided at the site being investigated. This paper discusses recent efforts in the United States by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) to address this issue. It summarizes information obtained from international sources, particularly recent safety scans that have been conducted, and notes the experience of the U.K. and Austroads. Additionally, this paper describes current efforts in the U.S. to develop computerized analysis tools and to implement Road Safety Audits. It also identifies a number of relevant studies either completed or underway. The current U.S. emphasis on pavement preservation presents an outstanding opportunity to improve the pavement condition and surface characteristics in order to reduce accidents and pavement-related noise. Technological advances in data collection, storage, and analysis make it possible to provide information to improve engineering decisions. Two examples of improved procedures are given. The first is a procedure adopted for texture and
friction requirements on airfield pavements. The second example is the recent improvement in the Texas Wet-Weather Accident Reduction Program to reduce data collection and analysis costs and to reduce the number of crashes and fatalities. Finally, some conclusions and recommendations are provided to develop safer roads. The emphasis is on providing better information on the effect of texture and friction on reducing accidents, so that more cost-effective engineering decisions can be made.


The surface characteristics of pavements contribute to good functional performance. These characteristics are gaining in significance with the shift of focus from new construction and major rehabilitation to pavement preservation. Functional performance is determined by how well the pavement serves the user. Until now, riding comfort—a concept developed in 1957—had been the dominant concern. Today the greater need is to improve other important functional surface characteristics of pavements. The new pavement preservation technologies may enable researchers to develop guidelines for the functional surface characteristics of pavements that maintain ride comfort but also contribute to reductions in fatalities and injuries, as well as in highway noise.


Most pavement design and construction specifications do not adequately define the pavement functional surface characteristics that are important to highway users. The result is that sometimes completed highway projects do not meet user expectations. Currently, most specifications address only smoothness (ride quality), whereas other desirable surface characteristics such as durability, and surface texture [friction (safety) and noise (environment)], and aesthetics are not often specifically addressed. The purpose of this paper is to look at the functional characteristics of well performing paved highway surfaces. First, functional performance will be described. Secondly, the individual surface characteristics affecting functional performance will be discussed. Finally, recent innovative techniques and equipment to measure and evaluate these characteristics will be explained. Consideration of these factors by the engineering profession will help ensure that the highway user expectations are met on completed projects.


Most pavement design and construction specifications do not adequately define the pavement functional surface characteristics that are important to highway users. The result is that sometimes completed highway projects do not meet user expectations. Currently, most specifications address only smoothness (ride quality), whereas other desirable surface characteristics such as durability, and surface texture [friction (safety) and noise (environment)] are not often specifically addressed. The purpose of this paper is to look primarily at the functional characteristics of paved highway surfaces. First, functional performance will be described. Secondly, the individual surface characteristics affecting functional performance will be discussed with emphasis on pavement texture which has a major effect on friction (safety) and noise (environment). Next, recent innovative techniques and equipment to measure and evaluate these characteristics will be explained. Safety efforts underway both internationally and in the U.S. will be addressed. Finally, examples of the best practices will be described. Consideration of these factors by the engineering profession will help ensure that the highway user expectations are met on completed projects by providing durable, safe and quiet highways.


Over a number of years the United Kingdom has published a series of guidance manuals and standards for Local Highway Authorities. These require Local Authorities to assess and manage the Skid resistance performance of their highway surfaces. The Road Death Investigation manual developed by the police has resulted in a new level of scrutiny of the LA’s skidding policy and its implementation.

By using a series of case studies from a range of LA’s this paper will outline the fundamental steps to be used in developing a practical skidding policy. This policy will be able to be managed by non-specialist engineers within the limited resources available to the LA’s. A summary of the current practice by LA’s on the use of warning signs is given.
The paper will consider the impact of the newly introduced SCANNER surveys and the use of technologically advanced computer systems, particularly in the areas of Global Positioning Systems, Graphical Information Systems and internet facilities. These systems combine to give fast and easy access to different data sets for efficient coordination. A demonstration of an automatic process that will give the engineer an early warning system of potential accidents at particular locations on the road network will be given.


The influence of the particle size distribution used in road surfacing mixes on both average macrotexture depth and skid resistance of pavements is described herein. It will then be shown how the nature of aggregates is able to influence the evolution in the pavement surface state when submitted to the effect of traffic-related polishing. Following a presentation of methods used for characterizing the level of aggregate polishing resistance, the correlation between this resistance and the trend in pavement skid resistance will be highlighted by results from recent experimental testing. Moreover, discussion will be provided on the aggregate selection criteria used for wearing courses.


Traffic accidents cause loss of life and property. Proper identification of accident causal factors is essential for composing countermeasures against traffic accidents and reducing related costs. However, two-lane rural roads have distinctive roadway characteristics compared with other types of roads. In order to find cost-effective countermeasures and prioritize roadway safety improvement plans, a better understanding of the relationship between accident risk and respective characteristics is necessary. This study focuses on accident analysis of two-lane rural road sections in Washington State. Six representative state routes (SRs), SR-2, SR-12, SR-20, SR-21, SR-97 and SR-101, are selected as study routes based on their location, length, accident history, and geometric characteristics. Along with six-year (1999-2004) accident data from the Highway Safety Information System (HSIS), roadway video image data and geographical information system data retrieved from Washington State Department of Transportation are employed in this study. Econometric modeling methods are utilized to identify accident causal factors and evaluate their impacts on accident risk. Poisson regression, negative binomial regression, and zero-inflated regression models were evaluated and negative binomial regression was found to be the most suitable form for modeling accidents on two-lane rural roads. In addition to modeling all-type accidents, a rear-end accident risk model is also developed since rear-end accidents are the most frequent accident type on all routes. Findings from this study not only help identify accident causal factors, but also provide valuable insights for developing countermeasures against two-lane rural road traffic accidents.


Because of the evident advantages associated with the smooth tire for the measurement of pavement friction, many highway agencies have become interested in the smooth tire. Pavement friction is the result of tire–pavement interaction. Because of the differences between ribbed and smooth tires, experiences with the ribbed tire may not apply to the smooth tire. Therefore, it is of great importance to evaluate those issues associated with the use of the smooth tire in network pavement inventory friction testing, such as variations in the friction testing system, seasonal friction variations, spatial friction variations, and temporal friction variations. The Indiana Department of Transportation (InDOT) has been using the smooth tire in the network pavement inventory friction test program since 1996. Large amounts of friction data have been obtained in the InDOT friction test track and network pavements. This paper presents the variations in the friction measurements obtained with the smooth tire because of testing system errors and seasonal and temperature effects. The paper also presents the spatial and temporal variations in the friction measurements. It was thought that the results provided in this paper would be useful for highway agencies for determination of test cycle, test spacing, and friction corrections for their network pavement inventory friction testing programs.

This study investigated many important issues associated with pavement surface friction testing, in particular using the smooth tire. This study utilized 3-D FEM program to investigate the fundamental friction phenomenon in light of energy dissipation during friction process. It was demonstrated that the pavement friction depends on many factors such as test tire, test speed, surrounding conditions, pavement surface texture, and pavement type. A great amount of friction data has been collected to investigate variations involved in pavement friction measurements. System variations depend on the features of the pavement surface. The standard deviations due to system errors are usually less than 5. The smooth tire tends to provide greater variations than the ribbed tire. As air temperature increases, the friction number does not necessarily decrease. No consistent relations were identified between friction measurements and test seasons. Seasonal friction variations are negligible. The largest directional variation is 16 with the smooth tire on a State road. The State and U.S. roads tend to produce greater directional variations than the interstates. Driving lane usually has lower friction than other lanes. The greatest lateral variation arose due to the effect of wheel track. Longitudinal friction variations depend on traffic distribution, pavement type, and surrounding conditions. Friction measurements taken at 1.0-mile spacing can provide realistic network pavement friction information. Pavement frictions on interstates decreased faster than those on State and US roads. The Indiana Department of Transportation (INDOT) conducts pavement inventory friction tests every year on interstates and every three years on State and US roads. The force transducers should be calibrated every month and the whole system performance verified every week to identify potential significant performance changes. A minimum of 3 to 5 test runs must be conducted for system verification. The standard smooth tire is recommended for INDOT network pavement inventory friction tests. In general, the friction number measured with the ribbed tire is greater than that with the smooth tire. However, the differences decrease as the surface texture becomes rougher. The average friction difference is about 20 on highway pavements. Friction test speed should be determined in light of the traffic conditions. Test speeds of 30 mph, 40 mph, and 50 mph are recommended for network pavement inventory friction testing. Determination of the minimum friction requirement should consider its impact on wet-pavement accidents and agency's budgets. Taking into account the minimum friction requirement recommended by NCHRP Report 37 and the differences between the ribbed and smooth tires, a friction number of 20 with the smooth tire at 40 mph is recommended as the minimum friction requirement for network pavement inventory friction testing. It was found that this requirement is economically reasonable.


Questions concerning the effect of skid resistance on traffic accidents have been investigated in various research studies. Apart from separation of the influence of skid resistance from other influence factors, one of the main issues in all these studies has repeatedly been the quantifying of the correlation between skid resistance and accident occurrence. The goal was finding a threshold or minimum value for the skid resistance. Whereas elder studies show quantified correlations between skid resistance and accident occurrence, recent research results tended to put these in question. Based on a large data set regarding freeways and a pilot study regarding main roads the present study shows that it was not possible to identify any such relation between skid resistance and accident occurrence for either wet or dry pavements. It was not possible to formulate no quantifiable correlation in this regard. It could, however, be found that a systematic search for notable areas where very low skid resistance values with high accident frequencies by wet pavement coincide is extremely worthwhile, as it serves to identify individual, randomly distributed danger zones. These can then be subjected to more detailed investigations.


Highway safety is one of the most important issues in transportation. Intersections are the locations with higher traffic crashes as compared with other highway locations. To evaluate or assess the safety performance of an intersection, traffic crash analysis is the most popular method and has been used for a long history. However, traffic crash analysis is based on a lot of crash data, which needs to be accumulated through a long time period. Besides, sometimes, traffic crashes randomly happen with the impacts of human driving behavior. Therefore, without sufficient data and crash history, traffic crash analysis may not give an overall evaluation for the intersection safety performance. This paper introduces an approach to evaluate highway intersection safety performance. This approach
is fully based on the existing conditions of the intersection, including geometrics, channelization, sight distance, pavement surface conditions, traffic control devices, traffic signal timing and phasing, etc. The non-accident based approach is based on field survey to the conditions mentioned before. The approach will also result in a safety index to indicate the safety performance degree of the intersection. Meanwhile, corresponding countermeasures are ranked and recommended based on the cost-benefit analysis. The content of this paper is based on the research results from a part of a research project (entitled “Safety Design of Highway Intersections”) sponsored by China Department of Transportation. In this paper, the approach (called diagnostic approach) is practically applied to evaluate the safety performance of some intersections in Shan Dong Province and Jiang Su Province. Results from the real application indicate that the approach has good applicability and can be used by field safety engineers in real application. In addition, the approach is implemented into software with friend operational interface.


Road traffic safety has substantially improved in The Netherlands since it peaked in the mid 1970s, and especially after Phase I (1998-2002) of the Dutch road infrastructure redesign programme "Duurzaam Veilige Infrastructuur" (Sustainable Safe Infrastructure). Surprisingly, however, from 2003 to 2006 Dutch traffic safety has considerably further improved without any stimulating national programme. Aiming to assist further Dutch policy making of road traffic safety, the paper analyses the Dutch situation and explores potential factors that may have contributed to the traffic safety improvement in the past years. In addition, it investigates the use of a first-order, one-variable grey model, denoted as GM (1,1), to model traffic accident severity (in terms of fatalities) in The Netherlands for the period 2003-2006, and to forecast the trend of the reduction of fatalities in the years 2007 and 2008 (based on the data of the previous four years). Error analysis shows that the applied model has a high degree of reliability. Therefore, it is concluded that GM (1,1) is applicable for short-term forecasting of this type of problem.


Aggregate properties are one of the important factors that influence the asphalt pavement skid resistance. This paper presents a detailed analysis of aggregate texture and its relationship to pavement skid resistance. A new method is developed for the evaluation of aggregate resistance to polishing. This method relies on the Micro-Deval test as the mechanism for polishing aggregates and the Aggregate Imaging System (AIMS) for quantifying the change in texture due to polishing. The results show that the Micro-Deval test is an effective method for polishing aggregates within a short time. Also, the AIMS texture analysis is able to rapidly and accurately quantify the influence of polishing on texture. The verification of the new method was achieved through measuring the skid resistance of pavements constructed using three different aggregate sources and three different aggregate gradations. The skid resistance was found to be related not only to average aggregate texture, but also to the texture distribution within an aggregate sample. The developed method can be used in models for predicting the change in asphalt pavement skid resistance as a function of aggregate texture, mixture properties, and environmental conditions.


The study examined the safety impacts of improving pavement skid resistance using data from New York State. The New York Department of Transportation (NYDOT) runs a skid accident reduction program that identifies sections of pavement with a high proportion of wet-road accidents, friction-tests these locations according to ASTM E-274 using the ASTM E-501 Ribbed Tire, and treats those with both a high proportion (35-40%) of wet-road accidents and low friction numbers (<32). An empirical Bayes before after study was conducted of locations that were treated under this program. The results indicate that this can be a highly cost-effect safety treatment for both intersections and road segments that warrant skid resistance improvement because of a high frequency of wet road accidents and low friction numbers.


This scan, cosponsored by the American Association of State Highway and Transportation Officials (AASHTO), the National Association of County Engineers (NACE), and the Federal Highway Administration (FHWA), was conducted to document and disseminate information on good practices by State Departments of Transportation.
(DOTs) and local agencies to integrate safety improvements into resurfacing and pavement restoration projects. Agencies have multiple objectives and limited resources. Programs and projects are developed to balance competing needs and limited funds. Integrating safety improvements into resurfacing is a resource-efficient method of pursuing infrastructure and safety goals. Resurfacing programs are not the only mechanism through which safety improvements are implemented. Further, resurfacing programs cannot be the means by which all existing highways are upgraded to meet all current criteria and standards related to geometry, traffic control, and safety appurtenances; however, incorporating selected, cost-effective safety improvements in resurfacing and restoration projects can provide extended public benefits. Attributes of successful programs include:

- The agency's resurfacing program is considered to be an element of its overall safety strategy.
- Agency leadership supports an integrated resurfacing-safety strategy.
- Funding of integrated safety improvements is recognized as an appropriate expenditure.
- Safety improvements are targeted and cost-effective.
- "Scope creep" does not interfere with timely resurfacing.

Integrated resurfacing-safety programs don't come into existence instantaneously. Successful programs are developed over time and may be akin to a journey that involves changing organizational paradigms and culture. The States and counties visited are all on a journey to the goal of well-integrated programs. Some agencies are further along than others. This report encompasses both how (i.e., process) integrated programs function and what is being accomplished (i.e., completed projects). It is written primarily for Federal, State, and local agency personnel in appointed and career executive positions, bureau and district/region managers that have a role in establishing direction and priorities within transportation agencies.


Nearly 25 percent of fatal crashes occur at or near a horizontal curve. Hence, addressing the safety problem at horizontal curves is one of 22 emphasis areas of the Strategic Highway Safety Plan prepared by AASHTO. Also, crashes at horizontal curves are a big component of the road departure crash problem, which is one of FHWA’s three focus areas. This publication was prepared to provide practical information on low-cost treatments that can be applied at horizontal curves to address identified or potential safety problems. The publication concisely describes the treatment, shows examples; suggests when the treatment might be applicable; provides design features; and where available, provides information on the potential safety effectiveness and costs. The treatments include:

- Basic traffic signs and markings found in the MUTCD.
- Enhanced traffic control devices.
- Additional traffic control devices not found in the MUTCD.
- Rumble strips.
- Minor roadway improvements.
- Innovative and experimental treatments.

The publication concludes with a description of maintenance activities that should be conducted to keep the treatments effective.

Midwest Regional University Transportation Center (MRUTC). “Incorporating Road Safety into Pavement Management: Maximizing Surface Friction for Road Safety Improvements.” (Research in Progress)

The objective of this research is to integrate road safety and pavement management strategies. Specifically, objectives include: (1) Determine the relationship between skid resistance and traffic safety; (2) Develop asphalt pavement mix design strategies that consider skid resistance as its primary measure of effectiveness; (3) Identify existing prediction models for skid resistance, propose modifications to models, and identify minimum skid resistance ranges to trigger the need for roadway maintenance; and (4) Incorporate skid resistance and safety in a pavement asset management tool. Traffic crashes and the associated injuries and fatalities continue to be a significant problem for transportation professionals. In 2001, 37,795 motor vehicle fatalities were reported in the United States as a result of over 6.3 million crashes (1). Over one-third of these crashes included personal injury to at least one of the vehicle occupants. The Region 5 states accounted for 6,360 of the 42,116 transportation fatalities in 2001, approximately 15 percent of the national total. Although numerous safety measures have been implemented in recent years, ranging from stricter safety laws and public awareness campaigns to roadway and
traffic control device improvements, total crashes and fatalities per year continue at unacceptable rates. Little has been done to incorporate safety into the pavement management and maintenance decisions that are made. Nevertheless, the results of numerous road crash investigations and statistical analysis have suggested that there is a relationship between crash frequency and pavement surface conditions. This relationship is not well understood. A vehicle that has lost contact with the pavement and entered a skidding maneuver is a safety hazard to drivers. High pavement skid resistance properties resulting in minimized skid lengths can be significant in reducing or eliminating the magnitude of a crash impact. Skid resistance can also be significant is keeping vehicles on the roadway during aggressive horizontal and lateral movements. The method used today for measuring resistance to skidding is measuring the friction provided by the surface to a typical tire traveling at a specified speed, under selected climatic and surface wetting conditions. There is a fair amount of variability within the specifics of these methods. It is well recognized that skidding is a phenomenon related to both the tire and surface characteristics. Normal load (weight), tire tread, temperature, and water all affect skidding. Thus it is essential to use standardized tires and conditions to compare resistance offered by surfaces to skidding.


The previous skid resistance standard was introduced was introduced into Scotland in 1994 since that time, major changes in the levels and type of traffic flow have occurred in Scotland. In particular, there has been a significant increase in traffic volumes, changes in the composition of the traffic with increasing numbers of four wheel drive sport utility vehicles, van like people carriers, and developments to the braking and suspension systems Therefore, in 2003 Transport Scotland decided to review the current standards. As part of this review not only were the current investigatory levels considered but also the site categories were reviewed to determine if a number of new site categories including approaches to: Lay by’s, Bus Stops, on and off Slips and exits to garages, should be included in the standard.

By analyzing the accident rates and densities at different sites categories and at different skid resistances, it was possible to determine a set of optimum investigatory levels. It was found from this study that there was no justification for adding the new site categories. Benefit cost calculations were undertaken and it was found that there was economic justification for implementing a number of revised investigatory levels. The results were discussed with TRL who were commission by the Highway Agency to undertake a similar study for the English trunk roads and it was found that with few compromises a single standard could be established for England and Scotland and a revised standard HD28/04 was implemented in 2004.

A procedural manual was written with the aim to provide clear unambiguous procedures for Managing the Skid Resistance of the Road Surface on the Scottish Trunk road system. This manual was released in September 2004 and since then, there has been various changes made and it is anticipated the manual will be rewritten to incorporate these changes in 2008. It should be noted that there are some changes between the Scottish procedures and those used in England. The key points of the Scottish procedures are outlined in the paper.


No abstract available.


The determination of skid resistance requirements is reported. The study focuses on wet pavement skidding accidents at intersections and curves. The feasibility of implementing these procedures was demonstrated in the field. A simplified version of the procedures was also developed. The three steps involved in the procedure for determination of skid resistance requirements are outlined. The system developed for measurement of longitudinal acceleration at intersections is based on the use of series of event detectors to determine the time-position signature of a vehicle over some known distance, from which acceleration values can be computed. Data was collected for an average of 350 vehicles at each of 12 intersections. Controlled skid studies were conducted to determine the relationship between longitudinal acceleration and skid resistance requirements. A simplified intersection demand model (IDM) for estimating skid resistance is desired. This is based on the apparent normality of distribution of

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observed deceleration values at the various distance intervals form the stop line of the 12 sites studied. The findings indicate a strong relationship between pavement skid resistance and locked wheel braking deceleration. Accelerations and speeds of vehicles braking at intersection are normally distributed; they exhibit stable standard deviations. A relationship exists between average approach speed and skid resistance requirements. Considerably more extensive field evaluations are necessary to verify the applicability of the procedures.


The American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan identified 22 goals to pursue in order to significantly reduce highway crash fatalities. One of the plan’s hallmarks is to comprehensively approach safety problems. Goal 15 in the Strategic Highway Safety Plan is Keeping Vehicles on the Roadway, and Goal 16 is Minimizing the Consequences of Leaving the Road. Subsequently, three emphasis areas evolved from these two goals: (1) Run-off-road (ROR) crashes, (2) Head-on crashes, and (3) Crashes with trees in hazardous locations. ROR crashes involve vehicles that leave the travel lane and encroach onto the shoulder and beyond and hit one or more of any number of natural or artificial objects, such as bridge walls, poles, embankments, guardrails, parked vehicles, and trees. Reducing the likelihood that a vehicle will leave the roadway through roadway design (e.g., flattening curves or installing shoulder rumble strips) prevents deaths and injuries resulting from ROR crashes. To reduce the number of ROR fatality crashes, the objectives should be to keep vehicles from encroaching on the roadside, minimize the likelihood of crashing or overturning if the vehicle travels off the shoulder, and reduce the severity of the crash.


One of the hallmarks of the AASHTO SHSP is to approach safety problems in a comprehensive manner. The range of strategies available in the guides will ultimately cover various aspects of the road user, the highway, the vehicle, the environment, and the management system. Two guides in the NCHRP Report 500 series discuss intersections: this volume covers signalized intersections, and Volume 5 discusses unsignalized intersections. This implementation guide provides guidance to highway agencies that desire to implement safety improvements at signalized intersections and includes a variety of strategies that may be applicable to particular locations.

Signalized intersections are generally the most heavily traveled intersection types and are therefore a major element of the highway fatality and crash problem nationally. Signalized intersections are operationally complex, with many factors contributing to the potential safety problems. The intent of a signal is to control and separate conflicts between vehicles, pedestrians, and cyclists to enable safe and efficient operations. Operation of a signal itself, however, produces conflicts (e.g., conflicts between through vehicles that could lead to rear-end crashes). In addition, varying signal operations (timing and phasing) place demands on drivers that are not always met. While the focus of the strategies discussed in this guide is on reducing fatalities at signalized intersections, the implementation of many of these strategies will likely lead to an overall reduction in intersection crashes. The objectives and the related strategies for improving safety at signalized intersections are explained.


This digest identifies liability risks associated with sharing safety data among transportation agencies pursuant to Section 409 of Title 23, U.S.C.; identifies best practices; reviews the Pierce County, Washington v. Guillen decision and its potential impact on managing state liability risk; and describes strategies for overcoming the impediments to data sharing, specifically those related to liability. Transportation lawyers and risk management practitioners for the states, metropolitan planning organizations (MPOs), and transportation planning organizations may find this digest useful.

Based on a scan of U.S. universities, the study reveals to what extent core competencies for highway safety professionals are incorporated into existing safety curricula and suggests strategies to expand their application to a broader audience. The core competencies, developed under this project, will be useful to managers identifying the knowledge, skills, and abilities an organization as a whole requires, adjusting job descriptions and announcements, and working with other departments and managers to hire for these skills. Supervisors may also use the competencies to assess the level of the team’s skills and make recommendations for individual training and assignments. The competencies include: (1) understanding the management of highway safety as a complex multidisciplinary system; (2) understanding of and the ability to explain the history of highway safety and the institutional settings in which safety management decisions are made; (3) understanding the origins and characteristics of traffic safety data and information systems to support decisions using a data-driven approach to managing highway safety; (4) (a) demonstrating the knowledge and skills to assess factors contributing to highway crashes, injuries, and fatalities; (b) identifying potential contributing factors; (c) applying countermeasures to user groups or sites to reduce crashes and injuries; and (d) implementing and evaluating the effectiveness of the countermeasures; and (5) developing, implementing, and managing a highway safety management program.


In this annual report, Traffic Safety Facts 2003 – A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System, the National Highway Traffic Safety Administration (NHTSA) presents descriptive statistics about traffic crashes of all severities, from those that result in property damage to those that result in the loss of human life.


Traffic crashes and the associated injuries and fatalities continue to be a significant problem for transportation professionals. In 2001, 37,795 motor vehicle fatalities were reported in the United States as a result of over 6.3 million crashes (1). Over one-third of these crashes included personal injury to at least one of the vehicle occupants. The Region 5 states accounted for 6,360 of the 42,116 transportation fatalities in 2001, approximately 15 percent of the national total. Although numerous safety measures have been implemented in recent years, ranging from stricter safety laws and public awareness campaigns to roadway and traffic control device improvements, total crashes and fatalities per year continue at unacceptable rates. Little has been done to incorporate safety into the pavement management and maintenance decisions that are made. Nevertheless, the results of numerous road crash investigations and statistical analysis have suggested that there is a relationship between crash frequency and pavement surface conditions. This relationship is not well understood.

A vehicle that has lost contact with the pavement and entered a skidding maneuver is a safety hazard to drivers. High pavement skid resistance properties resulting in minimized skid lengths can be significant in reducing or eliminating the magnitude of a crash impact. Skid resistance can also be significant is keeping vehicles on the roadway during aggressive horizontal and lateral movements. The method used today for measuring resistance to skidding is measuring the friction provided by the surface to a typical tire traveling at a specified speed, under selected climatic and surface wetting conditions. There is a fair amount of variability within the specifics of these methods. It is well recognized that skidding is a phenomenon related to both the tire and surface characteristics. Normal load (weight), tire tread, temperature, and water all affect skidding. Thus it is essential to use standardized tires and conditions to compare resistance offered by surfaces to skidding.


This synthesis will be of interest to state transportation agency personnel, as well as to others who work with them in the area of safety. It provides information for state departments of transportation (DOTs) on new technologies for the acquisition, processing, and overall management of crash, roadway inventory, and traffic operations data. The objective was to summarize the current state-of-the-practice and state-of-the-art use of technologies for efficient and
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

effective collection and maintenance of data for highway safety analysis. Information is presented about the U.S. DOT developing new safety and analysis tools to help state DOTs identify safety problems and countermeasures to increase highway safety. States are limited in their abilities to make informed decisions about the allocation of scarce safety resources because many states lack the database elements and linkages between databases to compile the data sets required by the new safety analysis tools. This synthesis effort contains information received from three individual surveys, developed to gather state-level information about the core safety data areas--crash, traffic operations, and roadway inventory. These surveys yielded approximately 60 returns from 34 different state DOTs and, along with a literature review, Internet search, and follow-up telephone contacts and interviews, generated the information used in this synthesis.

Ohio Department of Transportation (ODOT). 2006. Crash Base Rates for Intersections. Final Report. Ohio Department of Transportation, Columbus, OH.
The objective of the study is to develop a process or processes to ensure intersection crashes are analyzed based on intersection geometrics, traffic control and environmental factors. The validity of the process will be established and intersection crash base rates will be developed by studying appropriate variables for intersection crashes. The project tasks include analyzing at least the following variables for their affect on intersection crash rates:

- Roadway categories such as 2-lanes; 4-lanes divided/undivided
- Types of intersections such as 3-legged, 4-legged and 5-legged intersections with different number of lanes in each approach and with or without left/right turn lane
- Types of traffic control such as 2-way stops, 4-ways stops, overhead flashes, traffic signal with left turn phases and with or without exclusive turn lanes
- Number of lanes per approach, lane width, shoulder width, angle of approach
- Posted speed limit
- Number of residential/business driveways within the influence of intersection
- Horizontal/vertical curve influence on crashes at various types of intersections within certain distances from intersection
- Population density within 1 mile of intersection
- Number of vehicles entering the intersection, and effect of truck ratio if any
- Type of crashes related to various types of intersections
- The above list is not meant to be exhaustive. It is provided to illustrate that the research approach is expected to be broad and inclusive of all pertinent variables.

Ohio Department of Transportation (ODOT). 2006. Ohio’s Road Map to Fewer Fatalities. Ohio Department of Transportation, Columbus, OH.
Safer highways are at the heart of Ohio’s Road Map to Fewer Fatalities – a comprehensive highway safety plan, which has been developed by safety advocates and citizens throughout Ohio. The document is a tool that outlines the greatest threats to highway safety and identifies new strategies designed to lower the number of crashes, injuries and deaths that occur each year on Ohio highways. This document is considered comprehensive because it asks government agencies and safety advocates to work across jurisdictional boundaries to address crash problems regardless of where they occur. The document represents a broad approach to improving highway safety by drawing upon engineering, enforcement and educational strategies to prevent crashes. It also strengthens the relationship with emergency response and health care professionals, who respond to crashes and rehabilitate the injured. Their input can add new insight into the human and financial costs of crashes, which may influence how we prioritize and attack crash problems. This document also serves to complement hundreds of existing programs, projects and initiatives that have been developed and funded by federal, state and local agencies to improve roadway safety throughout Ohio.

Ohio Department of Transportation. “Continuing Investigation of Polishing and Friction Characteristics of Limestone Aggregates in Ohio.” (Research in Progress)
Asphalt concrete pavements gradually lose their skid resistance, creating a serious safety concern, especially when pavements are wet. As the driving speed and the Average Daily Traffic (ADT) increases, the chances of having skid-related accidents also increase rapidly. Thus, the Federal Highway Administration (FHWA) has issued a Wet Skid Accident Reduction Program to encourage each state highway agency to minimize wet weather skidding
accidents by identifying and improving the sections of roadways with high occurrences of skid accidents and by developing new surfaces which would have adequate and durable skid resistance properties. The objectives of Continuing Investigation of Polishing and Friction Characteristics of Limestone Aggregates in Ohio are to: (1) develop new accelerated polishing equipment for Superpave HMA to facilitate rapid simulation of wear and polish actions between the vehicle tires and asphalt pavement surface; (2) develop a complete test protocol to include sample preparation method, test sequence, data precision and bias analysis, and acceptance criteria; (3) develop recommended specifications for the new test methods; and (4) conduct training and transfer equipment to the Ohio Department of Transportation (ODOT) Bituminous Lab.


The project aim is to develop strategies and tools to help MRWA ensure that maintenance contractors provide appropriate levels of skid resistance throughout the network. Current skid resistance monitoring programs and investigatory levels used in Australia are derived from systems developed in the U.K. and these are unlikely to suit WA conditions. They have high cost implications in terms of monitoring, and in maintaining surfacings at inappropriately high skid resistance levels. The first part of the report addresses the development of investigatory levels for the British Pendulum Tester (BPT) since MRWA has BPT intervention levels incorporated into its Term Network Contract (TNC) specifications. Background information on the development of the Austroads and U.K. investigatory levels is provided. The second part of the report considers the desirability of replacing skid resistance investigatory levels with macrotexture levels for high speed roads. Several studies (U.K., Australia, France) all showed a strong correlation between accident rate and macrotexture. It is thought that high macrotexture permits increased levels of hysteretic (deformation) friction to be developed by vehicle tires thus permitting them to avoid accidents. A macrotexture requirement may be more effective in reducing accident rates on high speed roads (where the effect of hysteretic friction is greatest) than a skid resistance (SCRM) requirement. It is recommended that MRWA consider adoption of the BPT values presented in the report and consider the adoption of a 1.0 mm macrotexture investigatory level for high speed roads.


Policy makers too often have chosen to ignore the efficacy of science-based highway safety countermeasures in favor of education-based efforts, which rarely change user behavior, according to the author of this article who is a leader in highway safety research. The author concludes that progress on road user issues, such as belt use, motorcycle helmet use, alcohol-impaired driving, and speed, will depend on political action at the state level.


The use of grooving in pavement surface is a common approach to improve wet weather skid resistance and reduce hydroplaning risks. Field measurements have found transverse grooves effective in significantly improving skid resistance and reducing the occurrences of hydroplaning. On the other hand, despite reported wet-weather accident reduction effectiveness of longitudinal grooving, most experimental studies did not record any significant increase in the measured skid resistance of longitudinally grooved pavements. This paper presents an analytical study to evaluate the relative effectiveness of the two types of grooving in terms of their ability to reduce hydroplaning potential, and their respective skid resistance available at the onset of hydroplaning. The groove dimensions examined cover groove widths from 2 to 10 mm, groove depths from 1 to 10 mm, and center-to-center spacing from 5 to 25 mm. It is found that in terms of the ability to rise hydroplaning speeds (i.e. to lower hydroplaning risks) and skid resistance values, transverse grooving consistently produced much better results than longitudinal grooving. The simulation results confirm that for longitudinal grooving with dimensions within the practical ranges, there are only marginal improvements in both hydroplaning speed and skid resistance in the longitudinal directions. However, an analysis by the simulation model indicates that, unlike a smooth plane surface, which has the same skid resistance properties in all directions, longitudinally grooved pavements have significantly higher skid resistance as the skidding direction deviates from the true longitudinal direction. The quantitative simulation analysis suggests that this has the effect of enhancing traction to keep skidding vehicles within the roadway and to cut down wet-pavement accidents, a result that has been widely observed in field applications of longitudinal grooving.

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The current means of predicting the skid resistance of a wet pavement and the speed at which hydroplaning would occur are based on empirical models or relationships derived from experimental studies. These model and relationships are applicable only for the conditions specified, and extrapolations beyond the applicability range of parameters (e.g. range of vehicle speeds, tire loads, tire inflation pressures, water-film thickness, types of tires and pavement surfaces) are not advisable. Such restrictions could be overcome by developing an analytical model derived based on theoretical considerations. An analytical model would also provide a more in-depth understanding of the relative influence of different parameters. This paper presents a three-dimensional finite-element model to predict wet-pavement skid resistance and hydroplaning speeds under different magnitudes of passenger car wheel load, tire inflation pressure, water-film thickness and vehicle speed. The analysis shows that hydroplaning speed increases (i.e. hydroplaning risk decreases) with wheel load and tire inflation pressure, but decreases with the depth of water-film thickness. The skid resistance measured in terms of skid number decreases as the sliding wheel speed or the water-film thickness increases, but increases with the magnitude of wheel load and is affected marginally by the tire inflation pressure. Within the normal passenger car operation range of each of the parameters, the hydroplaning is affected most by tire inflation pressure, followed by water-film thickness, and is least influenced by the wheel load; while the skid resistance is most influenced by wheel sliding speed, followed by water-film thickness and wheel load, and is least affected by the tire inflation pressure.


Traffic noise has become a major concern in the last decade and many states have been looking for solutions to reduce noise levels. Reducing noise levels by proper selection of surface type may provide an alternative to sound walls. California Department of Transportation (Caltrans) has been using different open-graded mixes to reduce highway noise levels and to improve wet weather driving conditions. Before placing more open-graded mixes, there is a need to identify their noise reduction properties, durability, and safety, and to compare these with other asphaltic mixes. In 2005, Caltrans initiated a long-term program to investigate and monitor field performance of different open-graded mixes and other commonly used asphalt surface mixes.

This paper summarizes part of the first-year measurements of relevant parameters from asphalt pavements with different surface mixes. It was found that open-graded mixes generally reduce the tire/pavement noise level, and the amount of reduction is correlated with air-void content and surface texture. However, the noise-reduction benefit may be lost with the increase of pavement age.


This study was conducted to develop base crash rates for intersections in Ohio. The models were developed for the following crash types: (1) injury crashes, (2) PDP crashes, (3) total crashes, (4) wet crashes, (5) night crashes, (6) rear-end crashes, (7) sideswipe crashes, (8) fixed object crashes, and (9) left turn crashes. The base crash rates models considered different type of traffic control for different type of intersection approaches (legs), such as signalized intersection legs and no control legs at one-, two-, three-, and four-way intersections. The variables included in the analysis were number of left turns, number of through lanes, population density, speed limit, and average daily traffic (ADT). A master database was prepared by using data available form ODOT and data manually extracted from photologs by the researchers. To evaluate the complex interaction among the dependent and independent variables, Automatic Interaction Detection (AID) technique was used. Finally, based on stepwise multiple regression technique, the regression equations were developed to determine statewide base crash rates.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations


Recognizing the importance of providing safe pavements for travel during wet weather, highway agencies have established programs to provide adequate pavement friction. The Federal Highway Administration Technical Advisory T 5040.17, Skid Accident Reduction Program, which was issued in 1980, provides guidance to State and local highway agencies in establishing a skid accident reduction program. The main purpose of a skid accident reduction program is to minimize wet weather skidding accidents by: ensuring that new surfaces have adequate and durable skid resistance properties, identifying and correcting sections of roadway with high skid accident incidence, and utilizing resources available for accident reduction in a cost-effective manner. This synthesis summarizes skid accident reduction programs/practices of several State and foreign highway agencies. The synthesis also presents an overview of the components of a comprehensive skid accident reduction program.


No abstract available.


No abstract available.


There is a perception that transportation professionals can do little about adverse weather effects because it is “Mother Nature”. Accordingly, most of the weather responsive strategies are reactive such as speed management, access control and other operational practices. In fact, particular weather factors should be considered during the design, perhaps even the project planning stages, to avoid large remedial costs. The objective of this study is to develop a pragmatic safety audit process and procedure in which roadway and weather-related issues can be addressed proactively.

The paper introduces the development of the road safety checklist with the emphasis on potential weather influence on highway safety. A total of five road safety audit checklists were developed for a series of stages from the project development to the project completion: Feasibility Stage; Preliminary Stage; Detailed Design Stage and Pre-Opening Stage. Consistency and usability were key elements in the checklists development. A quantitative method is also provided to assist auditors in evaluating the severity of road weather safety problems. Meanwhile, this paper proposes an approach to institutionalizing the road weather safety audit by incorporating the road safety audit procedure as part of the Facilities Development Manual (FDM), which is the departmental procedure guidance for the development of road projects in Wisconsin.


Current UK standards for skidding resistance and texture depth are based on studies carried out in the 1970s, which showed that low-speed skidding resistance depends upon the microtexture of the road surfacing, but as speed increases, the skidding resistance falls, depending on the texture depth. In 1995, the Highways Agency commissioned further research in order to reassess the earlier work, particularly the influence of texture on the relationship between high- and low- skidding resistance, for the wide range of surfacings now used on UK trunk roads. A K J Law T1290 Pavement Friction Tester (PFT) was purchased by the Highways Agency, for this new study. The equipment has been used to make measurements of locked-wheel friction over a range of speeds from 20 to 130 km/h. Measurements have been made on more than 130 sites covering a wide range of types of surfacing, levels of texture and skidding resistance. The report presents the results of the first phase of analysis, which show clearly the loss of friction with increasing speed and confirm that this is more marked for surfacings with low texture.
depth. Significant findings were that texture has a greater impact on loss of friction at lower speeds than previously thought and that the effect is similar for both random-textured and transverse-textured impermeable surfacings.


No abstract available.


This paper discusses the issues relating to the calibration and comparison of skid resistance measurement devices, particularly in fleet operation. It reviews UK experience of over fifteen years of controlling a fleet of SCRIM machines in use providing survey data for comparison with skid resistance standards of the national road network. This includes the approach taken to setting and applying acceptance criteria, and briefly compares this with the approach taken in some other European countries in relation to the devices that they use. The paper also discusses the problems of correlating devices that operate on different principles, drawing on UK experience with GripTester and the Pavement Friction Tester. Additionally, the paper discuss the practical experience gained from the recent HERMES project in Europe conducted by FEHRL (Forum of European National Highway Research Laboratories) that evaluated a proposed standard process for harmonization of friction measurement devices.


The project was sponsored by the Illinois Concrete Council and had the following goals: (1) research of previous work on vehicle safety aspects of pavement surface defects, particularly, rutting and washboarding, and (2) implementation of a testing program based upon the panic stop test and report of the results. The testing program was aimed (1) to show the relative behavior of several typical domestic sedans (Chevrolet and Buick), and (2) determine if the results obtained are consistent with previous results reported in the scientific literature.


This EI describes the Department’s Skid Accident Reduction Program (SKARP) component of safety related asset management activities. This program identifies wet road accident locations on state owned roadways and arterials, friction tests them, and treats those locations which are experiencing both wet road accidents and pavement friction below the Programmatic Design Target Friction Number (PDTFN). Each year, the Traffic Engineering and Highway Safety Division identifies high wet road accident locations on State owned roadways and arterials, and produces a Wet Road Accident Priority Investigation Location (PIL) listing. Locations on the Wet Road Accident PIL listing are friction tested by the Technical Services Division. The Wet Road Accident PIL listing, and the results of the friction tests, are both forwarded to the Regions for consideration in the Regions’ capital programming and Preventive Maintenance Paving activities.


Skid resistance is an important factor in a rational maintenance program for pavement surfaces. Therefore, the skid resistance of a road surface is monitored by maintaining skid resistance inventories; in addition, spot checks are made at high accident sites. The equipment, called the dynamic friction tester (DF tester), is a disc-rotating-type tester that measures the friction force between the surface and three rubber pads attached to the disc. The disc rotates horizontally at a linear speed of about 80 to 20 km/hr under a constant load, so the DF tester can measure the skid resistance at any speed in this range with a single measurement. At the same time, the results provide speed dependency of skid resistance that will be as close as possible to the results obtained by other testing modes. The DF tester can measure on flat as well as rutted surfaces, the depths of which are less than 6 mm. In that case, the coefficient of variation is found to be less than 10%. The long-term characteristics of the coefficient of friction were measured by the DF tester, the British pendulum tester and the mini-texture meter. The coefficient of friction increases moderately with the traffic service period (up to 35 weeks) and decreases with increasing speed. The test results showed a significant speed dependency on the coefficient of friction measured by the DF tester although
there was a high relationship between the coefficient of friction of the DF tester and the British pendulum number at each point and at each measuring speed. A weak relationship was found between the coefficient of friction and the sensor-measured texture depth values produced by the texture meter. Results of the Permanent International Association of Road Congresses experiment to compare and harmonize texture and skid resistance measurements indicate that the DF tester is capable of reporting the friction component (F60) of the international friction index using the friction coefficient at 60 km.


Questions concerning the effect of skid resistance on traffic accidents, particularly by wet pavements, have been investigated in various research projects for many years. Apart from separation of the influence of skid resistance from other influence factors, one of the main issues in all these studies has repeatedly been the quantifying of the correlation between skid resistance and accident occurrence. The goal was finding a threshold or minimum value for the skid resistance. Whereas elder studies show quantified correlations between skid resistance and accident occurrence, recent research results tended to put these in question.

Based on a large data set regarding freeways and a pilot study regarding main roads the present study shows that it was not possible to identify any such relation between skid resistance and accident occurrence for either wet or dry pavements. It was not possible to formulate no quantifiable correlation in this regard. It could, however, be found out that a systematic search for notable areas where very low skid resistance values with high accident frequencies by wet pavement coincide is extremely worthwhile, as it serves to identify individual, randomly distributed danger zones. These can then be subjected to investigations that are more detailed.


This paper relates to an investigation into the performance of high skid resistant road surfaces with regard to the impact on traffic crash trends. This study built on previous work which investigated the total numbers of crashes and trends at specific sites. The investigation showed the high skid resistant treatments were effective in reducing the number of crashes, using up to 5 years of ‘before’ and up to 5 years of data ‘after’ placement.

The objective of this project was to investigate any trends for the types of crashes for ‘before’ and ‘after’ the high skid resistant surface was placed. The project investigated twenty-three high skid resistant treatments within Melbourne and Geelong, Australia. The investigation found the following trends in crashes:

- An overall reduction in crashes of 39% on the treated areas.
- High friction surface treatments were very effective in reducing loss of control crashes on high speed curves with free-flowing traffic.
- High friction surface treatments appear to be more effective when placed on the approach and centre of signalized intersections compared to sites with the treatment on the approach only.
- The sites in the project showed a slight increase to more serious injury crashes, and the high friction surface treatments followed this trend.
- A minority of sites displayed an increase in crashes and a larger increase in severity of injury.
- Although the total number of crashes was reduced, the proportion of different types of crashes remained the same.
- The skid resistant treatments altered the wet/dry road accidents ratio, and reduced the number of wet road crashes.


The United Kingdom skid resistance policy was published in December 1987 as Departmental Standard HD15/87 and was applicable to all Trunk Roads and Motorways. The policy required the whole of the network to be monitored using a Sideway-force Coefficient Routine Investigation Machine, SCRIM. The standard was innovative and introduced concepts of investigatory rather than intervention levels. At any location on the network where the skidding resistance became equal to or fell below the investigatory level, an investigation was required to determine
if treatment to improve its skidding resistance was justified. The recognition that the level of skidding resistance required to provide an equal risk of a wet road skid occurring would need to vary along a road depending on the geometry of the road and other factors. The varying characteristics were defined in terms of 13 SCRIM site categories e.g. dual carriageway no-event, single carriageway no-event, approach to major junction, bend of less than 250m, etc.

The aforementioned concepts have been proved and they remain features of the revised standard published as HD 28/04 in 2004. A major feature of the new standard is the greater range and detail of the advice included to guide those responsible for providing adequate skid resistance in the application of the standard. Clear advice and guidance is provided in setting investigatory levels and carrying out investigations to determine if treatment is required. This paper describes the development of the new standard, considers the main parameters to be considered when setting investigatory levels and carrying out site investigations and explains the costs and benefits that will accrue from its introduction.


Twenty years after the introduction of Standards for aggregates used in road surfacing materials and for in-service skid resistance, it is clear that these approaches have been widely adopted and have produced a number of benefits, including better skid resistance and an acceptably low level of claims arising from slippery surfaces. However, benefits in terms of accident reduction have not been quantified adequately, and so it is difficult to assess whether the anticipated benefits of these Standards are being delivered in practice. This paper reviews the extent to which these Standards have been successful, and identifies a need for better information to be gathered to facilitate monitoring of in-service skid resistance and to support quantification of accident benefits.


This report presents an overview of the major aspects of tire-pavement interaction as they relate to highway noise, safety, and economics. The many sources of sound in the highway environment are described and the perception and measurement of noise are discussed. The measurement of roadway friction and the impact of pavement texture on highway safety are described. Techniques for controlling sound form the highway environment are also discussed, including the use of noise walls and barriers and the management of pavement surface characteristics. The noise, safety characteristics and cost-effectiveness of traditional and newer concrete pavement materials and surface textures, including turf drag, longitudinal tining, exposed aggregate, porous concrete, diamond grinding and others, are described and documented through summaries of studies from around the world. Techniques for balancing noise, safety, economics and other factors in the selection of pavement surface type and texture are also reviewed.


This paper will describe the process whereby SCRIM data and the associated Investigation Levels (IL) derived from the joint Cornwall County Council (CCC) / WDM work (as set out in the complementary paper by Stephenson et al) are used to determine the default base level skidding resistance for the network; it will then deal with the process of validating, investigating and quantifying the true level of deficiency at a given location and present one possible method of establishing a prioritized list of sites for treatment and alternative means of managing the risk of wet weather skidding on a live highway network.

The paper will draw on the work undertaken within CCC’s Asset Team arising from the revision of SCRIM IL’s brought about by the authority’s response to the Highway Agency’s 2004 revision of HD 28; the subsequent impact on a predominantly unimproved rural network and the need to effectively manage risk in a period of restricted maintenance funding.

The growing use of GIS-based packages in planning practice is assisting in the development and implementation of methods that facilitate safety consideration in transportation planning. This paper presents a method of predicting safety for planning alternatives. Although applicable to large road networks, the method predicts crashes at the road facility level (intersections and segments), which makes it suitable to jointly evaluate modifications of the road network, changes in network traffic flows, and improvements in road geometry considered by planners. A complete set of crash prediction models were developed by the authors for seven types of road segments and four types of road nodes based on crashes reported on Indiana highways in 2003-2005. A mainstream research method has been used - Negative Binomial regression with a stepwise variable selection method with the AIC criterion. The obtained equations are transparent to transportation planners and allow efficient computations for large road networks.


Improving road safety through proper pavement engineering and maintenance should be one of the major objectives of pavement management systems. When pavements are evaluated in terms of safety, a number of factors related to pavement engineering properties are raised, such as pavement geometric design, paving materials and mix design, pavement surface properties, shoulder type, and pavement color and visibility. Each year there are voluminous annual reports on traffic accident statistics and discussions of such road safety issues as road safety modeling and pavement safety measurements and criteria. Although road safety may be considered a separate area, it should be incorporated into pavement management systems. The main pavement engineering relationships associated with road safety are identified, and the various aspects of road safety related to pavement management, such as pavement types, pavement surface macrotexture and microtexture, and pavement safety measurements, criteria, and evaluation methods, are discussed. A systematic approach is proposed for the coordination of pavement maintenance programs with road safety improvement and the incorporation or integration of safety management with pavement and other management systems. Finally, a list of possible remedial measures for road safety improvements associated with pavement maintenance activities is recommended.


Solving the U.S. highway safety problem is a task for everyone--local, state, and federal departments of transportation; legislative groups at all levels; national, state, and local safety organizations; insurance companies; citizen groups; utility companies; road contractors; and road users. It requires a concerted, collective will, the author maintains, citing ways to identify many problems and to apply simple and inexpensive corrections.


A major goal of the Long-Term Pavement Performance (LTPP) study is the development of recommendations for improving the design and construction of new and rehabilitated pavements to make them longer lasting. As part of the condition monitoring of the LTPP test sections, friction data are being collected on a regular basis at each test site. Friction data collection is the responsibility of the specific highway agency under whose jurisdiction the pavements are located. The LTPP data collection guidelines for friction data recommend using the ASTM E 274 (AASHTO T242) procedure as the preferred method for obtaining data. The ASTM E 274 procedure uses a locked-wheel skid tester in a trailer assembly. Friction test results are reported as Skid Numbers (SNs). This report provides an assessment of the availability, characteristics, and quality of the friction data collected as part of the LTPP study. Also, the availability of related pavement characteristics data was assessed. The report also contains recommendations for adjustments and refinements to current procedures for the collection of friction and related data. The LTPP database provides a one-stop source of reasonably good friction data collected in a systemic manner from a wide range of pavements subjected to a wide range of traffic loading and environmental conditions. The
friction data will be of use for analyzing why some pavement surfaces retain good friction characteristics with time and why some surfaces show rapid deterioration in friction over time.

**Transportation Pooled Fund Program.** Reducing Crashes at Rural Intersections: Toward a Multi-State Consensus on Rural Intersection Decision Support. Study TRF-5(086). Minnesota Department of Transportation, St. Paul, MN.

This research will build on recent advances in intelligent transportation systems (ITS) technology to address a significant public safety problem. Rural Intersection Decision Support focuses on enhancing the driver's ability to successfully negotiate rural intersections. It is a system which will use sensing and communication technology to determine the safe gaps and then communicate this information to the driver so that he or she can make an informed decision about crossing the intersection or entering a major road traffic stream. Our goal is to reduce crashes and fatalities at such intersections without having to introduce traffic signals which on high speed rural roads often lead to an increase in rear end crashes.

The State of Minnesota is already partner with California, Virginia and the FHWA in a pooled fund consortium (the Infrastructure Consortium) dedicated to improving intersection safety. Three research teams have been identified: The Intelligent Transportation Systems Institute at the University of Minnesota, the PATH (Partners for the Advancement of Transit and Highways) Program at the University of California's Berkeley campus, and the Virginia Tech Transportation Institute at Virginia Polytechnic. Each member of the consortium is tasked with addressing an aspect of intersection safety; Minnesota's efforts focus on the problem of rural intersection crashes.

The Minnesota objective is to develop a better understanding of the causes of crashes at rural intersections and then develop a toolbox of effective strategies to mitigate the high crash rate. Preliminary information seems to point to the driver's inability to correctly identify and select the gap needed for safe passage. Efforts proposed in this program address rural intersection crashes through the application of a suite of advanced surveillance technology, algorithms which predict vehicle and gap location, and driver interfaces designed to best provide necessary information to drivers at intersections. 'Low tech' solutions will also be considered. The main program emphasis is on the integration of these key components into an effective, affordable system. The study will focus on alternatives to traditional traffic signals as a means to decrease the frequency and severity of rural intersection crashes.


America’s economy and quality of life depend on a transportation system that functions well. As with other major infrastructure systems that support society—for example, water or electricity—the importance of the nation’s transportation system becomes apparent only when problems arise. The destruction caused by Hurricane Katrina in August 2005 demonstrated the vital importance of transportation in the response to natural disasters and in recovery, as well as in connecting regional economies to the nation’s. The loss of terminals, pipelines, railroad lines, and bridges along the Gulf Coast, for example, had an immediate impact on the energy supply nationwide. Perhaps transportation’s successes over the past century explain why it does not make the national list. Although the rate of population growth—and therefore of travel demand—is projected to slow in the coming years, the increase in population will amount to approximately 100 million by 2040. This could double the demand for passenger travel. Moreover, the added population will concentrate in selected states and regions, which will intensify the demand for transportation in these areas. Meanwhile, the U.S. population will become older and more diverse. With the emergence of China, India, and Mexico as major trading partners, international trade as a proportion of the gross domestic product (GDP) has almost doubled to more than 22 percent in little more than a decade. Truck and containerized shipments may double by 2025 as the globalization of the economy unfolds. 5 Trade will become an increasingly important component of the U.S. economy, intensifying the demand for transportation.

With these considerations in mind, the Executive Committee of the Transportation Research Board of the National Academies has outlined the most critical transportation issues facing the nation in this first decade of the new century:

- Congestion: increasingly congested facilities across all modes.
- Emergencies: vulnerability to terrorist strikes and natural disasters.
- Energy and environment: extraordinary challenges.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

- Equity: burdens on the disadvantaged.
- Finance: inadequate revenues.
- Human and intellectual capital: inadequate investment in innovation.
- Infrastructure: enormous, aging capital stock to maintain.
- Institutions: 20th century institutions mismatched to 21st century missions.
- Safety: lost leadership in road safety.

The Executive Committee of the Transportation Research Board of the National Academies has outlined these issues to focus attention on the most significant policy decisions facing the country and on the areas most in need of innovation.


TRB’s Transportation Research Record: Journal of the Transportation Research Board No. 1908 examines the use of a linear optimization model to maximize the safety benefits from highway improvements under specific budget constraints and types of crashes at signalized intersections with complete crash data. This volume of the TRR: Journal also explores the events leading to a sport utility vehicle rollover, as well as countermeasures for deer–vehicle crashes.


This Transportation Research Record contains 10 papers on the subject of statistical methods and crash prediction modeling. Specific topics discussed include the following:

- Bayesian Multivariate Poisson Regression for Models of Injury Count, by Severity.
- Calibration of Safety Prediction Models for Planning Transportation Networks.
- Comparison of Two Negative Binomial Regression Techniques in Developing Accident Prediction Models.
- Describing the Evolution in the Number of Highway Deaths by Decomposition in Exposure, Accident Risk, and Fatality Risk.
- Effects of Sample Size on Goodness-of-Fit Statistic and Confidence Intervals of Crash Prediction Models Subjected to Low Sample Mean Values.
- Refinement of Accident Prediction Models for Spanish National Network.
- Use of Propensity Score Matching Method and Hybrid Bayesian Method to Estimate Crash Modification Factors of Signal Installation
- Using the Rural Two-Lane Highway Draft Prototype Chapter.


This Transportation Research Record contains 23 papers on the analysis and evaluation of safety data. Specific topics discussed include the following: assessing crash occurrence on urban freeways; crash estimation at signalized intersections; crash mitigation by variable speed limits; the relationship between real-time traffic surveillance data and rear-end crashes on freeways; real-time indicators of sideswipe crashes on freeways; a new approach to accident analysis of hazardous road locations; the influence of land use, population, employment, and economic activity on accidents; reanalysis of encroachment frequency data; rural expressway intersection characteristics; driver assistance systems evaluation by traffic simulation; estimating right-angle collision frequency at traffic signals; crash estimation at signalized intersections; in-vehicle data recorders; traffic signal warrants; intersections with potential for red light-related safety improvement; the severity of head-on crashes on two-lane rural highways; safety effect of daylight savings time; the safety effect of continuous shoulder rumble strips on rural interstates; experience with road diet measures; right turn from driveways followed by U-turn on four-lane arterials; linking databases for analysis of injury specifics and crash compatibility issues; safety of jug handle intersections; and the safety evaluation of the Stop Sign In-Fill program.
Tire-pavement friction and pavement surface texture are very important safety characteristics that need to be considered in pavement surface design and monitored throughout the life of the pavement. This paper compares friction measurements obtained with different equipment (three locked-wheel trailers with smooth and ribbed tires and one Dynamic Friction Tester) and at different speeds. Five tests in each lane at each speed were conducted on each of eight pavement sections with a wide range of surface textures. The paper also compared the relationship between friction and speed for the different pavement sections and devices and the International Friction Index values obtained using the different equipment and tires. The investigation showed that the repeatability of the various locked-wheel trailers evaluated was considered acceptable and that the reproducibility obtained with the same type of tire was also good at the various speeds considered. The correlation between the measurements using the locked wheel trailers with the smooth and ribbed tires did not correlate that well to each other, when all of the evaluated pavement surfaces were included in the analysis. In all cases the measurements obtained with the ribbed tire were higher than with the smooth tire. Finally, discrepancies in the IFI F60 values calculated for the different devices suggest that the original coefficients determined during the PIARC experiment may need to be adjusted for the device evaluated before the IFI can be implemented in the participating agencies.


When, in 1988, the UK Department of Transport first introduced requirements for skid resistance on its trunk road network, it introduced the concept of “investigatory levels” to be compared with measurements from routine skid resistance surveys. At the heart of this process was a link between the risks of wet skidding accidents occurring and the levels of measured skid resistance on the road. Initially, this was based upon a survey of a sample of the network at which the time was limited by survey capacity and computing power. The skidding standards have recently been revised and as part of this process, a new assessment of the link between accident risk and skid resistance has been made. This has involved a study of the whole Trunk Road network. This paper will review the historic background and then describe in more detail the recent study and its findings, how the results compare with the historic work and the changes that were shown to be appropriate for application in the revised standard introduced in August 2004.


The skid resistance policy for UK trunk roads has been reviewed after fifteen years of operation. As a result, a revision to the policy is being implemented in 2004, which is described in this paper. A key part of the review has been a re-examination of the link between skid resistance and accidents. This confirmed the importance of skid resistance but also the site specific nature of the effect. As a result of the advice on determining Investigatory Levels of skid resistance has been strengthened to promote better engineering judgment of skid resistance requirements and more robust investigation of sites where the skid resistance measurements are found to be below...
the Investigatory Level. The review has also resulted in changes to the survey strategy, use of slippery road warning signs and on-going monitoring of the effectiveness of the policy.


The United Kingdom has implemented a policy to manage skid resistance and skidding accidents on its road network. This paper describes the results of the accident analysis, which has led to a revision of the site categories and investigatory levels and changes to the way that potential maintenance schemes will be evaluated. Information about pavement conditions, road geometry, and accident data was correlated to skid resistance information to produce a profile of accident risk. The study demonstrated that there is a wide range of accident risk present on sites within the same site category and that better procedures are needed to identify sites where accident risk could be reduced.


IAN98/07 was prepared to assist HA service providers in implementing the UK policy for managing the skid resistance on trunk roads effectively and, in doing so, to facilitate good record keeping, promote consistent and effective decision making and maximize the benefits by targeting maintenance to improve the skid resistance at those sites most likely to deliver safety benefits. The approach taken to developing the advice, combining the results of accident studies on the English trunk road network with a general knowledge of the factors influencing accident risk, is described in this paper.


No abstract available.


Doubtless, there is a strong correlation between road friction and accident risk. The problems arise when we demand a more detailed view of that correlation. The aim of the project behind this report was to gather information about the different friction methods in use and about published quantitative relations between road friction and accident risk. Regarding friction measurements, every country has instruments and methods of its own, and the friction values reported from different international investigations are therefore not directly comparable. Work on harmonization of friction measurements is in progress. Road friction is very important for traffic safety, but it is difficult to single out the effect of poor friction on the accident risk. Drivers adjust their driving behavior depending on many factors, e.g. the appearance of the road environment, the weather, the sound from the tires, and the sliding and skidding movements of the vehicle. For dry or wet bare roadway, however, the conditions are comparably homogeneous, and several studies show a dramatic increase in accident risk when the friction numbers decrease below certain threshold values. For winter circumstances there are few and unreliable estimations of the correlation between accident risk and friction.


Tests with four ground friction measuring devices—an electronic recording decelerometer, a GripTester, a runway analyzer and recorder, and a SAAB friction tester—were conducted on a variety of runway and taxiway winter-contaminated surfaces at Jack Garland Airport, North Bay, Ontario. These tests were part of a joint Transport Canada/Norsemeter winter runway friction program aimed at comparing, measuring, and understanding the effects of winter conditions on ground friction. Conditions included bare and dry from +2°C to - 24°C, bare and wet, slush, smooth and rough ice, loose snow, medium-packed snow, and hard-packed snow at variable temperatures as recorded. For a given contaminant, one to five loops were run by each of the four devices. Correlations between the equipment are given for the various speeds, tires, and ambient temperatures, as well as for the various contaminants.

Analysis of the frictional properties of the tire-pavement interface provides useful information to minimize wet-weather accidents and aid state agencies in making better pavement management decisions. In this paper, the surface friction and texture properties of 12 asphalt pavement sections placed at the Virginia Smart Road pavement facility were studied over a 6-year time period. The surfaces investigated include five SuperPaveTM mixes, an Open-Grade Friction Course (OGFC) and a Stone Matrix Asphalt (SMA) mix. The levels of friction and macrotexture of these pavement sections were compared and analyzed. Short-term (seasonal) and long-term (multi-year) variations of the surface characteristics were investigated in order to learn how the properties vary with temperature and time, which can be used to support asphalt mixture selection, determine the need for friction correction factors, and assess their suitability for use on the network pavement monitoring. The investigation confirmed that the environmental factors have a significant effect on the seasonal variation of friction. For all mixture types investigated, the friction measurements experienced variation within a year (short-term) and throughout several years (long-term). Both the friction number at zero speed [FN(0)] and percent normalized gradient (PNG) decrease in the summer and thus friction varies differently at low and high speeds. In the long term, the low speed friction increases first due to weathering of the asphalt film from the aggregate, and then starts to decrease, probably due to polishing and weathering. Macrotexture variations are almost unnoticeable within a year and small across 5 years. The measured texture depth initially decreases a little, and then starts a modest ascending trend. This is probably due to the loss of fines through weathering and/or washing by the rainfall.


This paper describes the approach of the Queensland Department of Main Roads (QDMR) to managing skid resistance on the State-controlled road network, as a means of improving road safety and reducing trauma associated with road crashes.

Queensland’s road traffic is concentrated in high rainfall sub-tropical and tropical Pacific coastal areas. QDMR developed a skid resistance management plan (SRMP) in response to studies of traffic crash histories around the world that have consistently found that, for wet road surfaces, a disproportionate number of crashes occur where the road surface has low surface friction.

Risk management is an integral aspect of the QDMR strategy for managing skid resistance. The QDMR strategy is based on a rational analytical methodology supported by field inspections and integration with related asset management decision tools. The aim is to make the probability of a crash with skid resistance or surface texture as a contributing cause uniform across the network, having regard to local circumstances such as traffic patterns and climate.

The QDMR SRMP defines the Department’s overall objective and central strategy for managing skid resistance, describes a corresponding suite of performance indicators, and describes specific actions including research and development necessary to achieve the overall objective.

The paper explains the SRMP in detail, and concludes that skid resistance should be a central aspect of asset management and performance reporting, and that implementation of the SRMP will reduce the incidence of crashes with low skid resistance as a contributory cause.


The durability of concrete pavement depends on its load bearing capacity and the performance properties of the surface texture during use. During wet weather conditions the textured surface should provide good tire grip for safety reasons. In recent years increased focus has been placed on the noise emitted by road traffic in Germany. Traffic and weather result in wear which changes the surface texture and affect the performance properties of the road surface. The durability of texture is especially dependent on the shape of the texture and the quality of the surface mortar, i.e. on the composition and the properties of the near surface concrete. Optimization of the surface
durability is essentially the task of concrete technology. Over the past years, extensive research work financed by the German Federal Ministry of Transport, Building and Housing represented by the Federal Highway Research Institute has been carried out in order to improve texture durability. A time accelerated assessment procedure for laboratory testing under simulated practice conditions was developed in order to systematically test texture durability. The changes of texture were recorded three dimensionally with a laser surface scanner, evaluated and expressed by means of geometrical parameters. In various test series, the effects of the texture shape and concrete composition on texture durability have been studied.


It is well understood that aggregate is rarely inert (either chemically or mechanically) and that its role in pavement construction is—or should be—far greater than that of a space occupier, as it was believed earlier. While such aggregate properties as soundness, durability, gradation, and bonding properties has become well recognized as important in controlling the aggregate performance, the skid resistance related characteristics are not so well understood. Although the evaluation of the skid resistance has a long history in U.S., establishing the standards based on the skid measurements remains to be a challenge. It occurs mostly due to poor repeatability of results obtained with locked-wheel trailers. Recently, two levels surface texture—microtexture and macrotexture—have been recognized as important factor affecting performance of the wet pavement in terms of skid resistance. Therefore, the texture measurements should be included in the skid evaluation procedure.

While the need in major surface rehabilitation increases rapidly, the cost effectiveness of the surface treatments becomes an issue. When pavement needs surface improvements, but is not structurally defective, the slurry seal placement appears to be fast and reliable technique to improve skid resistance and correct surface defects.


The use of 4.75mm asphalt mixtures is gaining popularity in the United States as an efficient paving alternative. These mixes are placed in thin lifts, thereby reducing the quantity and cost of materials, as well as construction time. Although there are many advantages associated with 4.75mm mixtures, there are some issues that must be considered prior to the placement of these mixes. 4.75mm mixtures are comprised primarily of fine aggregates that produce tight and smooth mixes, which could pose safety concerns related to surface friction.

The primary goal of this research effort was to determine what actions could be taken during the design of a 4.75mm Superpave asphalt mixture to improve its frictional performance. Specific tasks included 1) an investigation of variations in 4.75mm mix design properties with respect to the microtexture and macrotexture of the mixes, 2) an evaluation of the characteristics of the constituent aggregate materials in order to determine fine aggregate properties that can be used during design to improve the skid resistance of the resulting mixes, and 3) a relative comparison of the skid resistance of 4.75mm mixes with that of typical 9.5mm and 12.5mm surface mixes. Three aggregate sources were used to develop the Superpave mixtures. The British Pendulum Tester was used to quantify the microtexture of the mixes, and a modified laboratory sand patch test was used to quantify the macrotexture. A number of aggregate properties, including source and consensus properties were used to describe fine aggregate characteristics. The results indicate that, in general, both the microtexture and macrotexture of the 4.75mm mixes were relatively unaffected by the various mixture parameters. Aggregate source did produce a significant effect. Aggregate gradation affected the microtexture and macrotexture of the mixes such that a gap-graded blend could be used to increase skid resistance. Aggregate source and consensus properties can also be used to improve the frictional performance of mixes. Skid resistance can be improved by limiting the percent loss for durability and soundness of the fine aggregate, and by increasing the angularity of the fine aggregate. When compared to mixes composed of larger aggregates, the microtexture of the 4.75mm mixes was superior to that of the 9.5mm and 12.5mm mixes; although the 4.75mm mixes possessed limited macrotexture.

Overall, when fine aggregate properties are properly considered, 4.75mm Superpave mixes can be designed with adequate microtexture for use on low speed roadways, and in a manner that may partially compensate for the lesser macrotexture, thereby providing adequate skid resistance for high speed roadways.

In recent years, many Road Controlling Authorities have made concerted efforts to measure skid resistance in order to better understand how their asset are performing and to improve their decision making. Because of the prohibitive costs of skid testing measurements, usually only one ‘network level’ test are undertaken annually. This sampling period, while being reasonable for other pavement condition indicators, should be used with caution as a performance indicator of skid resistance. This paper discusses infrastructure asset management goals and the development in New Zealand (NZ) of the NZdTIMS system of predictive deterioration modeling. The paper then demonstrates that measured skid resistance varies significantly from month to month, week to week and even day to day, based on a number of external variables. The outcome being that it is very difficult to develop credible incremental deterministic prediction models for skid resistance. The paper then reports upon research that is currently being undertaken at the University of Auckland, New Zealand into the variability of road pavement skid resistance over time. The methodology includes the measuring and analyses of skid resistance with rainfall and contaminants in the field using the GripTester, SCRIM and the Dynamic Friction Tester (DFTester) and secondly by means of controlled laboratory experiments on prepared samples. The paper discusses the results of the experiments that were developed to try and simulate infield skid resistance variability. The research demonstrates the importance of understanding the significance of a single skid measurement as a ‘snapshot’ in time. This result must be qualified in the context of not only the method of measurement but an understanding of the surrounding local environmental factors in which the measurement was taken.


This paper discusses the results of a current Transfund NZ research project being undertaken by the Department of Civil and Environmental Engineering at the University of Auckland in conjunction with Works Infrastructure Limited on the “Effect of contaminant and rainfall on measured skid resistance.”

The “approximately sinusoidal seasonal” effect of low skid resistance in the summer and high skid resistance over the winter period is well known. This relates to the measurement of skid resistance in New Zealand by SCRIM over the summer period that is reported by Mean Summer SCRIM coefficient. However, the cause of this “approximately sinusoidal” effect is little understood. Recent research undertaken by the University of Auckland in the Northland transit New Zealand PSMC 002 Region and in Auckland clearly showed that the “approximately sinusoidal seasonal” effect of the variation in measured skid resistance is neither a repeatable, nor a predictable, phenomenon. Clearly, a better understanding of what causes the variation to occur is required. If the causal effects are known, this will enable better decision making by road managers, and will lead to more appropriate road management in terms of surfacing techniques and practices. This will ultimately lead to a safer road network for all road users.

The paper reports on Stage 1 of the project that developed a controlled laboratory experiment using the Dynamic Friction Tester (DFT), and an accelerated polishing machine to simulate in-field variation of measured skid resistance. The paper discusses the development of testing procedures, methodology and laboratory equipment and presents results to date in simulating the in-field polishing of road surface aggregates to equilibrium skid resistance levels to a range of high to low PSV aggregates. The experiments were undertaken on prepared chip sealed surface samples that were subjected to cycles of polishing and periodic skid testing.

Wisconsin Department of Transportation (WDOT). “Wet Pavements Crash Study of Longitudinal and Transverse Tined PCC Pavements.” (Research in Progress)

Since the late 1960s, the Federal Highway Administration and most states have favored transverse tines or grooves on concrete pavement as a safety measure offering greater skid resistance than would longitudinal measures parallel to the center line. Yet few studies have compared actual crash experience on both types of pavement. In the early 1990s, public concern about tire-pavement noise compelled a national investigation into issues of pavement texture, noise and safety, and recent research sponsored by WisDOT and FHWA has measured greater tire-pavement noise on transverse-tined highways than on longitudinally tined. Wisconsin researchers have also linked evenly spaced transverse lines to the highway “whine” found particularly objectionable by the public. The objective of this study is to clarify the relative safety characteristics of longitudinal- and transverse-tined pavements through an analysis of
actual crash data from Wisconsin and other states. Methods of research include gathering and evaluating information from various states on tining practices and creating a corresponding crash database, followed by analysis of safety performance of the tining methodology in wet and dry conditions. Expected benefits include evidence that neither type of texture has significant safety advantages over the other, which would allow texture choice based on tire-pavement noise, construction cost and other considerations, resulting in quieter roads.


This paper considers the prediction of skid resistance for differing types of UK thin surfacing materials in relation to mix properties such as aggregate type and size. This is based on different research projects that have been in response to meeting the needs for sustainable construction i.e. providing a safer and longer lasting pavement. The traditional UK requirement for high values of skid resistance and texture must now be viewed along with properties such as noise, fatigue, permanent deformation and rolling resistance. Using examples and case studies the paper considers the implication of combining these sometimes conflicting properties.


One of the benefits associated with the use of a pavement preservation program is improved safety characteristics. Improved safety can be realized in several ways. For instance, an agency with a pavement preservation program that includes the early application of preventive maintenance (PM) treatments can generally keep the road network in better condition for a longer period of time. As a result, the roads are relatively smooth, which reduces the cost of operating a vehicle and minimizes crashes associated with defensive driving to avoid potholes and other surface irregularities in the pavement. However, in addition to providing a smoother surface, PM treatments can be used to improve the surface characteristics associated with surface texture (friction) to reduce the likelihood of wet weather and dry weather crashes. In the United States and abroad, an increased emphasis is being placed on safety issues to reduce the number of fatal and serious injuries caused by crashes and the resulting traffic delays. However, the effect of microtexture and macrotexture on crash rates has not been quantified. Past studies have often shown a weak link between increased friction and reduced crash rates. Recently, there have been major advances in data collection and analysis capabilities that show promise for improving the ability of transportation agencies to better quantify the effectiveness of pavement preservation treatments on reducing crash rates by improving surface characteristics. For instance, it is now possible to collect continuous pavement macrotexture information at highway speeds. It is also possible to measure macrotexture under the tire during skid trailer friction testing. These technological advances will greatly enhance the ability of highway agencies to identify sites of potentially high accident rates and to proactively take preventive actions as part of a pavement preservation program. This paper focuses on the safety improvements that can be realized as part of a pavement preservation program. Specifically, the following areas are discussed in this paper:

- The use of network-level evaluations (including features such as pavement macrotexture and annual friction surveys) as a means of identifying pavement sections that could benefit from the use of certain PM treatments to enhance or restore friction values (such a microsurfacing, grinding and/or grooving, or chip seals).
- The development of safety investigatory levels based on microtexture and macrotexture data for various site categories.
- The incorporation of safety features into a pavement management analysis.

The application of these characteristics are demonstrated using examples from transportation agencies worldwide. For instance, the Texas Department of Transportation’s Wet Weather Accident Analysis Program is an example of the type of study used to illustrate the points raised. Internationally, work being conducted in the United Kingdom and New Zealand on continuous friction measurements and the use of the data to identify pavement sections where poor texture/friction may be contributing to higher than average crash rates are featured. Other examples, such as Australia’s recently established goal of achieving 19% of their 40% per capita accident reduction by providing safer roads is also documented.
APPENDIX B. SYNTHESIS ON PAVEMENT SURFACE CHARACTERISTICS

Introduction

Since at least the 1980s, the United States has suffered over 40,000 annual fatalities on its highways, with an estimated total annual cost of $260 billion (in year 2000 dollars). There are a number of factors contributing to this high number of fatalities, including poor roadway geometry, improper roadside design, poor surface characteristics, and unsafe drivers behavior (e.g., aggressive or impaired driving, not using a seat belt, and so on). Poor surface characteristics have been identified as a contributing factor in about 30 percent of the annual highway fatalities in the U.S. (Larson 2005). Additionally, the National Transportation Safety Board (NTSB) and the Federal Highway Administration (FHWA) have reported that 13.5 percent of fatal crashes and 18.8 percent of all crashes occur when the pavement surface is wet (Dahir and Gramling 1990). It is also estimated that 40 to 50 percent of all nonrecurring congestion is associated with traffic incidents (AAA 2008). Considering these statistics, many agencies on the Federal and State level, including the Ohio Department of Transportation (ODOT), have become interested in crash reduction programs with emphasis on a better understanding of the relationship between measurable surface characteristics (e.g. friction and texture) and the occurrence of roadway crashes.

A recent study for the North Carolina DOT found that crashes decrease significantly with an increase in pavement macrotexture (Pulugurtha, Kusam, and Patel 2008). Pavement macrotexture greater than or equal to 0.06 inches (1.5 mm) but typically less than 0.12 inches (3.0 mm) was found to be most appropriate to provide safe and efficient transportation to road users (Pulugurtha, Kusam and Patel 2008). Similarly, research underway in Canada indicated a mean texture depth of 0.07 inches (1.8 mm) would probably be adequate, but also noted that hot-mix asphalt (HMA) surfaces with complex macrotexture perform differently than portland cement concrete (PCC) pavements with simple macrotexture patterns (Ahammed and Tighe 2008).

The above findings notwithstanding, researchers from New Zealand found the road geometry factors (e.g., curvature and gradient) to have a more significant effect on the crash rate than the surface friction (Davies, Cenek and Henderson 2005). Furthermore, the effect of surface texture on the crash rate was found to be statistically insignificant.

Considering the somewhat conflicting results, more research is needed to determine the effect of pavement surface conditions on road safety. To address some of the shortcomings in this topic of research, the Ohio DOT is sponsoring this study to investigate the relationship between skid resistance, macrotexture, and wet-crash locations. Therefore the objective of the literature review is to determine the state-of-the-practice in what quantifiable pavement characteristics correlate with wet pavement and total and rear-end crashes. The literature review will focus on the following topics:

- Definition of and measuring techniques for pavement surface characteristics.
Road safety criteria, methods of assessment of the safety on the roads, and factors affecting road safety.

Investigation of the relationship between surface characteristics and site conditions and roadway safety, including methods of crash data assessment, field data collection, and methods of data analysis.

Identification of minimum and desirable levels of texture/friction for highway networks.

**Pavement Surface Characteristics**

**Definitions of Surface Characteristics**

**Pavement Surface Friction**

Pavement surface friction (or skid resistance) is the retarding force developed at the tire-pavement interface that resists sliding when braking forces are applied to the vehicle tires (Dahir and Gramling 1990). While adequate surface friction generally exists on dry pavements (although there are exceptions), the presence of water reduces the direct contact between the pavement surface and the tire. This film of water combined with the high speed of vehicle may result in hydroplaning (Hoerner and Smith 2002).

A number of quantitative friction indices have been developed since the late 1940s, when the skid number (SN) number was first introduced. The preferred term is now friction number (FN). The most popular and useful measures of a pavement’s friction are discussed in the next sections.

**Friction Number (FN)**

The friction number is computed as 100 times the force required to slide the locked tire (at the stated speed, usually 40 mi/hr [64 km/hr]) divided by the effective wheel load (Kuemmel et al. 2000). Friction numbers are reported in the form of: FN (Test Speed [in mi/hr]) followed by an R if a ribbed tire was used or an S if a smooth-tread tire was used. If the test speed is expressed in km/hr, it is enclosed in parentheses. For example, if a ribbed tire was used in a locked-wheel trailer test at a test speed of 40 mi/hr (64 km/hr), the friction number is reported as FN(64)R or FN40R (metric and English units, respectively). Usually, FN40R values in the range of 30 to 40 are targeted for major highways (interstate highways and other roads with design speeds of more than 40 mi/hr [64 km/hr]). Lower friction numbers are generally acceptable for low-speed and low-volume pavements with daily traffic less than 3000 vehicles a day (Hoerner and Smith 2002).

**International Friction Index (IFI)**

In 1992, the Permanent International Association of Road Congresses (PIARC) proposed the International Friction Index (IFI) as a method of incorporating simultaneous measurements of friction and macrotexture into a single index representative of a pavement’s frictional characteristics (Henry 2000). The IFI is dependent on two parameters that describe the pavement surface friction: a speed constant (Sp) derived from the macrotexture measurement that indicates the speed dependence of the friction, and a friction number (F60) that is a harmonized level of friction for a speed of 36 mi/hr (60 km/hr). Equation forms for these IFI parameters are as follows (Henry 2000):
\[ S_p = a + b \times TX \]  
(A-1)

\[ F60 = A + B \times FRS \times e^{\frac{S_{-60}}{S_p}} + C \times TX \]  
(A-2)

- \( S_p \) = IFI speed constant.
- \( a, b \) = Constants determined for a specific macrotexture measuring device.
- \( TX \) = Macrotexture parameter reported by the specific macrotexture measuring device (e.g., MTD or MPD).
- \( F60 \) = IFI friction number.
- \( A, B, C \) = Constants determined for a particular friction measuring device.
- \( FRS \) = Measurement of friction by a device operating at a slip speed (S).
- \( S \) = Slip speed of friction measurement (i.e., the speed at which a locked wheel is dragged for friction measurement).

One advantage of IFI is that tests may be conducted at any speed, since the F60 value for a pavement is the same regardless of the slip speed used (Henry 2000). It is believed that the adoption of the IFI will eliminate concerns related to the use of different equipment/procedures and test speeds when measuring surface friction.

In Europe, the European Friction Index (EFI) is being developed, the principles of which are being used to harmonize the devices commonly used for measuring skid resistance in Europe (e.g., the SCRM, GripTester, and the Pavement Friction Tester) (Roe and Caudwell 2008). These devices have different potential applications but it would be helpful to be able to compare their results more easily.

**Pavement Surface Texture**

A pavement’s microtexture and macrotexture have the most significant effect on surface friction and splash and spray. The definitions of these pavement surface components are provided in the next sections, with the differences in microtexture and macrotexture illustrated in figure A-1.

![Figure A-1. Illustration of macrotexture and microtexture of a road surface (Tighe et al. 2000).](image-url)
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

Microtexture

Microtexture is defined by wavelengths of 0.0004 in to 0.02 in (1 μm to 0.5 mm) and vertical amplitudes less than 0.008 in (0.2 mm). The relative roughness of the aggregate particles in asphalt mixtures contributes to microtexture in HMA pavements, while microtexture in PCC pavements is generally provided by the fine aggregate in the concrete mix. Good microtexture is usually all that is needed to provide adequate stopping on a pavement in dry-weather conditions, or in wet-weather conditions when speeds are under 50 mi/hr (80 km/hr) (Hoerner and Smith 2002).

Macrotexture

Macrotexture is defined by wavelengths of 0.02 to 2 in (0.5 mm to 51 mm) and vertical amplitudes between 0.004 to 0.8 in (0.1 mm and 20 mm) (Henry 2000). In HMA pavements, adequate macrotexture stems from a proper HMA mix aggregate gradation, whereas macrotexture in PCC pavements is most commonly produced through small surface channels, grooves, or indentations that are intentionally formed (plastic concrete) or cut (hardened concrete) to allow water to escape from beneath a vehicle’s tires. PCC pavements constructed for speeds 50 mi/hr (80 km/hr) or greater require good macrotexture to prevent hydroplaning (Hibbs and Larson 1996). The role of macrotexture on smooth and ribbed tire friction test results and on total, wet pavement, and rear-end crashes has not been adequately evaluated.

Under NCHRP Project 1-43, a Guide for Pavement Friction was developed and is being evaluated by AASHTO for publication (Hall et al. 2006). That document suggests a relationship between mean texture depth (MTD) and FN40R and FN40S, which will be addressed later.

Texture and Friction

There are two main components of tire-road friction: adhesion and hysteresis. Adhesion is generated by the establishment of chemical bonds between the tire rubber and pavement aggregate, and hysteresis is caused by deformation of the tire rubber by pavement surface projections. On a wet road surface, high microtexture can help improve friction since the sharp peaks can break through water films and thus allow for restoring of adhesion friction. An adequate macrotexture provides hysteretic (deformation) friction and escape paths for water. A lack of escape paths on the pavement surface may cause tires to hydroplane. Additionally, macrotexture as a characteristic of the longitudinal profile affects noise level and tire wear.

Theoretically, it should be possible to predict wet pavement friction from texture alone (FHWA 1977). In the 1960s, there were attempts to model the tire-pavement friction based on adhesion and hysteresis. However, since microtexture is difficult to measure, the model was not implemented, although some agencies (such as Mississippi DOT, Virginia DOT, and NASA) use macrotexture profiles that can be obtained at highway speeds in addition to friction measurements to determine the IFI (Henry 2000).

French researchers report that comparing the friction for identical pavement tread depths and water height conditions, the beneficial influence of texture depth on skid resistance as a function of speed is readily observed (Gothie 2005). Skid resistance levels for a half worn tire rolling on a semi-coarse asphalt concrete are diminished by up to 80 percent with 0.04 in (1 mm) of water
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

at 62 mi/hr (100 km/hr). Primary factors affecting the pavement include indenters over the microtexture range and surface drainage capacity which depends upon the size, shape, layout and distribution of surface aggregates (Gothie 2005).

Providing Adequate Texture on the Roads

As previously described, adequate pavement surface texture is an essential requirement for safety on the roads. HMA pavements develop macrotexture through an appropriate aggregate gradation, while a number of techniques are used in PCC pavements to create macrotexture. This section discusses the techniques for providing surface texture in newly constructed and rehabilitated HMA and PCC pavements.

Newly Constructed HMA Surface Texturing Techniques

HMA pavements designed in conformance with Superpave mix design will generally provide adequate macrotexture and microtexture without supplemental treatments (FHWA 2005). In areas where supplies of durable, nonpolishing aggregates are limited, an agency may choose to construct an asphalt pavement using high durability aggregates optimized for friction properties only in the top layer (surface course). Research is underway to incorporate friction and texture considerations during the HMA mix design process (Goodman, Hassan, and Abd El Halim, 2006; Hall et al. 2006; Noyce et al. 2007; Ahammed and Tighe 2008).

HMA Surface Courses

FHWA (2005) recommends using dense-graded asphalt mixtures with a high-quality, polish-resistant aggregate to provide adequate surface texture. Because of limited availability of the high quality aggregate, dense-graded mixtures are often expensive.

Open-graded HMA mixtures may be used on the top layer to provide better friction, although they have some the potential for stripping, raveling, and shoving because of higher asphalt binder contents (as compared with dense-graded HMA mixes). Additionally, the open-graded courses have limited structural capacity, and have to be placed over sound pavements with special preparations, such as sealing the existing pavement with a 50 percent diluted asphalt emulsion and heating the underlying surface to the temperature of 600 °F (315 °C) (FHWA 2005). To overcome some of the disadvantages of open-graded mixtures, some agencies use bonded wearing courses in northern climates where freeze-thaw cycles may otherwise preclude the use of porous friction courses (PFC) (Button 2004).

Stone matrix asphalt courses should be designed and constructed in conformance with American Association of State Highway and Transportation Officials (AASHTO) specifications MP8 and PP41 (regulating the void content in the HMA mix) (FHWA 2005). The stone matrix mix design is based on the idea of creating the aggregate skeleton so that stone-on-stone contact is maintained in the mixture. Stone-on-stone contact will provide load carrying capacity for heavy traffic situations. To maximize skid resistance of SMA pavement surfaces, German engineers use a process called “gritting” (“sanding” in the U.S.) during initial construction. This promising process appears to deserve further study to optimize its benefits and develop field guidelines (Button 2004). However, in the United Kingdom, the benefit of this operation is controversial due to the extra cost and the reduction in macrotexture depth (Lawrence 2008).
HMA Mix Properties and Friction

Proper texture characteristics of asphalt surfaces are very much influenced by asphalt content, voids in the mineral aggregate, dust-to-binder ratio, and void content. Proper mix design, following Superpave procedures, should be performed to ensure the necessary ratio of these elements. It is recommended that the test procedures listed in AASHTO specifications PP28 and M323 be used in performing Superpave volumetric mix design (FHWA 2005).

Surface characteristics of asphalt surfaces are also dependent on aggregate characteristics. This is particularly important after the surface is exposed to wear from traffic and weather conditions. The following aggregate characteristics affect surface friction (FHWA 2005):

- **Aggregate angularity.** Frictional resistance of the wearing course is improved when angular aggregates are used in the HMA mixture. Increasing fractured faces of the coarse aggregate will also improve the stability of the HMA mix.
- **Aggregate soundness.** Soundness is an indication of an aggregate's resistance to weathering. It is tested using sodium and magnesium sulfate tests.
- **Aggregate toughness.** Toughness is an indication of an aggregate's resistance to abrasion and degradation during handling, construction, and in-service. The recommended specification value for a Los Angeles abrasion loss (AASHTO specification T96) ranges from 35 to 45 percent maximum.
- **Polish resistance.** The use of aggregates that polish easily should be avoided. It is recommended that the polishing resistance of aggregates be measured in the laboratory using tests such as AASHTO T-279 (Accelerated Polishing of Aggregates Using the British Wheel) or AASHTO T-278 (Surface Frictional Properties Using the British Pendulum Tester).

The *Guide for Pavement Friction*, developed under NCHRP Project 1-43 and currently being considered for adoption by AASHTO, contains additional guidance on incorporating friction and texture considerations in the mix design process (Hall et al. 2006). Similarly, research in Canada is underway to specifically address this issue in Superpave mixes (Goodman, Hassan, and Abd El Halim 2006).

Surface Treatments on Existing HMA Pavements

Various types of surface treatments can be used on existing HMA pavements (Whitehurst 1977). Microsurfacing is an advanced form of slurry seal that uses a combination of emulsified asphalt, water, fine aggregate, mineral filter, and polymer additives that is being used more frequently. In quick-traffic applications as thin as 0.38-in (9.5 mm), microsurfacing can increase skid resistance, color contrast, surface restoration, and service life to high-speed, heavy-traffic roadways. Microsurfacing is applied to the problem sections of roads or runways to eliminate hydroplaning problems that occur during periods of rain. Microsurfacing restores the surface profile and improves the frictional qualities of the pavement. However, macrotexture depths needed to meet user demands are often not evaluated and researchers are evaluating additional guidelines for thin surfacings (Woodward et al. 2008; Simpson 2008).
Thin epoxy-bonded laminates can be used to restore surface texture in existing HMA pavements (FHWA 2005). For example, volcanic mineral with a microcellular structure composed of tiny air cells combined with cement/concrete can be chosen as the overlay material. PCC overlays may also be considered to restore adequate surface texture on asphalt pavements (FHWA 2005).

A recent study documents the performance of high skid resistant treatments on 23 sections in Melbourne and Geelong, Australia (Simpson 2008). The data for the sites in this project showed an overall reduction of crashes by 39% over a 5-year period on the treated areas. In addition, the investigation found the following trends (Simpson 2008):

- An overall reduction in crashes of 39 percent on the treated areas.
- High friction surface treatments were very effective reducing loss of control crashes on high speed curves with free-flowing traffic.
- High friction surface treatments appear to be more effective when placed on the approach and centre of signalized intersections compared to sites with the treatment on the approach only.
- The sites in the project showed a slight increase to more serious injury crashes, and the high friction surface treatments followed this trend.
- A minority of sites displayed an increase in crashes and a larger increase in severity of injury.
- Although the total number of crashes was reduced, the proportion of different types of crashes remained the same.
- The skid resistant treatments altered the wet/dry road accidents ratio, and reduced the number of wet road crashes.

The investigation indicates high friction surface treatment is very effective in reducing loss of control crashes on curved sites with free flowing conditions, and very effective when placed on the approach and centre of signalized intersections. It appears these types of sites with loss of control crashes can be used to target candidate sites.

The crash data indicated rear-end crashes made up the bulk of the crashes. The data showed only minor changes in the types of crash for “before” and “after” crashes. The high friction surface treatment does not appear to alter the types of crash, although it has resulted in a significant total reduction of crashes. The data suggests that the total number of crashes should be considered as more important than the number of rear-end crashes when selecting candidate sites. The data also suggests the treatments have reduced the ratio of wet crashes and supports the use of wet weather ratios to select candidate sites (Simpson 2008).

**Newly Constructed PCC Surface Texturing Techniques**

**Transverse Tining**

Transverse tining, preceded by a longitudinal artificial carpet or burlap drag, has been the most commonly used surface texture method on new high-speed (50 mi/hr [80 km/hr] or greater) PCC pavements (Hoerner and Smith 2002). This texture proved to be a cost-effective method of
consistently providing a durable pavement, although it has also been associated with increased tire/pavement noise levels. To reduce noise emissions, FHWA (2005) recommends a tine width of 0.12 in (3 mm) and a tine depth of 0.12 in (3 mm). Additionally, a random spacing of either 0.5 in (13-mm) or 1 in (25-mm) average tine spacing can be provided. The recommended tine spacings for these are (FHWA 2005):

- For the 0.5- (13-mm) average spacing: 10/14/16/11/10/13/15/16/11/10/21/13/10 mm.
- For the 1-in (25-mm) average spacing: 24/27/23/31/21/34 mm.

**Longitudinal Tining**

Longitudinal tining has been used by several highway agencies, including California, Virginia, Michigan, Iowa, and Colorado (Hibbs and Larson 1996). Longitudinally tined surfaces are generally quieter than transversely tined surfaces, although British and Australian research states that longitudinal textures may fail to provide satisfactory friction characteristics (Hibbs and Larson 1996). Recent research suggests that for the same texture configuration, transverse tining exhibited 7 to 14 percent higher skid resistance as compared to longitudinal tining (Ahammed and Tighe 2008). However, the advantage of longitudinal tining over transverse tining is realized on horizontal curve sections. To provide the adequate friction on longitudinally tined sections, the uniform tine spacing of 0.8 in (20 mm) with an average texture depth of 0.03 in (0.8 mm) and a minimum of 0.02 in (0.5 mm) for individual tests is recommended (Hibbs and Larson 1996).

**Longitudinal Plastic Brushing**

As reported from Spain, a combination of a longitudinal burlap drag followed by a plastic brush provides high friction with low noise levels (Hibbs and Larson 1996). To provide satisfactory microtexture, the siliceous sand was used with a minimum content of 30 percent. The higher friction numbers (both with blank and ribbed testing tires) were obtained for deeper texture rather than shallower (Hibbs and Larson 1996).

**Exposed Aggregate Surface (EAS)**

The exposed aggregate surface treatment technique is usually constructed on a pavement composed of two layers (Hibbs and Larson 1996):

- Top layer 1.6- to 2.8-in (40- to 70-mm) thick with 30 percent siliceous sand of size 0 to 0.04 in (0 to 1 mm) and 70 percent high quality chips of size of 0.16 to 0.32 in (4 to 8 mm).
- Bottom layer with maximum aggregate size 1.25 in (32 mm) with lower quality yet durable aggregates.

A high-quality concrete with low water-cement ratio and a plasticizer and entrainment admixture should be used.

Several studies in Europe reported that the EAS technique provided noise similar to porous asphalt, excellent high-speed skidding resistance, and low splash and spray. For example,
Sweden has reduced the water-cement ratio and added microsilica to improve wear resistance against studded tires (Hibbs and Larson 1996). The United Kingdom used 0.25 to 0.4 in (6 to 10 mm) chips for a 0.055-in (1.4-mm) average texture depth and obtained excellent high-speed (81 mi/hr [130 km/hr]) performance (Hibbs and Larson 1996). Belgium has constructed CRCP in one layer with EAS by reducing the maximum aggregate size to 0.8 in (20 mm) and increasing the amount of 0.16 to 0.28-in (4 to 7-mm) chips (Hibbs and Larson 1996).

The disadvantages of the EAS texturing technique are the low cost-effectiveness of the high-quality aggregates and the technological complexity of the process requiring the qualified labor. That might be a reason why this method has not seen widespread use in the U.S. (Hoerner and Smith 2002). However, the EAS texturing method has been identified as a potential implementation activity from a recent U.S. scan tour of European concrete pavement construction practices (FHWA 2007).

**Other Research**

There is significant research underway in the U.S. to optimize PCC surface texturing. Minnesota has had long-term experience with a longitudinal artificial carpet drag and has recently evaluated the accident rate and found it to be similar to the transverse tining previously used (Izevbekhai and Eller 2008). NCHRP Project 10-69 *Texturing of Concrete Pavement* is nearing completion and should be available in late 2008. A joint FHWA and industry program to optimize texture and friction is underway to determine the interrelationship among noise, friction, smoothness, and texture properties of concrete pavements. Friction and noise were found to have no relationship, demonstrating that quieter concrete pavements can be achieved without compromising this important characteristic (Ferragut et al. 2007)

**Existing PCC Surfaces**

Retexturing the existing surface or applying the overlay can significantly contribute to the improvement of the friction characteristics of the existing PCC. The following rehabilitation options should be considered (Hibbs and Larson 1996):

- Longitudinal or transverse grooving with diamond saws.
- Diamond/carbide grinding or shotblasting.
- Bonded concrete overlays.
- Surface treatments like epoxy resin/calcined bauxite, Ralumac, or Novachip.
- HMA overlays (dense- or open-graded).

**Selection of Pavement Surface Texture and Safety Issue**

The primary purpose of the surface texture is to help reduce the number and severity of wet-weather crashes. To provide good friction characteristics during wet-weather conditions, the surface texture should be selected considering the following local conditions (Hibbs and Larson 1996):

- Climate.
• Traffic levels, including vehicle type distribution.
• Percent grade.
• Conflicting movements (intersections or frequent side approaches).
• Materials quality and cost.
• Presence of noise-sensitive receptors.

Hibbs and Larson (1996) also suggested that the comparison of the texturing methods should be conducted based on friction measurement according to ASTM E-274 (locked-wheel trailer), preferably with a smooth tire (ASTM E-524). Based on the comprehensive review of the state-of-the-art in PCC texturing techniques, it was concluded that (Hibbs and Larson 1996):

• Sufficient microtexture can be provided by the following techniques and practices:
  − Use of PCC mix with minimum siliceous sand content of 25 to 49 percent of the fine aggregate portion of the mix.
  − Two-layer construction, wet on wet, with a higher quality mix on the top in the case where the cost-effective aggregates are not available.

• Adequate macrotexture should be provided by:
  − Transverse or longitudinal tining preceded by a longitudinal artificial carpet or burlap drag.
  − Plastic brushing (Spanish technology).
  − Exposed aggregate treatment.

In HMA pavements, adequate surface friction can be achieved by the following (FHWA 2005):

• Use of the densely graded asphalt mixtures with a high-quality, polish-resistant aggregate.
• Use of surface treatments such as microsurfacing and thin epoxy-bonded laminates.

Finally, the selection of the best pavement type and surface texture is a complex problem that, in addition to safety, requires consideration of several other factors, such as durability, noise, rolling resistance, cost-effectiveness, and sustainability (Austroads 2003; Hall et al. 2006; Snyder 2006; Ferragut et al. 2007; Ahammed and Tighe 2008; Woodward et al. 2008).

**Pavement Surface Friction Measurement Techniques**

**Measurement of Friction Number**

Today, the majority of agencies in the United States measure pavement friction with an ASTM E-274 locked wheel trailer using either a standard ribbed or smooth (blank) tire (in accordance with ASTM E 501 or ASTM E 524, respectively) to determine friction numbers (Henry 2000; Hall et al. 2006). However, a number of other field measurement methods along with laboratory testing methods are used abroad, specifically, in the United Kingdom, France, New Zealand, Australia, and Japan (Henry 2000; Gothie 2005). A description of those methods is provided in the following sections.
**Field Testing Equipment**

There are four basic types of full-scale friction measuring devices: (1) locked-wheel trailer, (2) side force meter, (3) fixed slip, and (4) variable slip devices. The locked-wheel trailer (see figure A-2) produces 100 percent slip condition and measures braking and drag forces at a moment of peak friction. Two types of tire (ribbed or smooth) are used under this method. According to the ASTM E-274 standard, the friction number, either FN40R (with ribbed tire) or FN40S (with smooth tire), is reported in the test (Henry 2000).

![Figure A-2. Photo of a locked-wheel trailer](http://nersp.nerdc.ufl.edu/~tia/5837-5.pdf).

Another way to evaluate tire-pavement friction is to measure side friction. In this case, the test wheel is maintained in a plane at the yaw angle (usually 20 degrees) to the direction of motion, and a side force perpendicular to the plan of rotation is measured. There are two devices currently available for measuring side friction. The first—the Mu Meter, shown in figure A-3—was developed in the U.K. and is designed for use on airports, but also has been used on highways. The second device (shown in figure A-4) is the Sideway-Force Coefficient Routine Investigation Device (SCRIM), which was developed in the U.K. and is used in the U.K., France, Germany, New Zealand, and other countries. (Henry 2000; Gothie 2005; FHWA 2006).

![Figure A-3. Photo of MuMeter](http://www.airport-technology.com).
The main advantage of the side-force measuring devices is their ability to measure friction continuously over the length of the test section, whereas locked-wheel devices usually sample friction over the distance corresponding to 1 second of the vehicle travel (Henry 2000). However, because these devices are low slip speed systems, they are sensitive to microtexture, while not reflecting the macrotexture. For this reason, they are usually used in conjunction with a macrotexture measurement (Henry 2000).

The third group of friction measuring devices is equipped by a braked wheel that is operated at fixed slip (usually 10 to 20 percent). The horizontal and vertical component of friction can be continuously monitored without! excessive wear of tire. A low-speed friction at the slip speed V (percent slip divided by 100) is reported in the test. However, there is no ASTM currently available, which restricts the use of those devices. Nevertheless, they are often used on airports for runway friction evaluation. Several examples of fixed slip devices are shown in figure A-5.

The ODOT Road Grip Tester (RGT) (figure A-5b) was developed by Ohio Department of Transportation. This system measures road surface friction by utilizing an existing hydraulic system to deploy and retract a wheel that is located in the front of the drive axle underneath the vehicle or using a wheel mounted to a tow hitch at the rear of the vehicle. The RGT provides the ability to detect deteriorated pavement surface conditions associated with winter weather that are otherwise not visibly evident (Clonch 2006).

The Highway Slip Friction Tester used by the Arizona Department of Transportation is currently manufactured by Dynatest. It measures friction continuously and is one of a few of its type currently used by a state DOT for testing on highways. Florida is using a similar device on both airports and highways.
a) Towed GripTester (http://www.tradewindscientific.com).

b) ODOT Road Grip Tester (Clonch 2006).

c) AZ Highway Slip Friction Tester.

Figure A-5. Photos of Fixed Slip Testers
The final type of field friction measuring device performs a controlled sweep through a range of slip ratios, as required by ASTM E-1859 (Henry 2000). These devices are referred to as “variable slip” testers and are not used in U.S. (except for winter maintenance) but are used in a few European countries (France, Norway, and Denmark) as well as Japan. One variable slip tester (the Norsemeter) is shown in figure A-6. The Norsemeter SALTAR is being used on a winter maintenance research project by Minnesota and Michigan with the objective of optimizing the amount of salt used by continuously monitoring the friction during salt application.

As discussed above, each method of measuring friction has its specific advantages, as follows:

- The locked-wheel method simulates emergency braking without anti-lock brakes.
- The side-force method measures the ability to maintain control during curves.
- The fixed and variable slip methods allow for assessing the effects of anti-lock braking systems.

**Laboratory Testing Equipment**

Laboratory methods are used for evaluating the friction characteristics of core samples or laboratory-prepared samples, and for evaluating the pavement surface friction in the field in the stationary mode. Devices that are currently in use are described in this section. Also, research on promising three-dimensional techniques including photogrammetric methods are discussed.

The British Portable Tester (BPT), shown in figure A-7, has been in use since the early 1960s. The BPT complies with ASTM E-303 and is operated by releasing a pendulum from a height adjusted so that a rubber slider contacts the surface over a fixed length. As the rubber slide moves over the surface, the friction reduces the kinetic energy of the pendulum in proportion to the level of friction. The recovered height of the pendulum is measured in terms of British Pendulum Number (BPN) over a range of zero to 140 (Henry 2000).
The testing speed of BPT corresponds to the testing slip speed of 6 mi/hr (10 km/hr). The device is sensitive to microtexture due to a low slip speed and therefore, the British Pendulum Number (BPN) reported in the test is used as a surrogate for microtexture. This is very useful because the direct measurement of microtexture is difficult (Henry 2000).

The Dynamic Friction Tester (DFTester) was developed in Japan and uses the following operation principle: a motor drives the disk with three rubber sliders until the tangential speed is 55 mi/hr (90 km/hr); water is then applied, the motor is disengaged, and disk contacts with a pavement surface (Henry 2000). The friction force and a speed during the spin down are reported in this method, as specified in ASTM E-1890. The main advantage of DFT is that it is able to measure high-speed friction over a range of 0 to 90 km/hr (0 to 55 mi/hr). Additionally, it provides a good estimate of the friction number of the IRI when used at speed of 12 mi/hr (20 km/hr) together with a texture measurement (Henry 2000). Figure A-8 shows images of the DFTester.
Photographic-based systems are currently under development in France (Do 2005), Canada (Goodman, Hassan, and Abd El Halim 2006; El Gendy and Shalady 2008), and the U.S. (Flintch 2008). The use of three-dimensional photographic techniques to evaluate both microtexture and macrotextue is extremely encouraging especially for laboratory testing and in place field measurements.

Another prototype piece of equipment is the Robotic Texture (RoboTex) Measurement System that is built around the LMI-Selcom RoLine Line Laser (see figure A-9). It is capable of measuring continuous three-dimensional texture profile in both the transverse and longitudinal directions at a slow speed. This device is being used to help optimize PCC surface texture to address ride, safety, and noise issues (Ferragut et al. 2007).

![Figure A-9. Robotic Texture Measurement System (Ferragut et al. 2007).](image)

**Calibration of Surface Friction Measurement Devices**

It is not possible to define an absolute value for surface friction (Roe and Sinhal 2005). Rather, at any particular time, the “correct” result can only be estimated, and perhaps the best estimate for any particular type of measurement device is the average value given by all devices of that type. With a greater number of devices in service and more widespread use, the importance of regular checking and calibration of the equipment is apparent. The main issues when calibrating the friction measurement equipment are repeatability of the testing results by each particular device and reproducibility of the results by different devices of the same type. The key findings and recommendations of some studies in the U.K. and Australia on the calibration-related issues are provided in this section.

**Gathering Appropriate Data**

There are many factors affecting the performance of the friction testing devices. To make sure that the performance of the device itself is assessed, the effect of those factors should be
minimized, or at least randomized. To achieve this, Roe and Sinhal (2005) recommended the following strategies:

- All devices make a similar number of tests.
- All devices test the same surfaces.
- Surfaces are chosen to test the device over a range of skid resistance levels.
- All devices carry out three repeat tests on each surface for each set of measurements.
- All devices make at least three sets of measurements.
- All devices use the same test tires (or a subset of at least three from a pool of four or five standard tires).
- Running order is randomized during the day and an individual machine’s measurements are spread through the day in case track conditions change.
- All devices operate at a constant speed.
- The test line on each surface is clearly identified and the path followed by individual drivers is audited from time to time during the day.

**Reference Sections**

The set of sections tested during the calibration should include a range of surfacings with an average surface friction levels closer to the typical level found on much of the network. The sections that provide the average surface friction level against which the devices are compared should be used as the reference sections. Note that the average value may vary from day to day during the trials in certain weather conditions (Roe and Sinhal 2005).

**Device Repeatability**

As reported by Roe and Sinhal (2005), the units of SCRIM Reading (SR) were used at the calibration trials. The SR is the value recorded by the device every 33 ft (10 m) and equals the sideways-force coefficient (SFC) multiplied by 100. The between-run standard deviation on any individual section for any individual device and tire should be 3.0 or less.

A research study conducted in Australia (Dardano and Wickham 2005) was concerned with the repeatability of the friction measurements in Sydney Airport performed by the GripTester since 1995. It was suggested that the poor repeatability could be due to the following factors:

- Environment and tire variability: the variability in results that a fully calibrated device will return along the same surface when temperature and tire are different.
- Device variability (reproducibility): the correlation between a device and another device of the same type.

In the Australian study, the measured friction value was adjusted for the change in tire wear (equation A-3) and for the temperature variations (equation A-4) using the normalization procedure.
\[ NF = GN * \frac{SD - CD}{MD - CD} \]  \hspace{1cm} (A-3)

\[ NF = GN - 0.002 * (MT - 20) \]  \hspace{1cm} (A-4)

where:

- \( NF \) = Normalized friction value.
- \( SD \) = Standard tire diameter = 260 mm.
- \( CD \) = Chain cog effective diameter = 130 mm.
- \( GN \) = GripTester Number recorded.
- \( MD \) = Measured tire diameter.
- \( MT \) = Mean Temperature, which is the average of air and pavement temperature.

The normalized values were then harmonized by using the linear regression approach as shown in equation A-5 below:

\[ F_v = A_v + B_v * NF_v \]  \hspace{1cm} (A-5)

where:

- \( F_v \) = Harmonized Friction Value.
- \( A_v \) = Harmonizing Constant.
- \( B_v \) = Calibration Ratio.
- \( NF_v \) = Normalized Friction Value.
- \( V \) = Speed at which the testing was performed.

The normalization and harmonization of the friction testing data allowed the airport engineers in Australia to be confident in the results that the devices produced (Dardano and Wickham 2005).

**Overall Fleet Variability**

In the U.K. study, the reproducibility of the fleet was checked, so that each approved device gave results consistent with the rest of the fleet during normal surveys (Roe and Sinhal 2005). The maximum standard deviation between the devices means was 2.6 SR units.

Because the standard deviation will be influenced by any outlying devices, those devices will be rejected, if necessary, in order to reduce the standard deviation to an acceptable level. When the between-device standard deviation exceeds the maximum permitted level, it will be necessary to identify outlying devices. The following principles were used (Roe and Sinhal 2005):

- Any device that is three standard deviations from the all-device mean would be rejected outright.
- Any device that is between two and three standard deviations from the mean would be subject to further investigation in the context of the overall distribution and performance on the full range of surfacings.
In the U.S., the Florida Department of Transportation (FDOT) initiated a field study to assess the level of precision of its own locked-wheel testers for field measurements (Choubane, Holzschuh, and Gokhale 2003). Four testing units measured friction on five sites representing two types of pavement surface: open-graded and dense-graded. The repeatability of the results for each unit and the variability in friction measurements between the units was assessed using statistical analysis of variance. The researchers reported a high level of repeatability and reproducibility of the friction measurements regardless of the surface texture type or level of serviceability. Thus, the standard deviation of around 4 SR units was reported, which is lower than the ASTM requirement.

**Correlation between Different Friction Measurement Techniques**

While many different devices have been developed for measuring the friction parameters, one challenge is the ability to compare their results and standards. The correlation between friction measurement techniques has been the subject of many studies.

Tests with four friction measuring devices—an electronic recording decelerometer, a GripTester, a runway analyzer and recorder, and a SAAB friction tester—were conducted at Jack Garland Airport, North Bay, Ontario. The correlations between the results obtained with these devices were reported to be between 0.75 and 0.85, which indicates fair agreement of the results considering the winter conditions (snow contamination and icy surface) (Wambold 1996).

Researchers in the U.K. (Roe and Sinhal 2005) compared skid measurement results obtained with the SCRAM, the GripTester, and the Pavement Friction Tester (PFT), which is the European analog of the ASTM locked-wheel trailer. An informal trial in 2004 demonstrated good correlation between GripTester and SCRAM (see figure A-10). Additionally, a reasonable correlation was found between the measurements made with the PFT at 12.5 mi/hr (20 km/hr) and those made by the SCRAM at 31 mi/hr (50 km/hr), when the equivalent slip-speed of the SCRAM tire is approximately 10.5 mi/hr (17 km/hr) (see figure A-11). However, although a linear relationship could be deduced, there was wide scatter that limited the value of applying a generalized correlation equation in a specific situation (Roe and Sinhal 2005). Further research is underway using the European Friction Index principles to harmonize the devices and the results are encouraging (Roe and Caudwell 2008).

The studies discussed above indicated a need to standardize the measurements from the different devices so they can be compared to one another. The major difficulty is that, although all skid resistance testers use the same basic principles, they perform the testing differently. For example, both the British Pendulum Tester and DF Tester use the rubber slider, but the former operates the pendulum, while the latter uses rotating sliders. Additionally, the locked-wheel testers use different loads and tire sizes, and the slip force testers use different slip levels.

The International Friction Index (IFI) has emerged as a harmonized criterion for skid resistance. However, its weakness is the difficulty of having sufficient confidence in precision of the results when compared through the IFI to make them of practical use (Roe and Sinhal 2005). For the purposes of predicting friction at high speed, there is a simple alternative. A texture of 0.05 in (1.25 mm) (volume of the ribbed tire grooves) is added to the texture measured on the road (Viner et al. 2000).
Figure A-10. Comparison of SCRM and GripTester in the 1990s (Roe and Sinhal 2005).

Figure A-11. Comparison of measurements from PFT with SCRM on a range of surfacing types (Roe and Sinhal 2005).
Smooth Versus Ribbed Tread Tire

The original ASTM E-274 standard (issued in 1966) for the locked wheel method specified the use of ribbed tire for testing. The ribbed tire was chosen for two reasons: (1) a five-ribbed tire was already available as a standard for use in an earlier period, and (2) ribbed tires are not sensitive to the water flow rate. The presence of channels that are much larger than the flow area provided by the macrotexture made skid measurements with the ribbed tire insensitive to the macrotexture, but mainly affected by microtexture (Henry 2000).

On the other hand, the smooth tire was used in the 1970s for the special purpose of surface friction testing to not only demonstrate high sensitivity to the macrotexture, but also to provide good correlation with crash data (Henry 2000). This increased the interest in the use of the smooth tire for skid testing. However, there are two reasons that agencies may not want to use the smooth tire. One is that the reported friction numbers would be lower. Another reason is that changing to a smooth tire would produce data that could not be compared with historical data (Henry 2000).

Recently, several studies were conducted in the U.S. to compare surface friction measurements obtained with ribbed and smooth tires. In Virginia, Flintch et al. (2002) found that for the finer mixtures (maximum aggregate size 0.38 in [9.5 mm]), the skid number determined using the ribbed tire (FN40R) was higher than that using the smooth tire (FN40S). The coarse mixtures appeared to have lower FN40R but comparable FN40S after being subjected to research traffic for approximately 16 months. Those finding clearly indicated the sensitivity of the ribbed tire to the microtexture (which is determined by the fine aggregate in HMA). On the other hand, the smooth tire has been shown to measure primarily macrotexture-induced surface friction. Figure A-12 shows that the difference between FN40R and FN40S increased when mean texture depth decreased.

![Graph](image)

Figure A-12. Relation between tire measurements and mean profile depth (Flintch et al. 2002).
The International Friction Index Speed Constant (IFI $Sp$) incorporating the macrotexture was validated during the study conducted by Flintsch et al. (2003) on HMA pavements. The skid resistance testing indicated disagreement between results obtained using the ribbed and smooth tires. The smooth tire showed noticeably higher dependency on speed than the ribbed tire (see figure A-13). Also, the oscillations in the PNG ($PNG = 100/Sp$) time were observed, which were believed to be due to seasonal variations (Flintch et al. 2003). Additionally, the measured $Sp$ did not correspond to the computed value. The researchers related this discrepancy to a possible bias provided by the equipment (Flintch et al. 2003).

Figure A-13. Variation of the average percent normalized gradient (PNG) over time: (a) smooth tire, (b) ribbed tire (Flintch et al. 2003)
However, a recent paper evaluating the International Friction Index Coefficients showed that the repeatability of various locked-wheel trailers was considered acceptable and that the reproducibility obtained with the same type of tire was also good at the various speeds considered (Trifiro et al. 2008). The measurements using the locked wheel trailers with the smooth and ribbed tires did not correlate well to each other when considering all pavement surfaces included in the analysis. In all cases, the measurements obtained with the ribbed tire were higher than with the smooth tire. Finally, discrepancies in the IFI F60 values calculated for the different devices suggest that the original coefficients determined during the PIARC experiment may need to be adjusted for the device evaluated before the IFI can be implemented in the participating agencies (Trifiro et al. 2008).

A high sensitivity of the smooth tire to macrotexture was also proved by the recent study in Indiana that indicated that the smooth tire may produce better results as the surface texture becomes rougher (the variation in SN decreases) (Li et al. 2005). In another study comparing tire types, the Colorado DOT tested PCC pavement surfaces with different textural characteristics using ribbed and smooth tire (Ardani and Outcalt 2005). In that study, the smooth tire showed significantly lower skid numbers for test sections that received only transverse and longitudinal astro-turf (microtexture) (sections 2 and 8 on figure A-14), and showed higher skid numbers for the rest of the test sections with higher macrotexture surfaces. Finally, both ribbed and smooth tires have their advantages in the evaluation of skid resistance, since both microtexture and macrotexture are important for assessment of pavement texture. However, the smooth tire data is more reliable for determination of friction number F60 than the ribbed tire data if the IFI is used to evaluate the surface friction characteristics (Ardani and Outcalt 2005).

A recent synthesis addresses skid resistance on high speed corridors and safety issues related to splash and spray and future research needed to fill the gaps in knowledge. This information suggests that friction test results vary little at speeds greater than 60 mi/hr (96 km/hr) (Button, Fernando, and Middleton 2004).

Other Considerations in Friction Testing

Sample Frequency

Although fixed slip and side force devices can measure friction continuously, the locked wheel test method allows for measuring friction only at fixed intervals because test tire cannot be locked continuously without excessive tire wear. The ASTM E-274 for locked wheel method establishes the following requirements concerning the uniformity of test sections and reliability of the test:

- Test sections shall be defined as sections of pavement of uniform age and uniform composition that have been subjected to essentially uniform wear” (e.g., uniform gradient, curvature, and the cross-section slope).
- At least five skid resistance measurements, at intervals not greater than 0.6 mi (1 km), should be performed in each section with the test vehicle at the same lateral position in any one lane and at each specified test speed.
Wheel Path Measured

Normally, pavement surface friction is lowest in the left wheelpath (LWP) of the driving lane as compared to the right wheelpath (RWP) (Henry 2000). Therefore, most of state highway agencies (SHAs) measure friction in the LWP. An Indiana study (Li et al. 2005) found that the SN was lower in the inner wheel path than that in outer wheel path, and the driving lanes demonstrated lower friction than passing lanes. France has reported 20 percent variability due to location of test in wheel path (Gothie 2005).
Seasonal and Short-Term Variations

Pavement surface friction is expected to decrease with pavement age, largely because of two factors (Henry 2000):

- Polishing of aggregate under traffic, which decreases the microtexture.
- Wearing of aggregate, which decreases the macrotexture.

However, seasonal and short-term variations in friction measurements have been observed when taken during different seasons, or before and after rainfall (Hill and Henry 1981; Corsello 1993; Henry 2000). The seasonal effect is expressed in lower friction measurements in late summer and fall compared with those collected in spring and earlier summer. It occurs because the winter conditions (particularly in northern climates), together with winter maintenance operations (snow plowing), are likely to increase the microtexture of the aggregate. For instance, in Texas, the maximum SN was measured during the winter and early spring, and the minimum values were measured in the summer (Jayawickrama and Thomas 1998).

The friction measured during dry periods is usually lower than the friction measured shortly after a rainfall (Jayawickrama and Thomas 1998; Kennedy, Haydon, and Donbavand 2005; Donbavand and Kennedy 2008). This occurs because the water applied during the test mixes with dust and oil accumulated on the pavement surface (Henry 2000). Caltrans has recently updated their estimated wet time exposures rates to improve their estimate of wet pavement crashes (Huang, Wang, and Shi 2008).

Two agencies (Virginia DOT and the Slovak Road Administration) are known to account for seasonal variations (Henry 2000). Table A-1 indicates that friction can vary depending on the season up to 14 percent. In Australia, seasonal variations as large as two thirds of the above range were noted (Oliver 2005), while in France, seasonal variations up to 30 percent have been noted (Gothie 2005).

Table A-1. Seasonal correction factors (Henry 2000).

<table>
<thead>
<tr>
<th>Month</th>
<th>SLA Multiplier</th>
<th>VDOT Reduction (SN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.86</td>
<td>-3.7</td>
</tr>
<tr>
<td>February</td>
<td>0.87</td>
<td>-3.7</td>
</tr>
<tr>
<td>March</td>
<td>0.87</td>
<td>-3.1</td>
</tr>
<tr>
<td>April</td>
<td>0.88</td>
<td>-1.7</td>
</tr>
<tr>
<td>May</td>
<td>0.92</td>
<td>-0.7</td>
</tr>
<tr>
<td>June</td>
<td>0.98</td>
<td>-0.3</td>
</tr>
<tr>
<td>July</td>
<td>1.00</td>
<td>0.0</td>
</tr>
<tr>
<td>August</td>
<td>1.00</td>
<td>0.0</td>
</tr>
<tr>
<td>September</td>
<td>0.96</td>
<td>-0.6</td>
</tr>
<tr>
<td>October</td>
<td>0.90</td>
<td>-1.7</td>
</tr>
<tr>
<td>November</td>
<td>0.87</td>
<td>-3.1</td>
</tr>
<tr>
<td>December</td>
<td>0.86</td>
<td>-3.7</td>
</tr>
</tbody>
</table>
Hill and Henry (1981) also reported large variations in surface friction over the short term, and previous work by the Ohio DOT (Bazlamit and Reza 2005; Murad 2006) indicated that temperature adjustments to friction testing may be important. Seasonal corrections are now a very important part of the way New Zealand manages skid resistance of its network (Cook, Kennedy, and Newland 2008). However, it should be noted that some studies did not find the seasonal variation in friction to be statistically significant. For example, no significant effect of the air temperature on friction was found in Indiana (Li et al. 2005), whereas work in Washington State (Corsello 1993) concluded that no temperature adjustment was required.

The U.K. has a long term study of skid resistance on in-service roads underway (Donbavand and Kennedy 2008; Greene and Caudwell 2008). A total of 39 benchmark sites are being surveyed by the SCRIM three times a year, once in each of the three SCRIM periods (early, mid and late) between May and September. It has been found that the skid resistance for the 2006 and 2007 results are significantly lower than those from the years 2002 to 2005; this suggests that the summer periods for 2006 and 2007 are dryer than they have been in the previous 4 years.

**ASTM Tire versus Natural Rubber Tire**

Special tests were performed to evaluate the effects of temperature and speed on American Society for Testing and Materials (ASTM) tires, as opposed to natural rubber tires (Wambold 1996). In the case of the SAAB friction tester, the natural tire measures considerably below the ASTM tire, whereas in the case of the GripTester, the natural tire still measures lower, but only about half that of the SAAB friction tester (Wambold 1996). The effect of temperature on the two tires of the SAAB friction tester and GripTester showed that, in the case of the SAAB friction tester, the ASTM tire read about the same value throughout the temperature range. However, for the GripTester, both tires gave about the same values (Wambold 1996).

The temperature effects on the ASTM and natural tires on the SFT and the GripTester were inconclusive. However, the natural rubber tires appeared to measure lower frictional values than the ASTM tire at all slip speeds (Wambold 1996). The TX DOT is now testing with a smooth tire with nonstandard rubber at 50 mi/hr (80 km/hr).

**Use of Friction Data**

In the late 1990s, a survey of the pavement friction measurement and evaluation practices of 43 transportation agencies in the U.S. and Canada was conducted, which revealed the following (Henry 2000):

- Hawaii, Massachusetts, and New Hampshire do not use the friction data at all.
- 28 out of 43 agencies perform network surveys for pavement management.
- 20 out of 37 agencies use friction data on a regular basis to create specifications for restoration of pavements and for newly constructed pavement evaluations.
- 26 out of 40 agencies perform friction testing at the crash sites.
- 5 out of 42 agencies (Michigan, Nebraska, New Jersey, Washington, and NASA) measure friction for winter maintenance on highway and runways.
A large amount of friction data has been collected and assessed under the Long Term Pavement Performance (LTPP) program (Titus-Glover and Tayabji 2000). These data can be potentially used for crash and risk assessment analysis, evaluation of the effect of pavement design features, material properties, and construction techniques on skid resistance, and evaluation of the need for intervention to improve skid resistance.

In its advisory circular on friction, the Federal Aviation Administration (FAA) identifies desirable friction and texture values for both HMA and PCC airfield pavements (FAA 1997). It also provides useful specifications to implement the process.

There have been some recent updates regarding the use of friction data, the most important being the draft guide for pavement friction developed under NCHRP Project 1-43 (Hall et al. 2006). Other recent reports that contain updated information on friction testing are also available (FHWA 2006; Perera, Pulipaka, and Kohn 2006; Noyce et al. 2007). FHWA is currently updating its 1980 technical advisory on skid accident reduction program (FHWA 1980), and has also proposed to revise the rules for the Highway Safety Improvement Program (Federal Register, April 24, 2008). These revised guides should be considered when updating skid resistance management programs.

To use the friction data obtained from skid testing effectively, there must be other relevant and complementary data available (e.g., pavement texture, road geometry, rut depth) (Henry 2000). Such data are used with the friction data to develop models and procedures for identifying potential risk and crash areas. It is important to realize that the friction measured in skid testing cannot be used to calculate vehicle-stopping distance for many reasons (Henry 2000). The effect of friction on vehicle-stopping distance is discussed in more detail in a number of publications (Farber et al. 1974; Hall et al. 2006; Noyce et al. 2007). One of the important issues is the significantly greater stopping distances required for trucks compared to automobiles.

**Pavement Texture Measurement Techniques**

**Microtexture Measurement**

Currently, there is no system capable of measuring microtexture profiles at highway speeds. Because of the difficulty in measuring microtexture profiles, a surrogate indicator for microtexture is usually obtained. The British Portable Tester (BPT) can be used to evaluate microtexture based on British Pendulum Number (BPN). It also yields the results highly correlated with the friction at zero-speed of the Penn State Model ($\mu_0$) (Henry 2000).

DFTester measurements taken at the slip speed of 12 mi/hr (20 km/hr) are highly correlated with BPN values ($R^2=0.86$), as the National Aeronautics and Space Administration (NASA) reported based on the results from the Wallops Flight Facility (Henry 2000). Furthermore, the variability among the DFTesters is significantly lower than in the BPTs, which allows for obtaining results that are more reliable (Henry 2000).

One of the newer pavement texture testing devices is RoboTex which is a robotic texture measuring system. It is currently being used primarily to evaluate various PCC surfaces (Ferragut et al. 2007).
Photogrammetric based techniques to measure both microtexture and macrotexture are being investigated (Do 2005; Waters 2006; Goodman, Hassan, and Abd El Halim 2006; El Gendy and Shalady 2008). Also, a proof–of-concept test of the “static” stereo vision texture measuring system has been conducted at the Virginia Smart Road under the Transportation Pooled Fund Program (Flintsch 2008). These techniques show promise for laboratory mix design evaluations and limited field research studies.

In the United Kingdom, SCRIM results are associated with microtexture. Although SCRIM operates at traffic speeds, the slip speed in SCRIM measurements is relatively low. Therefore, it can serve as a surrogate for a microtexture measurement (Henry 2000). Where the macrotexture is lower than 1.0 mm (as indicated by the sand patch), the microtexture required is increased 0.05 SR (Viner, Sinhal, and Parry 2004).

**Polished Stone Value and Aggregate Abrasion Value**

The polished stone value (PSV) is used in U.K., Australia, and New Zealand to assess the susceptibility of aggregate to polishing and to study the relationship between surfacing materials and safety. The procedure includes two steps (Haydon 2005):

1. Accelerated polishing of the aggregate using an accelerated polishing machine (see figure A-15).
2. Determination of the resulting friction using the British Pendulum tester (shown previously in figure A-7).

![Accelerated polishing machine](image)

Figure A-15. Accelerated polishing machine (Haydon 2005).

The aggregate abrasion value (AAV) test measures resistance of the surface to the wear by abrasion under traffic. Poor abrasion resistance can lead to early loss of the texture required for high-speed skid resistance. The test measures different aggregate properties, as compared to the Los-Angeles AAV (LAAV) specified by ASTM C131 (percent weight loss due to abrasion). The problem is that there is no or poor correlation between PSV and AAV (Haydon 2005).
The Micro-Deval test is also being used more frequently to evaluate the quality of aggregates. Typical ranges of test results for various aggregate properties, including the Micro-Deval test, are included in the proposed draft guide for pavement friction (Hall et al. 2006).

**Polished Stone Value and Skid Resistance**

Based on the friction surveys conducted in New Zealand, the following relationship between the polished stone value (PSV) and the skid resistance (SR) value was established (Haydon 2005):

\[
PSV = 100 \times SR + 0.00663 \times CVD + 2.6
\]  

(A-6)

where:

- **SR** = Investigatory level (IL or TL) for the site.
- **CVD** = Commercial Vehicles (>3.5 ton)/lane/day at the end of surfacing life.
- **PSV** = Polished Stone Value of the surfacing aggregate.

It was found that even the aggregates with high PSV rapidly lose skid resistance. Therefore, more experimental data are needed to better correlate PSV and SR (Haydon 2005).

The German Wehner Schulze test is now being proposed within Europe as a replacement for the PSV test (Allen et al. 2008). The test device (see figure A-16) subjects laboratory prepared asphalt samples or cores extracted from the roadway to simulated traffic and measures the change in skidding resistance with time. This test has been accepted by German contractors to predict performance of the mix.

Figure A-16. Wehner Schulze machine (Dunford 2008)
A description of the test procedure and the results of an experiment to test asphalt samples using similar PSV aggregate has been reported. Research on the capabilities of this equipment is ongoing in both the UK (Dunford 2008; Allen et al. 2008) and France (Ledee, Delalande, and Dupont 2005). The availability of both a test device and method for proceeding with laboratory measurements not only on polishing resistance of aggregates, but also directly on the wearing course materials (for the purpose of predicting, as of the mix design stage, the skid resistance potential generated under actual site conditions) now appears to be of fundamental importance (Ledee, Delalande, and Dupont 2005).

Measuring Macrotexture

Measuring pavement macrotexture has been a common practice in Europe for many years. The U.K. has specified macrotexture depths on construction since 1976. France started measuring macrotexture in 2002 (Dupont and Bauduin 2005). Recognition of the importance of the role of pavement macrotexture in providing adequate surface friction is increasing in the U.S. For example, research in North Carolina demonstrated significantly fewer accidents if the mean texture depth was 0.06 in (1.5mm) or greater (Pulugurtha, Kusam, and Patel 2008).

The values of low-speed friction and average texture depth, both of which help explain the conventional longitudinal skid resistance measurements, prove insufficient when it comes to predicting the level of skid resistance mobilized with antilock brake systems. Other indices in the area of macrotexture, and more specifically the density and angularity of indenters, play a vital role in the frictional force generation process at the tire/pavement interface (Delanne 2005).

A number of different methods have been used to measure surface texture. Some of the most commonly used texture parameters, and the measurement methods used to collect the data needed to compute them, are described below.

**Mean Texture Depth (MTD)**

The mean texture depth (MTD) is a texture characteristic that is determined using the traditional *volumetric* method (commonly referred to as the “sand patch test,” shown in figure A-17). As specified in ASTM E-965, the volumetric method uses a special tool to spread a specified volume of very small glass spheres (similar to the size of sand particles) on the pavement in a circular motion. The MTD is computed by dividing the known volume of glass spheres by the calculated average of four equally spaced diameters of the circular patch (Henry 2000).

![Figure A-17. Sand-patch test (Hanson and Prowell 2004)](image-url)
To provide adequate surface friction, the average MTD should be 0.03 in (0.8 mm) with a minimum of 0.02 in (0.5 mm) for any individual test (Hibbs and Larson 1996). A recent survey found that New Zealand, Quebec, and South Australia specified MTD intervention levels in the 0.015 to 0.035-in (0.4 to 0.9-mm) range on higher speed roadways (Henry 2000). Great Britain has also reported a goal of providing an MTD of 0.06 in (1.5 mm) on their newly constructed PCC pavements (Henry 2000). In the U.S., the Minnesota DOT requires a minimum 0.04-in (1-mm) deep macrotexture for newly constructed PCC pavements with a longitudinal artificial carpet drag (MnDOT 2001). However, it is reported that 0.01 in (0.3 mm) depth is lost the first winter due to snowplowing operations (Izevbekhai and Eller 2008).

**Mean Profile Depth (MPD) and Mean Texture Depth (MTD)**

In the past decade, advances in laser technology and computational power have led to the development of systems that measure pavement longitudinal profile at traffic speeds (Henry 2000). The mean profile depth (MPD) is a statistic computed by analyzing 4-in (102-mm) long segments of the collected profile data. After dividing each segment in half, the average of the highest profile peaks in each half is computed (peaks are measured in relation to a determined zero mean profile). The MPD is then computed as the average of all individual segment peaks averages (Henry 2000).

The measured MPD may be used to estimate the more traditional MTD measurement. However, when MPD is used to predict MTD, the result is referred to as an estimated texture depth (ETD). The ETD is comparable to the MTD value that results from the volumetric method (Henry 2000). The expression given for the ETD in the ISO and ASTM practices for calculating MPD is the following (ASTM E-1845):

\[
ETD = 0.8 \times MPD + 0.2
\]  

(A-7)

where:

- **ETD** = Estimated texture depth (mm).
- **MPD** = Mean profile depth (mm).

The MPD is measured using modern high-speed vehicle-mounted laser-based measuring devices or using portable devices. Two of those devices are briefly described below.

The Road Surface Analyzer (ROSAN) system, shown in figure A-18, consists of a van equipped with laser sensors mounted on the front bumper. The instruments can measure the profile accurately at speeds up to 70 mi/hr (112 km/hr) (Henry 2000). The laser measurements are then analyzed and used to compute ETD. However, Flintsch et al. (2003) reported that the laser profiler they tested yielded relationships different than the one used in ASTM E-1845, which suggested a possible bias of approximately 10 percent in the device. Furthermore, some researchers believe that macrotexture measurements on open-graded surfaces are questionable because the laser profiler cannot detect some of the voids that are filled with sand (Flintsch et al. 2003).
The portable CTMeter (figure A-19), introduced in 1998, uses a laser to measure the profile of a circle 11.2 inches (284 mm) in diameter or 35 inches (892 mm) in circumference (Henry 2000). The profile is then divided into 8 segments of 4.4 in (112 mm) and the mean depth of each segment or arc of the circle is computed according to the standard practices of ASTM E-1845. It has been found that the MPD is most accurately estimated when all eight segments depths are averaged. Excellent results have been observed using this method (even on grooved pavements) and the MPD produced by the CTMeter is highly correlated with MTD (Henry 2000).
**Outflow Time (OFT)**

The outflow time (OFT) is a texture-related statistic measured using the Outflow Meter (see figure A-20). The Outflow Meter consists of a transparent vertical cylinder that rests on a rubber annulus placed on the pavement. A valve at the bottom of the cylinder is closed and the cylinder is filled with water. The valve is then opened and the time it takes for the water level to fall by a fixed amount is measured, with the measured amount of time reported as the OFT (Hoerner and Smith 2002). The OFT is highly correlated with the MTD and the MPD on non-porous pavements (Henry 2000). The correlation between MTD and OFT, as measured by the FHWA outflow meter for nonporous surfaces at the NASA Wallops Flight Facility, was found to be as follows (Henry 2000):

\[
\frac{1}{OFT} = 0.58 \times MTD - 0.15
\]

(A-8)

where:

- **OFT** = Outflow time, seconds.
- **MTD** = Mean texture depth, mm.

![Figure A-20. Outflow Meter (Hoerner and Smith 2002).](image)

**Use of Texture Data**

Henry (2000) identified the following areas where the texture measurements are used by transportation authorities worldwide: routine survey, crash analysis, construction, rehabilitation, and pavement management. According to a survey in the U.S., only five SHAs, as well as NASA, use texture data to evaluate pavement surface, as compared with 26 SHAs using the friction measurements (Henry 2000). Among the U.S. state highway agencies, only Louisiana conducts routine surveys of texture, Minnesota incorporated the texture depth requirements into the warranty policies for newly constructed PCC pavements (MnDOT 2001), and Mississippi and Virginia included texture data in their pavement management system.
Several recent studies in the U.K., New Zealand, and Australia (Viner, Sinhal, and Parry 2004; Davies, Cenek, and Henderson 2005; Oliver 2005) indicated that, while the correlation of the crash rate with surface friction appeared to be questionable, the pavement texture depth was found to have a strong relationship with the crash rate. Therefore, including the texture measurements along with friction data in the crash analysis should not be neglected.

The relationship between texture and crashes is being evaluated in a number of current projects. New Zealand reports considerable success in reducing total road crashes 17.5 percent over the past 12 years since beginning an annual SCRIM survey and requiring minimum texture depths on new projects (Owen, Cook, and Cenek 2008).

The State of Victoria, Australia recently reported on an analysis of the relationship between road surface characteristics and crashes on undivided two-way roads (Cairney and Bennett 2008). Surface condition data from multi-laser profilometer surveys was linked to geometry, traffic, and crash data using GIS and the resulting tables analyzed to investigate the relationships. The three road surface characteristics were either uncorrelated or showed small enough correlations to disregard possible interactions among the variables. Crash rates were higher for road sections with low macrotexture and were also higher for roads where roughness was extreme. No clear relationship emerged between rutting and crash rate. VicRoads has for some years relied on macrotexture as the basis for its rural skid resistance monitoring program, and adopts a minimum SPTD of 0.05 in (1.2) mm in its maintenance guidelines.

The NC DOT recently conducted an analysis of macrotexture vs. crash rates on 330 ft (100 m) segments on five different projects (Pulugurtha, Kusam, and Patel 2008). The analysis showed a strong relationship exists between pavement macrotexture and crash incidences on NC roads. Analysis and evaluation indicate that crashes decrease with an increase in pavement macrotexture. Pavement macrotexture greater than or equal to 0.06 in (1.5 mm) but typically less than 0.12 in (3 mm) was considered most appropriate to provide safe and efficient transportation to road users (Pulugurtha, Kusam, and Patel 2008).

Finally, the fact that the texture data have not yet seen widespread use may be explained by the false belief that macrotexture is highly correlated with skid numbers, which can be obtained by testing at the traffic speeds. Conversely, it was recently believed that the most reliable macrotexture measuring devices are static and require interruption of the traffic flow, while the laser profiler has not yet reached the desirable level of reliability. Recent research has shown both of these beliefs to be either incorrect or misleading. However, research also has revealed that better information on detailed microtexture and macrotexture characteristics related to specific mixes is necessary to develop prediction of performance and to improve the correlation of texture with both total and wet crash rates.

**Relationship Between Pavement Texture, Friction Number and Skid Resistance**

The surface friction of a pavement is an important component of overall road safety. Therefore, there is a desire to predict the changes in surface friction over time using currently available friction and texture data. The following three options have been proposed for predicting the skid resistance (FHWA 1977):
1. Obtain the skid number (SNV) at a particular speed by interpolation or extrapolation from SN values obtained at two different speeds.

2. Predict SNV at a specified speed from the measurements of SN_{40} and from the evaluation of macrotexture.

3. Predict SNV from parameters of microtexture and macrotexture.

**Interpolation (Extrapolation) Method**

Based on the data obtained from 31 test sections subjected to three different surface treatments (sprinkle, hot-mix, and seal-coat) and three speeds of testing (40, 50, and 60 mi/hr [64, 80, and 96 km/hr]), the linear relationship between the test speed and SN was analyzed by linear regression method. As shown in figure A-21, the results yielded high coefficients of correlation between predicted and measured SN_{50} (r = 0.99 for interpolation and r = 0.98 for extrapolation), while the extrapolation errors were larger. Nevertheless, the variations were tolerable with standard deviation of 1.66SN (FHWA 1977).

![Figure A-21. Comparison of two prediction equations (FHWA 1977).](image-url)
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

**Prediction of \( SN_V \) from the Measurement of \( SN_{40} \) and from the Evaluation of Macrotexture**

**Texture and Friction in Asphalt Pavements**

According to a model developed by the European corporation ENSCO, the skid number \( SN_V \) at a specified speed \( V \) can be derived from the skid number \( SN_{40} \) obtained at the speed of 40 mi/hr (64 km/hr) and the speed gradient \( PNG \), as follows:

\[
SN_V = SN_{40} e^{\frac{PNG(V-40)}{100}} \quad (A-9)
\]

where:

- \( SN_V \) = Skid number at a specified speed \( V \).
- \( SN_{40} \) = Skid number at the speed of 40 mi/hr (64 km/hr)
- \( PNG \) = Percent normalized gradient (the speed gradient times 100 divided by the friction).

The gradient PNG was modeled in the ENSCO procedure based on the West Virginia asphalt pavement texture data. The mean texture depth (MTD) measured by sand-patch method was used as a predictor, and the following exponential relationship was modeled:

\[
PNG = A \cdot e^{-B(MTD)} \quad (A-10)
\]

where:

- \( MTD \) = Mean texture depth, mm
- \( A, B \) = Regression coefficients

The Pennsylvania Transportation Institute (PTI) independently developed a different model based on the same (West Virginia) data. This model involved the power relationship between PNG and MTD, expressed as follows:

\[
PNG = C \cdot (MTD)^D \quad (A-11)
\]

where \( C \) and \( D \) are regression coefficients.

As can be observed from figure A-22, the PTI model corresponds well with the ENSCO model for values of MTD not exceeding 0.02 in (0.5 mm) and PNG calculated for speed varying between 30 and 40 mi/hr (48 to 64 km/hr). However, for deeper texture, the PTI tends to predict much higher PNG compared with the ENSCO model, which results in underestimating skid resistance (\( SN_V \)). Nevertheless, the field measurements conducted in Texas to verify those models yielded a very good correlation between predicted and measured skid resistance at a speed of 60 mi/hr (96 km/hr) (\( SN_{60} \)), as shown in figure A-23 (FHWA 1977).
Figure A-22. Comparison of equations for predicting PNG from macrotexture (sand-patch) measurements (FHWA 1977).

Figure A-23. Predicted versus measured SN$_{60}$ from Texas study (FHWA 1977).
Texture and Friction in PCC Pavements

An experimental study conducted on PCC pavements in Georgia indicated that texture affects both pavement friction characteristics and speed gradients (FHWA 1977). Among five finishing techniques discussed, the surface with grooves cut in the plastic concrete demonstrated the highest skid resistance and yielded the lowest gradient with an increase in the test speed, as shown in figure A-24.

![Figure A-24. Speed gradient curves for different texturing techniques (FHWA 1977).](image)

Prediction of \( SN_V \) from Microtexture and Macrotexture

Four procedures for predicting \( SN_V \) from parameters associated with microtexture and macrotexture are discussed in the 1977 FHWA report. The first two are useful for prediction from in situ measurements, while the other two are based on laboratory test data.

The Lees and Katekhda Method

In this model, the skid number \( SN_V \) at a specified speed \( V \) is calculated based on \( SN_{20} \)—low-speed skid number correlated with British Pendulum Number (BPN), which is measure of microtexture,—and on the macrotexture parameter \( (m) \) as measured by the outflow meter. The equation for the Lees-Katekhda model resembles equation A-2 and looks as follows (FHWA 1977):

\[
SN_V = SN_{20}e^{-m(V-20)}
\]  

(A-12)

where:
SN_V = Skid number at a specified speed V.
V = Speed of testing, mi/hr.
SN_{20} = Skid number at the speed of 20 mi/hr (32 km/hr).
m = Macrotexure parameter.

It should be noted that the model was not verified on an independent dataset. Additionally, this method may not be valid for a laboratory design procedure (FHWA 1977).

**The Leu and Henry Model**

This model was developed based on BPN as a measure of microtexture and MTD obtained by sand-patch method. The regression analysis of the data from 20 bituminous pavements in West Virginia yielded the following relationship (FHWA 1977):

\[
SN_V = (1.38(BPN) - 31)e^{-0.041V(MTD)^{-0.47}} \tag{A-13}
\]

where:

SN_V = Skid number at a specified speed V.
V = Speed of testing, mi/hr.
MTD = Mean texture depth, mm.
BPN = British Pendulum Number.

The equation above was tested on an independent dataset, and the correlation between the predicted SN_{40} and the measured SN_{40} was 0.68 and 0.83 for the fit of the open-graded courses and dense-graded courses, respectively.

**The Hankins and Underwood Design Procedure**

This procedure was developed to predict the skid resistance of dense-graded AC surfaces. The researchers used six Schonfeld parameters, as follows (FHWA 1977):

1. Macrotexure height.
2. Macrotexure width.
3. Macrotexure shape.
4. Density of macrotexure.
5. Microtexture harshness of the macrotexure.
6. Microtexture harshness of the background or matrix.

By applying this procedure, the “as polished” or terminal skid numbers of proposed mixes can be predicted in terms of SN_{30} and SN_{60} (and SN_{40} by interpolation). Texas validated this approach on 14 existing designs and obtained an excellent correlation of 0.97.
Relationship Among Surface Characteristics and Roadway Safety

Safety (reducing deaths, injuries and traffic delays) on public roads and highways is becoming a prevailing concern to transportation authorities, as well as to highway users. While many other factors (driver awareness, driver behavior, automobile safety features, and so on) affect road safety, poor pavement surface parameters (including surface friction and texture) are reported to contribute to (not cause) approximately 30 percent of the annual fatalities in U.S. (Larson 2005). Before analyzing the relationship between safety and its influencing factors, the quantitative and qualitative criteria of road safety are described in the following sections.

Definitions of Roadway Safety Criteria

This section describes quantitative and qualitative definitions of road safety criteria used by the transportation authorities in the U.S. and overseas. It also discusses the approach to a crash data assessment.

Crash Risk

When road safety is assessed, the crash risk, or the risk of involvement in an injury-producing crash, is used as the primary criterion. It is usually defined as a qualitative parameter (e.g., high, moderate, and low crash risk), although it is assessed using quantitative components (Haydon and Rambisheswar 2005). Thus, according to the Australian guidelines of risk management, risk has three components: the hazard, the consequence of that hazard (safety, environmental and economic) and the likelihood with which the hazard occurs, or is expected to occur (Haydon and Rambisheswar 2005). These three terms can be combined, as shown below.

\[ \text{Risk}_{\text{hazard}} = \text{Consequence} \times \text{Likelihood} \]  

(A-14)

Figure A-25 illustrates the risk matrix for the Auckland city network obtained by production of the consequence and likelihood matrices (Haydon and Rambisheswar 2005). The consequence matrix is associated with each hazardous situation and takes into account speed, environment, visibility, event category (e.g. pedestrian crossing, one-way bridges, and so on), and potential skid hazard (in Australia and NZ, this is related to the use of PSV 52-54 aggregates). The likelihood matrix involves traffic volume as an indicator of the exposure to the risk suggesting that high traffic volumes are usually associated with greater crash risk. The quantitative values of likelihood and consequences are translated to the qualitative descriptors associated with the risk investigation routine, and the risk matrix is created as shown in figure A-25. The letters in side each cell depict high (H), medium (M), and low (L) level of the crash risk, while the digit presents the number of sites associated with this level of the crash risk.

Crash Rate and Crash Density

The crash rate is one of the criteria of the crash risk used in New Zealand (Kennedy, Haydon, and Donbavand 2005). It is defined as a ratio of the total average number of injury crashes per site over the total average daily number of vehicles entering the site over year divided by 10^8. Usually, the crash rate is used to assess the existing investigatory levels of surface friction and to establish the new ones, when the crash rates changes.
<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Insignificant (No injuries)</th>
<th>Minor (First Aid required)</th>
<th>Moderate (Med/Hospital treatment)</th>
<th>Major (Extensive injury)</th>
<th>Critical (Fatal, v.serious injury)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (almost certain)</td>
<td>H-0</td>
<td>H-0</td>
<td>E-0</td>
<td>E-0</td>
<td>E-0</td>
</tr>
<tr>
<td>B (likely)</td>
<td>M-0</td>
<td>H-6</td>
<td>H-0</td>
<td>E-0</td>
<td>E-0</td>
</tr>
<tr>
<td>C (possible)</td>
<td>L-9</td>
<td>M-29</td>
<td>H-9</td>
<td>E-3</td>
<td>E-0</td>
</tr>
<tr>
<td>D (unlikely)</td>
<td>L-15</td>
<td>L-22</td>
<td>M-10</td>
<td>H-4</td>
<td>E-0</td>
</tr>
<tr>
<td>E (rare)</td>
<td>L-59</td>
<td>L-65</td>
<td>M-7</td>
<td>H-4</td>
<td>H-0</td>
</tr>
</tbody>
</table>

Figure A-25. Skid risk matrix for Auckland city network (Haydon and Rambisheswar 2005).

The *crash density* is the number of crashes per year for each kilometer of the road and is calculated for each of the sites (Kennedy, Haydon, and Donbavand 2005). This factor does not depend on traffic and, when used in conjunction with the crash rate, can be very useful in the investigation of road safety issues.

**Crash Data Assessment**

Before linking crash data with the influencing factors, it should be assessed in terms of site classification and crash location. The practice of crash site classifications differs between the transportation agencies, as do the crash location techniques. However, the main goal of the crash data assessment is identifying the relationship between pavement geometric characteristics, friction measurements, and prevailing climatic conditions and the crash data.

**Crash Database and Site Classifications**

**U.S. Experience**

Larson (2005) reported that the Highway Safety Information System (HSIS) is a comprehensive multi-State safety database containing crash, road inventory, and traffic volume data from nine state (California, Illinois, Maine, Michigan, Minnesota, North Carolina, Ohio, Utah, and Washington State) roadway systems. He noted that, although the HSIS data are used for studying the current safety issues and for evaluating the effectiveness of crash countermeasures, the HSIS system does not include detailed pavement condition and surface characteristics data (Larson 2005). However, the expected publication of the Highway Safety Manual in the U.S. in 2009 includes safety tools (the Integrated Highway Safety Design Model-IHSDM and the SafetyAnalyst model) to evaluate these issues.
Council and Harkey (2006) emphasized the need of improving safety data in the U.S. before making sound decision on the roadway design and operation. The authors suggested the following strategies to overcome deficiencies in safety databases (Council and Harkey 2006):

- Increase support for both safety programs and safety information systems from top-level administrators in State and local transportation agencies.
- Define good inventory data and institutionalize continual improvement toward established performance measures.
- Make safety data easier to collect, store, and use.
- Increase the use of critical safety analysis tools.
- Store and link safety data with critical nonsafety data.

**U.K. Experience**

A comprehensive safety study was conducted in the U.K. based on the English trunk roads database (Viner, Sinhal, and Parry 2005). In this database, the network was divided into lengths of 1660 ft (500 m) on motorways and 660 ft (200 m) for other roads. All crash sites were classified into 13 site categories, as shown in table A-2, and were linked to the pavement condition and road geometry data available from routine surveys of the trunk road network. Details of over 100,000 personal injury crashes recorded in the period between 1994 and 2000 were examined, along with other applicable information such as the condition of the road at the time of the crash (wet/dry) and whether skidding was involved. However, it is known that skidding accidents are significantly underreported, and in a subsequent study, it was decided to incorporate all accidents that occurred on wet/damp surfaces, not just wet skidding accidents (Morrison, Grant, and Donbavand 2008).

**New Zealand Experience**

The 22,000-mi (35,000-km) long network safety database was analyzed in New Zealand (Davies, Cenek, and Henderson 2005). In that study, the crash data was divided into the following four subsets:

- All injury and fatal crashes.
- Selected crashes involving different types of vehicle movement (see table A-3).
- Wet weather crashes.
- Crashes satisfying both wet and selected criteria.

The researchers reported that only about 75 percent of data could be retrieved, largely due to the following reasons: (1) insufficient data about the location, (2) location data do not correspond to a valid section of state highway, (3) location not surveyed by Sideway-Force Coefficient Routine Investigation Device (SCRIM).
Table A-2. Summary of data available for the analysis (Viner, Sinhal, and Parry 2005).

<table>
<thead>
<tr>
<th>Site category</th>
<th>Number of length with data</th>
<th>Median length (m)</th>
<th>Total length (km)</th>
<th>Data coverage (% of whole network)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorway</td>
<td>3979</td>
<td>500</td>
<td>1901</td>
<td>56</td>
</tr>
<tr>
<td>Dual c/way non-event</td>
<td>8246</td>
<td>200</td>
<td>1648</td>
<td>59</td>
</tr>
<tr>
<td>Single c/way non-event</td>
<td>9026</td>
<td>200</td>
<td>1711</td>
<td>67</td>
</tr>
<tr>
<td>Dual c/way minor junction</td>
<td>359</td>
<td>93</td>
<td>41</td>
<td>40</td>
</tr>
<tr>
<td>Single c/way minor junction</td>
<td>2096</td>
<td>70</td>
<td>202</td>
<td>73</td>
</tr>
<tr>
<td>Major junction</td>
<td>909</td>
<td>57</td>
<td>80</td>
<td>49</td>
</tr>
<tr>
<td>Gradient 5 to 10%</td>
<td>708</td>
<td>200</td>
<td>126</td>
<td>82</td>
</tr>
<tr>
<td>Gradient steeper than 10%</td>
<td>14</td>
<td>190</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>Bend&lt;250m</td>
<td>453</td>
<td>120</td>
<td>62</td>
<td>46</td>
</tr>
<tr>
<td>Approach to roundabout</td>
<td>57</td>
<td>75</td>
<td>6</td>
<td>22</td>
</tr>
<tr>
<td>Approach to signals, crossings etc.</td>
<td>402</td>
<td>53</td>
<td>22</td>
<td>42</td>
</tr>
<tr>
<td>Bend&lt;100m</td>
<td>534</td>
<td>50</td>
<td>31</td>
<td>59</td>
</tr>
<tr>
<td>Roundabout</td>
<td>286</td>
<td>196</td>
<td>52</td>
<td>42</td>
</tr>
</tbody>
</table>

Table A-3. Description of vehicle movement codes (Davies, Cenek, and Henderson 2005).

<table>
<thead>
<tr>
<th>Movement Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Overtaking and Lane Change</td>
</tr>
<tr>
<td>B</td>
<td>Head On</td>
</tr>
<tr>
<td>C</td>
<td>Lost Control or Off Road (Straight Roads)</td>
</tr>
<tr>
<td>D</td>
<td>Cornering</td>
</tr>
<tr>
<td>F</td>
<td>Rear End</td>
</tr>
</tbody>
</table>
Locating Crashes

The transportation authorities in the U.S. use different methods of crash site identification, as was reported in a 1990 survey (Dahir and Grambling 1990). When asked how the crash locations are identified and reported, 52 percent of the agencies answered that they use a milepost system, 24 percent reported using a variation of a log mile, and the remaining 24 percent of the participants used nodes of the nearest landmark. The participants of the survey reported a great variability in the accuracy of the crash location. In 32 of 50 agencies surveyed, it varied from 0.01 mile (0.016 km) to 0.5 mile (0.8 km). Eight agencies reported the accuracy over the range of 40 to 93 percent. The other 10 agencies gave descriptive responses (2 – good, 1 – fairly good, 2 – as good as report, 1 – poor to excellent, 2 – unknown) (Dahir and Grambling 1990). Finally, the survey indicated concern about how many of the crashes reported are located with sufficient accuracy to satisfy the analysis requirements of the data.

Improved tools for locating crashes are being developed in conjunction with the development of the Highway Safety Manual. Information on GIS based Safety Tools is available from the FHWA Turner-Fairbank Highway Research Center. Additional information on using new technology in safety analysis is found in a recent NCHRP synthesis (Ogle 2007).

Overseas, researchers have utilized advanced techniques for reporting crash locations. For example, in the U.K., researchers used a GIS package (Viner, Sinhal, and Parry 2004), while in New Zealand, researchers reported using X/Y coordinates of crashes to the nearest centerline point of the appropriate road section (Davies, Cenek, and Henderson 2005). Nevertheless, there exists a concern about the precision of locating the crash, if the section length is small. Haydon (2005) found that instability in the data was influenced by the following factors: (1) small sample size (small amount of data), (2) short sections length (166 ft [50 m]), and (3) relatively great tolerance permitted by the local marking standard (33 ft [10m] +0.3 percent). As a result, the crash location could be in error of 150 to 230 ft (45 to 70 m) over a 9.5 to 12.5 mile (15 to 20 km) route.

A new method of referencing skid resistance measurements has been developed in New Zealand. The use of a differential global position system is used to produce an improved method of location along a linear-based referencing system. One obvious deficiency of this system is in locations where GPS coverage is not available (Blagdon, Kennedy, and Mitchell 2008).

After the crash data are assessed, as discussed above, the next step is to identify the factors affecting safety and analyze the relationship between those factors and crash risk, as presented in the next section.

Factors Affecting Safety

Understanding the factors affecting road safety is vital for minimizing the number of roadway crashes. The results from a number of crash investigations have suggested that there are relationships between crash occurrence and pavement conditions. Researchers have not yet reached an agreement regarding which factor is most important to safety. For instance, some research identified the environmental and climatic conditions as most important for drivers (Tighe et al. 2000). However, other investigations estimate that poor surface conditions...
including low friction and inadequate pavement texture contribute to approximately 30 percent
of annual highway fatalities (Larson 2005). This section documents the findings from several
studies on the investigation of the following groups of factors that potentially affect road safety:

- Pavement surface characteristics (skid resistance and texture).
- Pavement roughness (IRI) and surface distresses (ruts, faults, potholes, cracks and
  others).
- Pavement geometric design (gradient, horizontal curvature, cross-sectional slope).
- Other factors (environmental and weather conditions, visibility of the surface, paving
  materials and pavement mix design, lane marking, safety signs, and roadside obstacles).

**Analysis Approach**

**Choosing Variables and Data Collection**

The texture depth (MPD) and skid resistance (SCRIM coefficient) were collected to evaluate the
relationship between surface friction and number of crashes in the U.K. (Viner, Sinhal, and Parry
2004) and New Zealand (Davies, Cenek, and Henderson 2005). Other pavement data collected
by the SCRIM device and used in the analysis included:

- Gradient, percent.
- Horizontal curvature radius, m.
- Cross-sectional slope, percent.
- International Roughness Index (IRI), m/km.
- Rut depth, mm.

The data were collected over 33 ft (10 m) intervals (with the exception that IRI and rut depth
were obtained at 66 ft [20 m] intervals) and were linked to the crash data by the survey year.

**Methods of the Data Analysis**

Two outstanding studies related to the investigation of the relationship between surface
characteristics and road safety in the U.K. and New Zealand are discussed below in terms of the
analysis approach.

**Viner, Sinhal, and Parry 2004**

A two-stage analysis was conducted in the U.K. study based on the data collected from English
trunk roads (Viner, Sinhal, and Parry 2004). First, the mean and 95 percentile crash risk was
calculated for each site category to relate the crash rate to the specific range of investigatory
levels (IL) of skid resistance. Crash risk was defined as the total number of crashes per 100
million-vehicle km driven. Then, the crash models were developed using a Generalized Linear
Modeling (GLM) approach to evaluate the effect of other factors, such as traffic flow, road
condition and geometry, on the skid resistance. All variables that were significant individually
were then combined in a model of the form (Viner, Sinhal, and Parry 2004):
\[ R = k \cdot Q^\alpha \cdot L^\beta \cdot \exp(a_1x_1 + a_2x_2 + a_3x_3) \] (A-15)

where:
- \( R \) = Number of crashes.
- \( Q \) = Traffic flow.
- \( L \) = Length of the road section.
- \( x_1 \) to \( x_3 \) = Other variables including the skid resistance.
- \( k, \alpha, \beta \) = Regression coefficients.
- \( a_1 \) to \( a_3 \) = Regression coefficients.

Any variables found to be non-significant in the combined model were dropped, starting with the least significant, until a final model was reached and the contribution of skid resistance could be assessed for each site category (backward-eliminating method of regression analysis).

Davies, Cenek, and Henderson 2005

To evaluate the effect of skid resistance and texture depth along with other pavement characteristics on crash risk in the New Zealand state highway network, the analysis of the crash and road data was conducted using two methods:

1) One-way and two-way table analysis to indicate the factors affecting the crash risk.

2) Regression analysis based on Poisson’s distribution to identify the important variables and estimate their influence.

One-Way Tables

Segments of the State Highway network were divided into categories using only one road characteristic (e.g. Annual Daily Traffic [ADT], horizontal curvature [R], SCRIM Coefficient [SC]) and average crash rate for each category. The results are summarized in table A-4, presenting crash rate versus the SCRIM coefficient.

Table A-4. Classification by pavement skid resistance (Davies, Cenek, and Henderson 2005).

<table>
<thead>
<tr>
<th>SCRIM Coefficient (SC)</th>
<th>Road Length (km)</th>
<th>Number of Crashes between 1997 &amp; 2002</th>
<th>Total Traffic Exposure (10^6 v-km)</th>
<th>Crash Rate (10^8 vkt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC &lt; 0.3</td>
<td>18</td>
<td>40</td>
<td>150</td>
<td>27</td>
</tr>
<tr>
<td>0.3 &lt; SC &lt; 0.4</td>
<td>294</td>
<td>730</td>
<td>3125</td>
<td>23</td>
</tr>
<tr>
<td>0.4 &lt; SC &lt; 0.5</td>
<td>2610</td>
<td>5144</td>
<td>28048</td>
<td>18</td>
</tr>
<tr>
<td>0.5 &lt; SC &lt; 0.6</td>
<td>4953</td>
<td>5421</td>
<td>32649</td>
<td>17</td>
</tr>
<tr>
<td>0.6 &lt; SC &lt; 0.7</td>
<td>2046</td>
<td>1287</td>
<td>7637</td>
<td>17</td>
</tr>
<tr>
<td>SC ≥ 0.7</td>
<td>116</td>
<td>62</td>
<td>372</td>
<td>17</td>
</tr>
</tbody>
</table>
Two-Way Tables

Two-way tables present the crash data versus two classifying variables at a time. Thus, table A-5 reports the crash rate versus horizontal curvature (R) and SCRIM coefficient (SC) (Davies, Cenek, and Henderson 2005). The results in the table look somewhat controversial, that is, when SC exceeds 0.5 and R is greater than 32,800 ft (10,000 m), the crash rate grows. However, the tables can be somewhat misleading because they do not consider the errors in locating crashes and may not indicate the presence of masked variables, so it was decided to conduct a regression analysis.

Table A-5. Crash rate by horizontal curvature and SCRIM coefficient (Davies, Cenek, and Henderson 2005).

<table>
<thead>
<tr>
<th>Horizontal Curvature, R (m)</th>
<th>Crashes per $10^8$ vkt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SCRIM Coefficient Range</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.3</td>
</tr>
<tr>
<td>10 ≤ R &lt; 100</td>
<td>55</td>
</tr>
<tr>
<td>100 ≤ R &lt; 1000</td>
<td>55</td>
</tr>
<tr>
<td>1000 ≤ R &lt; 10000</td>
<td>13</td>
</tr>
<tr>
<td>10000 ≤ R &lt; 100000</td>
<td>32</td>
</tr>
<tr>
<td>R ≥ 100000</td>
<td>0</td>
</tr>
</tbody>
</table>

Regression Analysis

Davies, Cenek, and Henderson (2005) used the exponential regression of expected number of crashes per year (CRASH) on road condition and road geometry parameters to link the crash data with the pavement design features and surface friction characteristics. The analysis was made under the following assumptions:

- Crashes are statistically independent.
- The number of crashes per 10 m of road per year follows a Poisson distribution.

The general form of the model was expressed as follows:

\[ CRASH = ADTe^L \quad (A-16) \]

where:

- \( CRASH \) = Expected number of crashes per year
- \( ADT \) = Average daily traffic
- \( L = \sum \beta_i x_i \)
and:

$$\beta_i = \text{Regression coefficient}$$

$$x_i = \text{Various road characteristics such as:}$$

- Absolute gradient.
- Horizontal curvature.
- Cross-sectional slope.
- Skid-site category.
- Skid resistance (SCRIM).
- $\log(ADT)$.
- Year.
- TNZ administration region.
- Urban/rural classification.

To neutralize the effect of traffic, the model was simplified by converting $CRASH$ to $CRASHRATE$ (number of crashes per $10^8$ vehicle-km) by multiplying by a factor equal to $10^8/(ADT*365*Road Length)$:

$$CRASHRATE = \frac{10^{10}}{365} e^L$$

Finally, the linear model was converted to an exponential model, which was more convenient for analysis:

$$\ln(CRASHRATE) = \ln\left(\frac{10^{10}}{365}\right) + L$$

Surface Friction and Safety

A survey conducted among drivers on 5,000 mi (8,050 km) of road network in the U.S. (see table A-6) surprisingly revealed the relatively low sensitivity of drivers to surface texture and friction, as compared with environmental conditions and visibility (Tighe et al. 2000). Clearly, the low driver awareness of the surface friction does not prove the lack of the effect of the available pavement surface friction on the potential crash risk, as other research reports.

The crash data collected on English trunk roads between 1994 and 2000 in the U.K. was analyzed using the generalized linear modeling (GLM) approach (Viner, Sinhal, and Parry 2005). Figure A-26 illustrates the results for the three groups of sites included in the analysis:

1. “Non-event” highway sections (motorways, two-lane roadways, single-lane roadways).
2. Junctions (two-lane minor, single-lane minor, major).
3. Approaches (roundabout approaches, signal approaches, roundabouts).
Table A-6. Classes of factors associated with safety attributes (Tighe et al. 2000).

<table>
<thead>
<tr>
<th>Class of Factors</th>
<th>Safety Attributes or Indicators</th>
<th>Sensitivity of Drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Texture or Friction</td>
<td>• macrotexture and microtexture characteristics, such as International Friction Index (IFI)</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>• skid resistance or skid number measures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• vehicle tire type standards</td>
<td></td>
</tr>
<tr>
<td>Pavement Roughness or Riding Quality</td>
<td>• riding comfort rating, or roughness, such as International Roughness Index (IRI)</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>• roughness vs. speed relationship</td>
<td></td>
</tr>
<tr>
<td>Pavement Surface Distress</td>
<td>• severity and extent of surface distresses, such as ruts, faults, potholes, cracks, spalls, etc.</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>• distress index</td>
<td></td>
</tr>
<tr>
<td>Pavement Geometric Design and Location</td>
<td>• widths of lanes and shoulders, median, and pedestrian paths, paved or gravel shoulders</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>• cross slopes of pavement surface</td>
<td></td>
</tr>
<tr>
<td>Visibility of Pavement Surface Features</td>
<td>• pavement surface color and reflectivity</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>• lane markings and signings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• visibility at night and bad weather conditions</td>
<td></td>
</tr>
<tr>
<td>Pavement Materials and Pavement Mix Design</td>
<td>• type of pavement</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>• texture and color of paving materials</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• mineralogy and anti-skid properties</td>
<td></td>
</tr>
<tr>
<td>Road Safety Measures and Facilities</td>
<td>• safety warning signs</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>• safety protection facilities</td>
<td></td>
</tr>
<tr>
<td>Environmental and Weather Conditions</td>
<td>• place and time of crash occurrence</td>
<td>Very High</td>
</tr>
<tr>
<td></td>
<td>• roadside obstacles and safety facilities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• precipitation (fog, rain, snow) and wind, etc.</td>
<td></td>
</tr>
</tbody>
</table>
Figure A-26. Mean crash risk by the site categories for English trunk roads (Viner, Sinhal, and Parry 2005).
The following conclusions could be drawn from the analysis of the trends presented in figure A-26 (Viner, Sinhal, and Parry 2005):

- The effect of skid resistance on the mean crash risk on motorways is not significant, although there is a small increase in crash risk when the SCRIM Coefficient (SC) is below 0.35.
- The effect of skid resistance on the mean crash risk on carriageways is consistent, while the single-way pavements (one traffic lane in each direction) are prone to a greater crash risk than the dual-way pavements (two traffic lanes in each direction).
- For junctions, a clear relationship between the mean crash risk and skid resistance was observed for two-lane minor junctions and signal approaches. However, the main conclusion that can be drawn from figure A-26 is that the skid coefficient alone cannot be used to predict the crash on junctions and roundabouts, since other more important factors are present.

In a study of freeways in Switzerland, based on a very large data set obtained between 1999 and 2002, researchers failed to identify any conclusive relation between pavement skid resistance and crash occurrence for either wet or dry pavements (Lindenmann 2004). Figure A-27 shows the trends that were observed. However, it was concluded in this study that a systematic search for areas with very low skid resistance (SFC<0.32) would allow identifying individual, randomly distributed danger zones.

![Figure A-27. Correlation of skid resistance and crash rate/wet crash rate (Lindenmann 2004)](image)

An investigation performed in New Zealand involved crash data collected between 1996 and 2002 on a 13,660-mi (22,000-km) long highway network, and showed the strong association of the crash rate with skid resistance (SCRIM coefficient was used as a measure of friction) (Davies, Cenek, and Henderson 2005). Figure A-28 illustrates the decrease in crash rate with the increase in skid number.
The site investigation process used extensively in the U.K. has been described in detail. The information from the Preliminary Investigation should be recorded by the Site Investigator as part of a site investigation report (Stevenson, Philips, and Trotman 2008). The report should include the following details:

- Surface characteristics i.e. surface type, age, PSV, and so on.
- Collision records.
- Whether a secondary investigation is required.
  - If a treatment is needed.
  - If it is believed the investigatory level (IL) should be reduced.
  - If a revision is needed to the site category.
- Whether further investigation is required (along with justification).

Once the preliminary investigations have been completed, there will remain a list of sites where further more detailed investigation is warranted. This secondary investigation will look at the site with a view to determining the extent of any change in IL if appropriate. This investigation will also provide the information required for treatment selection and to enable subsequent prioritization of the site for maintenance treatment. The information obtained during the Secondary Investigation should as minimum include (Stevenson, Philips, and Trotman 2008):

- General condition of the road at the site:
  - Does low skid resistance also coincide with low levels of texture?
  - Are there extreme levels of rut depth that could make ponding of water likely?
  - Do the surface characteristics comply with original design criteria?
  - Is the structural condition adequate to provide a reasonable life for any surface treatment?

Figure A-28. Crash rate versus SCRIM Coefficient (Davies, Cenek, and Henderson 2005).
relationship between skid resistance numbers measured with ribbed and smooth tire and wet-accident locations

- Volume and type of traffic including vulnerable road users:
  - Are the observed traffic speeds appropriate to the nature of the site?
  - What are the types of maneuvering made at the site and the consequences of not completing them successfully (e.g., potential for head-on or side impact at speed)?
  - Is there a need to redesign junction areas to control maneuvers?
  - Are other road users vulnerable (i.e., pedestrians, cyclists, and motor cyclists)?

- Road layout:
  - Does the road layout deviate significantly from the current standards for geometric design?

- Visibility:
  - What is the general visibility for the road user?

- Pavement markings:
  - Are the warnings and direction signs appropriate and effective?
  - Are the markings clearly visible?

- Reasons for a proposed change in the sites IL and the suggested new level.

The comprehensive review of studies related to the safety and pavement condition issues showed that the majority of studies identified skid resistance as a very important factor to decrease the crash rate (Larson 2005). Although a significant amount of friction-related research is being conducted in other countries (U.K., Australia, and New Zealand), a few U.S. states are initiating surface friction studies in an effort to establish new standards and enhance safety.

Pavement Texture and Safety

It has been reported that 16 to 19 percent of the fatal crashes occurred on wet pavement when the tire-surface friction was minimal (Hoerner and Smith 2002; Larson, Scofield, and Sorenson 2004). However, since the 1980s, considerable research (in the U.K., New Zealand, France, and Australia) has been conducted to evaluate the effect of pavement texture as an essential surface characteristic on the potential crash risk. The key findings of some noticeable studies are discussed in this section.

The analysis of the crash rate on English trunk roads in the period between 1994 and 2000 showed texture depth to be a significant variable in a number of categories (Viner, Sinhal, and Parry 2004). It was observed that the highest crash risk arises from a combination of low skid resistance and low texture depth and that the trend with skid resistance is even more pronounced at low texture depth (see figure A-29).
Larson, Scofield, and Sorenson (2004) estimated that 70 percent of wet weather crashes could be prevented with improved texture/friction. Therefore, an analysis of friction and texture versus average crash rate would more clearly demonstrate the benefit of increased texture and friction on reducing fatalities and serious injuries.

Davies, Cenek, and Henderson (2005) in New Zealand found that reduced mean crash risk was apparently associated with increasing texture, although this relationship was not statistically significant. As shown in figure A-30, a texture depth increase from 0.02 to 0.12 in (0.5 to 3.0 mm) reduces crash risk from 18.8 to 17.6 crashes per $10^8$ vehicle-km in the model considered here (i.e., a reduction of 1.2 crashes per $10^8$ vehicle-km, corresponding to a 7 percent reduction in crash rate).
Several studies in the U.K. and Australia showed a strong correlation between crash rate and macrotexture (Oliver 2005). It was thought that high macrotexture permits increased levels of hysteretic (deformation) friction to be developed by vehicle tires thus reducing crashes. Figure A-31 demonstrates that the crash rate on pavements with texture depth shallower than 0.04 in (1 mm) was significantly higher than on pavements with texture depth deeper than 0.04 in (1 mm).

![Figure A-31. Proportion of crashes of different types at different texture levels compared with distribution of texture levels in Network C (Oliver 2005).](image)

It was also found that the SCRIM results associated with microtexture underestimated the available friction, which implied that including the macrotexture requirement in pavement management guides might be more effective in reducing crash rates on high speed roads than the skid resistance requirements associated with SCRIM numbers (Oliver 2005).

As opposed to the U.K. study, the analysis of the macrotexture data against the crash data in three Australian states (Western Australia, South Australia, and Victoria) did not yield conclusive results (Oliver 2005). In Western Australia, for example, a strong association of the higher crash rate with low level macrotexture was found for all rural sites on the Great Eastern Highway, and for some urban sections. However, in South Australia and Victoria, the statistical analysis identified mixed trends. A significant correlation was found between crashes and macrotexture for rural sections in the South Australian network, but such correlation for rural sites in the Victorian network was nonsignificant at the 5 percent level. In the case of urban sections, the researchers did not find a significant correlation for South Australian sites but did find a highly significant correlation for Victorian sites (Oliver 2005). Furthermore, crashes involving heavy vehicles appeared to be concentrated on sections with a high level of macrotexture rather than on sections with a low level of macrotexture for both rural and urban sites.
Despite the controversial results obtained in some Australian studies presented above, the following findings appear to be accepted (Oliver 2005):

- The low-speed skid resistance (as measured by SCRIM) did not correlate with the crashes on the high speed roads.
- The increased risk of crashes was highly associated with a low level of macrotexture (less than 0.04 in [1 mm]).

A recent paper reports on an analysis of the relationship between road surface characteristics and crashes on high speed undivided two-way roads in the state of Victoria, Australia (Cairney and Bennett 2008). The crash rate was observed to be higher for road sections with low macrotexture, and an economic analysis suggests that resurfacing sites with macrotexture of 0.04 in (1 mm) SPTD or less would produce crash savings which would provide a very good return on the investment (Cairney and Bennett 2008).

The North Carolina DOT recently completed a study evaluating the role of pavement macrotexture in crashes on selected roads (Pulugurtha, Kusam, and Patel 2008). Laser profilometer data were processed to calculate estimated pavement macrotexture at 330-ft (100 m) intervals. Crash data were collected over the same lengths. The resulting data analysis showed a strong relationship between macrotexture and crash incidences on the five projects evaluated, and indicated that crashes decrease with an increase in pavement macrotexture. Macrotexture greater than or equal 0.06 in (1.5 mm) but typically less than 0.12 in (3 mm) would be the most appropriate to provide safe and efficient transportation to road users (Pulugurtha, Kusam, and Patel 2008).

**Relationship Between Safety and Pavement Roughness and Surface Distress**

The impact of pavement conditions and surface distress on rural roads was recently investigated (Tighe et al. 2000). The effect of the International Roughness Index (IRI) and Pavement Serviceability Rating (PSR) on single-vehicle, multiple-vehicle, and total crash rates was evaluated using mathematical modeling and regression analysis. Based on the regression analysis, it was found that a decrease in single-vehicle crash rate was associated with an increase in IRI, or with the deterioration of ride quality. It might be explained by the decrease in operational speed due to reduction in the quality of driving, and consequent reduction in the probability of crashes. Conversely, an increase in the multiple-vehicle crash rate was associated with the increase in roughness, which could be explained by the following two factors (Tighe et al. 2000):

- The increase in the lateral variation in the vehicle path with increase in roughness, and consequent reduction in the clearance distance between vehicles.
- The presence of road defects (potholes, severe alligator cracks, and so on) that force drivers to change their driving speeds abruptly.
Davies, Cenek, and Henderson (2005) in New Zealand attempted to predict crash rates from a number of factors, among them pavement roughness (IRI) and rut depth in the top asphalt layer. The fitted regression plots presented in figure A-32 suggests no relationship between the crash rate and the rut depth; however, the effect of IRI on crash rate appeared to be significant. When observing the fitted line on the plot of crash rate versus IRI, one should take in account only the part of line starting with \( \log_{10} IRI = 0.3 \), which corresponds to an IRI of 126 in/mi (2 m/km) (lower boundary of the IRI range included in the model).

![Figure A-32. Crash rate versus IRI and rut depth (Davies, Cenek, and Henderson 2005).](image_url)

An updated report on “The Influence of Roadway Surface Discontinuities on Safety” has been prepared, with a number of important changes since the original 1983 document, including (TRB 2008):

1. **Hydroplaning** – It was found, contrary to common engineering understanding in 1983, that large tractor/trailer rigs are also subject to hydroplaning at usual highway speeds when in an unloaded condition. Further advances were made in predicting hydroplaning critical speeds.

2. **Holes and Bumps** – Research was completed in defining road roughness frequencies that are most influential in affecting tire-pavement friction. For example, the movement to 17 to 20 in (432 to 508 mm) rims in many new automobiles are more susceptible to damage due to interaction with holes, bumps and edges.

3. **Edge Conditions** – In 1983, few tests of edge conditions above 55 mi/hr (88 km/hr) had been conducted. With speed limits of 70 mi/hr (112 km/hr) now more common, research has shown some pavement edges to be of more concern at elevated speeds. Research on certain edge shapes has shown safety improvements that can be made during construction and maintenance. These improved methods are gaining acceptance through a combination of research and positive experience.

4. **Discontinuities** – A new chapter has been added that deals with positive influences of discontinuities such as rumble lines, rumble strips, rumble zones and speed bumps.
**Lane Width and Shoulders**

A study by Tighe et al. (2000) on nearly 5,000 mi (8,050 km) of two-lane highways in the United States identified the lane width and the shoulder width as very important factors affecting road safety. It was found that widening the lane by 4 ft (1.2 m) reduces the number of crashes by 40 percent, while widening the shoulder by 8 ft (2.4 m) reduces the number of crashes by 49 percent (Tighe et al. 2000). However, research conducted in New Zealand over a 13,660-mi (22,000-km) long network found that lane width was not a significant factor influencing crash rate (Davies, Cenek, and Henderson 2005).

The development of the Highway Safety Manual (expected to be published in 2009) and the Integrated Highway Safety Design Model and the SafetyAnalyst models being developed/refined by FHWA will significantly aid the analysis of geometric design features on safety.

**Curvature and Gradients**

In the U.K. study, the effect of gradient on the crash risk on English trunk roads could not be evaluated because of a lack of sections with a steep gradient (Viner, Sinhal, and Parry 2004). In the same study, the effect of curvature on crash risk was evaluated in terms of interaction with the skid resistance on the curves. When evaluating the two-way effect of skid resistance and road curvature on crash risk, the researchers concluded that the lower the skid coefficient the larger the effect of curvature on the crash risk. Additionally, at any radius of curvature, the higher the skid resistance, a lower crash risk would be expected (Viner, Sinhal, and Parry 2004).

Davies, Cenek, and Henderson (2005) found that in New Zealand the crash rate was expected to decrease when the radius of road curvature increased from 328 to 3280 ft (100 to 1000 m), and from 1640 to 32,808 ft (5000 m to 10,000 m). The increase in the crash rate with an increase of curvature within 32 to 328 ft (10 to 100 m) (this range is usually associated with intersections) could be explained by the presence of hazards other than high curvature of the road (see figure A-33). The effect of the gradient on the crash rate was difficult to interpret because upward and downward gradients cannot be distinguished (Davies, Cenek, and Henderson 2005).

![Figure A-33. Crash rate versus curvature and gradient (Davies, Cenek, and Henderson 2005).](image-url)
Other Factors Affecting Safety

Tighe et al. (2000) evaluated the potential effect of different factors on the crash occurrence based on the results of the survey conducted on 5,000 mi (8050 km) of U.S. highways. They revealed that the environmental and weather conditions including place and time of the crash occurrence, road obstacles, and precipitation were the most sensitive issue for drivers. In addition, the study identified the high sensitivity of drivers to the visibility of pavement surface features, which included pavement surface color and reflectivity, lane marking and signings, and visibility at night and during bad weather conditions.

Another survey conducted on English trunk roads reported that drivers had a low awareness of the slippery road warning signs (Sinhal 2005). As a result, the following was recommended:

- Warning signs should be fewer in number but better targeted.
- Warning signs should be erected as soon as possible following receipt of data.

The review of literature related to the investigation of the factors affecting safety revealed no strong agreement among researchers about the significance of the correlation between friction number as measure of the surface friction and the crash risk. On the other hand, the effect of macrotexture on the crash rate was indicated in the majority of the studies. Nevertheless, as the low speed friction is acknowledged to be the microtexture-related parameter, the friction measurements along with texture measurement are included by many transportation agencies (primarily in Australia, Europe, and New Zealand) in their guidance on assessing road safety.

Development of Desirable Levels of Texture/Friction for Highway Networks

The review of the state of practice related to the road safety in the U.S. and overseas showed that the pavement surface friction and texture significantly affect the wet-crash risk. Therefore, assuring the appropriate level of safety on the roads should be included in pavement management system. However, different site categories may require different level of skid resistance and macrotexture. For example, junctions and bends with low radius of curvature require higher levels of friction and texture than high-speed highways in rural areas (Viner, Sinhal, and Parry 2004). The definitions and approach to establishing the skidding standards for use in pavement management activities are discussed in this section.

Determining Intervention Levels of Skid Resistance

As discussed previously, surface friction and texture depth measurements can be used to assess the pavement safety conditions. Additionally, these parameters can help pavement engineers determine pavement maintenance strategy and programs (Tighe et al. 2000). For example, the SCRIM coefficient along with MPD may be used to guide maintenance treatment strategies, as illustrated in figure A-34.
In this figure, the chart is broken into four quadrants. The upper right-hand quadrant represents a pavement that meets the agency’s standards for friction and safety levels from a pavement surface point of view. The bottom right quadrant represents pavements that have good macrotexture (MPD), but poor microtexture (which is associated with SCRIM). The opposite conditions exist in the upper left quadrant, where the microtexture is good but the macrotexture needs improvement. In the bottom left quadrant, both macrotexture and microtexture are in need of improvement.

Although each agency must develop its own chart for establishing the friction trigger levels based on the equipment being used to measure these values, the approach shown above provides a framework for establishing guidelines to address a strategic issue such as safety in a consistent manner throughout the agency. Each agencies pavement preservation program provides an opportunity to significantly improve the overall friction and texture on their network (Zimmerman and Larson 2005).

While the emphasis in the U.S has been on setting minimum friction levels rather than desirable levels, the U.K. and New Zealand use desirable and investigatory levels of skid resistance in their safety management programs, as described in the next section.

**Threshold versus Investigatory Levels of Skid Resistance**

Extensive research has been conducted since the 1930s in the U.K. to determine an appropriate level of skid resistance. By the early 1970s, different skidding standards were assigned to three types of sites (Viner, Sinhal, and Parry 2004):
1. “Most difficult sites” (e.g., roundabouts and sharp bends).
2. “Average sites” (e.g., motorways and high-speed roads).
3. “Other sites” (mainly straight roads with easy gradients and curves and no junctions).

In addition, macrotexture levels have been specified since 1976. However, the use of a single threshold value (TL) sometimes led to the interpretation that a value below the TL indicated that a dangerous situation existed. Such interpretation could trigger unjustifiable pavement treatment and eventual spending. In the 1990s, an alternative “investigatory level” (IL) of skid resistance was introduced in the U.K. The IL would require a detailed examination of the site and assessment of need for remedial work rather than automatic intervention to improve skid resistance. This approach is highly recommended and is now being considered in the U.S. (Chelliah et al. 2003; Hall et al. 2006).

The recent study in the U.K. (Viner, Sinhal, and Parry 2005) indicated a high variability of the crash risk within the same site category. This, along with the changes in traffic and pavement materials, called for revision of the existing skid resistance policy. As a result, new site categories and Investigatory levels were introduced. These are summarized in table A-7, where dark shading indicates the normal range of IL and light shading indicates a lower IL appropriate for low risk situations (e.g., very light traffic).

Table A-7. Site categories and investigatory levels used in the United Kingdom (Viner, Sinhal, and Parry 2005).
Allocating Skid Resistance Investigatory Levels on the Basis of Risk Analysis

The research in the U.K. demonstrated the advantage of using a range of ILs for each category site (Viner, Sinhal, and Parry 2005). It allowed for lowering IL for the sites with a lower risk of crash than would be expected for the particular site and, consequently, for allocating funds to those sites where improvements are required. On the other hand, the sites with a greater crash risk would be assigned a higher IL.

A study was conducted in New Zealand to apply the concepts of variable IL and to access the benefits and cost of changing the skid resistance policy (Kennedy, Haydon, and Donbavand 2005). A methodology consisting of the following five steps was employed:

1. Select a sample network.
2. Validate the site category definition.
3. Incorporate the latest friction survey data and evaluate.
4. Assessment of the crash risk.
   - Site visits.
   - Incorporate crash data into the database.
   - Investigate the overall risk associated with the validated sites.
5. Determine benefits and costs of changing from the current policy to a risk management based approach

Both the U.K. (Viner, Sinhal, and Parry 2005) and the New Zealand study (Kennedy, Haydon, and Donbavand 2005) found, as follows:

- The risk management approach can be objectively used to assign appropriate investigatory levels of skid resistance and to estimate the saving in number of crashes.
- The benefit cost analysis indicated that even when using expensive surface treatments (e.g., calcined bauxite), the benefits due to crash savings outweighed the cost of treatment.

Since 1995, New Zealand has conducted an annual SCRIM survey and also introduced a mandatory macrotexture survey, which is measured in terms of Mean Profile Depth (MPD). New surfacings require a minimum of 0.03 in (0.9 mm) MPD and a Threshold Level of 0.02 in (0.5 mm) MPD. It has been determined that SCRIM data are a valuable input into the selection of surfacings and aggregate and is a good project tool (Boyle 2008).

An evaluation of the effectiveness of Transit New Zealand’s T/10 specification for skid resistance was recently undertaken, evaluating time-series data over a 12-year period from 1995 to 2006 (Owen, Cook, and Cenek 2008). The principal findings from the analysis are summarized below (Owen, Cook, and Cenek 2008):
- There has been a significant reduction (between 25 and 50 percent) in crash rates between 1995 and 1998 for all crash categories investigated, with the reductions being greater for urban roads than for rural roads and for “wet” crashes than for “all” crashes.
- The fatal and injury crash rate on wet rural State Highways over the period 1998 to 2006 is trending downwards (reducing 1.1 percent per year), whereas the rate of all crashes is largely static for this period. By comparison, both “all” and “wet” crash rates on local authority rural roads are trending upwards, with the “all” crash rate increasing by 1.2 percent per year since 1998 and the “wet” crash rate increasing by 0.9 percent per year.
- The “all” and “wet” crash rates for urban roads has remained relatively static for both State Highways and Territorial Local Authorities over the period 1998 to 2006.

Improvements in macrotexture and microtexture, as demonstrated by annual measurements, have helped to improve the skid resistance of the state highway network, thereby reducing the risk of loss of control type crashes in wet conditions and consequently contributed to the wet road crash statistics. This data supports the effectiveness of New Zealand efforts to improve friction and texture on their State Highway network (Owen, Cook, and Cenek 2008).

In September 2007, the U.K. issued an interim document providing guidance on implementing their skid resistance policy, with specific information on setting the investigatory level, conducting the site investigation, prioritizing treatments, and using slippery road warning signs (Highways Agency 2007). A summary of guidance on implementation and a discussion of the objectives of the additional guidance is also available (Viner and Caudwell 2008).

Twenty years after the introduction of Standards in the U.K. for aggregates used in road surfacing materials and for in-service skid resistance, it is clear that these approaches have been widely adopted and have produced a number of benefits, including better skid resistance and keeping claims arising from slippery surfaces to an acceptably low level. However, benefits in terms of accident reduction have not been quantified adequately, and so it is difficult to assess whether the anticipated benefits of these Standards are being delivered in practice. Gathering information to allow better monitoring of in-service skid resistance and to support quantification of accident benefits is therefore a future priority for the Highways Agency (Sinhaal and Viner 2008).

Approaches similar to that used by the U.K. are now being considered in the U.S. (Hall et al. 2006). The Highway Safety Manual currently being developed and expected to be published in 2009 will significantly expand guidance in this area. In addition, the work under NCHRP 17-25 will contain an appendix that includes an evaluation of crash modification factors for improving the pavement surface friction and texture (Lyon and Persaud 2008). This is the first time that skid resistance has been included as a specific countermeasure.

**Determining Safety on the Network Using Macrotexture**

Australia has conducted an analysis of the relationship between road surface characteristics and crashes on high speed rural undivided two-way roads in the state of Victoria (Cairney and Bennett 2008). The research results indicated a power relationship between crash rate and macrotexture, and a polynomial relationship between crash rate and roughness, both of which
will need further scrutiny. The crash rate for the lowest texture category is more than double the crash rate for most of the range. Macrotexture was less than 0.04 in (1.0 mm) SPTD on 5.7 percent of the network. From an economic analysis, it was postulated that resurfacing sections where macrotexture is 0.04 in (1.0 mm) SPTD or less would have substantial benefits in terms of crash reductions. VicRoads has for some years relied on macrotexture as the basis for its rural skid resistance monitoring program and adopts a minimum SPTD of 0.05 in (1.2 mm) in its maintenance guidelines (Cairney and Bennett 2008).

Safer communities is one of the five key long-term priority objectives of Queensland, Australia and safer roads is one of its top four key outcomes (Weligamage and Dowling 2008). During the period from 1992 to 2003, the fatality rate dropped 40 percent and has recently remained stable with about 330 annual fatalities (Weligamage and Dowling 2008). Introduction of the new emphasis on skid resistance prompted the Queensland Department of Main Roads (QDMR) to compile a Skid Resistance Management Plan (SRMP), which (Weligamage 2006):

- Defines QDMR’s overall objective and central strategy for managing skid resistance.
- Establishes a corresponding suite of Key Performance Indicators (KPIs).
- Describes action necessary to achieve the overall objective and to implement the central strategy for skid resistance.
- Identifies QDMR’s processes for managing skid resistance.

The SRMP also serves as an interim depository for technical guidelines on skid resistance, such as the measurement regimes for skid resistance and surface macrotecture, pending completion of sufficient research and development to warrant issuing QDMR guidelines. The SRMP is structured around the generic asset management framework used by QDMR, and comprises a six-step process of (Weligamage 2006):

1. Consistent measurement of skid resistance and surface texture (Chapter 5);
2. Consistent management of data on skid resistance and surface texture (Chapter 6);
3. Consistent analysis of data on skid resistance and surface texture (Chapter 7);
4. Consistent use of data in reaching decisions about remedial actions (Chapter 8);
5. Consistent design, construction and maintenance practices (Chapter 9); and
6. Quantified performance targets, regular reviews and feedback (Chapter 10).

In addition, Chapter 11 in the SRMP suggests 38 future actions for QDMR to consider that are likely to support further improvements in the management of skid resistance. These future actions are similar to the “Suggested Improvements to Friction Practices and Desired Areas of Friction Guidance” found in Appendix D of the recent NCHRP guide document (Hall et al. 2006). The suggested improvements listed clearly indicate the need for additional research and guidance to practicing engineers to help provide the public the safer roads that they deserve and expect.
Closing Remarks

A review of published studies and ongoing research concerning the effect of pavement surface conditions on road safety suggests that providing an adequate pavement surface friction and texture could significantly reduce the number of wet weather and total crashes in the U.S. However, other pavement characteristics (surface distress, roughness), geometry, and roadside design should not be neglected when designing for safe pavements. Traffic volumes and climatic conditions also have a significant effect.

Skid testing along with texture depth measurements provide a robust estimate of surface friction characteristics. While a wide range of skid testing and texture measuring devices are used in the U.S. and overseas, the main concern is the correlation between different measuring techniques and their harmonization to make the test results meaningful to practicing engineers. The calibration of testing devices is essential to minimize the errors and to provide repeatability and reproducibility of the testing results. In the future, greater quantification of the pavement texture will be needed to improve correlations of smooth tire friction test data and crashes and to better quantify the friction developed by anti-lock brake systems.

However, it must be recognized that no single variable (ribbed tire friction, smooth tire friction, or macrotexture) by itself is highly correlated to crash rates. The correlation of these single variables and crash rates is always less than 10 percent. Therefore it is critical that the wet/total crash rate and a minimum number of annual wet crashes also be considered in identifying sections where surface treatments will be cost-effective.

Understanding the factors affecting road safety is vital for minimizing the number of roadway crashes. The results from a number of crash investigations have suggested that there are relationships between crash occurrence and pavement conditions. Analysis of the correlation between skid and texture data and crash risk allows for the prediction of crash risk in the future and for the planning of pavement management activities based on safety considerations.

Managing the pavement skid resistance and texture depth at the appropriate level allows for reducing the probability of crashes. Given the current state of the practice, it is essential that fatal and serious injury accidents be accurately identified, located, and quickly entered into a database for analysis. The total and wet/total crash rates are critical for identifying sections where low friction/texture may be contributing to increased numbers of accidents. Other factors like surface distress, roughness, and traffic levels must not be ignored. Therefore, assuring an appropriate level of safety on the roads should be included in pavement and asset management systems. Monitoring systems should be developed to include key performance indicators that are updated annually to verify that improvements are being made to the overall system and that they are cost effective.

As mentioned throughout this appendix, there is a significant amount of research underway in this area. Some of the major products expected within the next year include:

- Publication of the Guide for Pavement Friction (conducted under NCHRP project 1-43) as an AASHTO document.
• Updated guidance on Highway Safety Improvement Programs (See Notice of Proposed Rulemaking 23 CFR 924 4/24/08).
• Updated 1980 FHWA Technical Advisory on Skid Accident Reduction Program.
• Iowa State University Report of PCC Pavement Surface Texturing.
• Completion of NCHRP Project 10-69, *Texturing of Concrete Pavement*.
• In 2009, the TRB Highway Safety Manual.

**References**


Clonch, D. 2006. “Ohio Department of Transportation Road Grip Tester Project.” *Proceedings, GIS for Transportation Symposium*. Columbus, OH.


Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations


Minnesota Department of Transportation (MnDOT). 2001. MnDOT TH 14/218 Design-Build RFP. Minnesota Department of Transportation, Saint Paul, MN.


APPENDIX C—DATA PLOTS

During the analysis portion of this project, many different data plots were produced to help identify potentially meaningful trends in the data. While not all of these produced data plots were referenced in the main body of this report, all are interesting in their own context. This appendix summarizes all of the data plots that were produced during the analysis portion of this project. In order to help the reader find plots of interest, the different general categories of investigations (and the associated figure numbers) are summarized in table C-1 below.

Table C-1. Summary of data plot categories included in Appendix C.

<table>
<thead>
<tr>
<th>Data Plot Type</th>
<th>Data Set Explanation</th>
<th>Associated Figure Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet/total crash ratio vs. various variables</td>
<td>All from all three site categories are analyzed together.</td>
<td>C-1 through C-6</td>
</tr>
<tr>
<td>Wet/total crash ratio vs. various variables</td>
<td>Data are analyzed separately within each of the three site categories.</td>
<td>C-7 through C-17</td>
</tr>
<tr>
<td>Total crashes per year vs. various variables</td>
<td></td>
<td>C-18 through C-23</td>
</tr>
<tr>
<td>Rear end crash rate vs. various variables</td>
<td></td>
<td>C-24 through C-29</td>
</tr>
<tr>
<td>Total crashes per year in test direction vs. various variables</td>
<td></td>
<td>C-30 through C-35</td>
</tr>
<tr>
<td>FN statistics vs. MTD statistics</td>
<td></td>
<td>C-36 through C-42</td>
</tr>
<tr>
<td>FN statistics vs. other miscellaneous variables</td>
<td></td>
<td>C-43 through C-47</td>
</tr>
<tr>
<td>Total crashes in test direction for different FN ranges and cumulative percentage of all crashes (in test direction) vs. FN</td>
<td></td>
<td>C-48 through C-59</td>
</tr>
</tbody>
</table>
Figure C-1. Wet/total crash ratio vs. FN40 for all sections.

Figure C-2. Wet/total crash ratio vs. friction number at posted speed limit for all sections.
Figure C-3. Wet/total crash ratio vs. mean texture depth (Avg. and Min) for ALL sections.

Figure C-4. Wet/total crash ratio vs. speed gradient for ALL sections.
Figure C-5. Wet/total crash ratio vs. IRI for ALL sections.

Figure C-6. Wet/total crash ratio vs. average daily traffic for ALL sections.
Figure C-7. Wet/total crash ratio vs. FN40 for different site categories.
Figure C-8. Wet/total crash ratio vs. FN at posted speed limit for different site categories.
Figure C-9. Wet/total crash ratio vs. mean texture depth for different site categories.
Figure C-10. Wet/total crash ratio vs. speed gradient for different site categories.
Wet/Total Crash Ratio vs. IRI (Avg and Max) for Congested Freeways

\[ y = 0.0032x - 0.0073 \quad R^2 = 0.2381 \]

\[ y = 9E-05x + 0.2055 \quad R^2 = 0.0351 \]

Wet/Total Crash Ratio vs. IRI (Avg and Max) for Signalized Intersections

\[ y = -9E-05x + 0.2919 \quad R^2 = 0.0019 \]

\[ y = -9E-05x + 0.3246 \quad R^2 = 0.028 \]

Wet/Total Crash Ratio vs. IRI (Avg and Max) for Unsignalized Intersections

\[ y = -0.0004x + 0.2919 \quad R^2 = 0.0145 \]

\[ y = -0.0002x + 0.305 \quad R^2 = 0.0543 \]

Figure C-11. Wet/total crash ratio vs. IRI for different site categories.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

Wet/Total Crash Ratio vs. Average ADT for Congested Freeways

\[ y = 2 \times 10^{-6}x + 0.0463 \]

\[ R^2 = 0.3232 \]

Wet/Total Crash Ratio vs. Average ADT for Signalized Intersections

\[ y = 2 \times 10^{-6}x + 0.2471 \]

\[ R^2 = 0.0054 \]

Wet/Total Crash Ratio vs. Average ADT for Unsignalized Intersections

\[ y = 9 \times 10^{-6}x + 0.1377 \]

\[ R^2 = 0.0939 \]

Figure C-12. Wet/total crash ratio vs. average daily traffic for different site categories.
Figure C-13. Wet/total crash ratio vs. FN40R for different crash ratio categories (low, medium, high) within different site categories.
Figure C-14. Wet/total crash ratio vs. FN40S for different crash ratio categories (low, medium, high) within different site categories.
Figure C-15. Wet/total crash ratio vs. MTD average for different crash ratio categories (low, medium, high) within different site categories.
Figure C-16. Wet/total crash ratio vs. FN40R for different locations (urban vs. rural) within different site categories.
Figure C-17. Wet/total crash ratio vs. FN40R for different ADT levels within different site categories.
Total Crashes Per Year vs. FN40 (Avg and Min) for Congested Freeways (Ribbed and Smooth Tires)

\[ y = -58.281 \ln(x) + 239.39 \]
\[ R^2 = 0.1606 \]

\[ y = -59.488 \ln(x) + 240.05 \]
\[ R^2 = 0.1857 \]

\[ y = -48.91 \ln(x) + 189.32 \]
\[ R^2 = 0.134 \]

\[ y = -56.424 \ln(x) + 208.24 \]
\[ R^2 = 0.1831 \]

Total Crashes Per Year vs. FN40 (Avg and Min) for Signalized Intersections (Ribbed and Smooth Tires)

\[ y = -7.4972 \ln(x) + 35.511 \]
\[ R^2 = 0.1806 \]

\[ y = -7.4496 \ln(x) + 34.864 \]
\[ R^2 = 0.201 \]

\[ y = -6.4728 \ln(x) + 29.452 \]
\[ R^2 = 0.118 \]

\[ y = -5.5801 \ln(x) + 26.047 \]
\[ R^2 = 0.1186 \]

Total Crashes Per Year vs. FN40 (Avg and Min) for Unsignalized Intersections (Ribbed and Smooth Tires)

\[ y = -1.7719 \ln(x) + 11.767 \]
\[ R^2 = 0.0347 \]

\[ y = -1.5932 \ln(x) + 11.018 \]
\[ R^2 = 0.0288 \]

\[ y = -1.4314 \ln(x) + 10.028 \]
\[ R^2 = 0.0268 \]

\[ y = -0.7781 \ln(x) + 7.7938 \]
\[ R^2 = 0.0091 \]

Figure C-18. Total crashes per year vs. FN40 for different site categories.
Figure C-19. Total crashes per year vs. FN at posted speed limit for different site categories.
Figure C-20. Total crashes per year vs. mean texture depth for different site categories.
Figure C-21. Total crashes per year vs. speed gradient for different site categories.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

Total Crashes Per Year vs. IRI (Avg and Max) for Congested Freeways

y = 0.6433x - 24.602
R² = 0.2136

y = 0.0338x + 11.527
R² = 0.1048

Total Crashes Per Year vs. IRI (Avg and Max) for Signalized Intersections

y = -0.0093x + 10.714
R² = 0.025

y = -0.0031x + 10.857
R² = 0.042

Total Crashes Per Year vs. IRI (Avg and Max) for Unsignalized Intersections

y = 0.008x + 4.427
R² = 0.0252

y = 0.0008x + 5.0711
R² = 0.0036

Figure C-22. Total crashes per year vs. IRI for different site categories.
Figure C-23. Total crashes per year vs. average daily traffic for different site categories.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

Figure C-24. Rear end crash rate vs. FN40 for different site categories.
Figure C-25. Rear end crash rate vs. FN at posted speed limit for different site categories.
Figure C-26. Rear end crash rate vs. mean texture depth for different site categories.
Figure C-27. Rear end crash rate vs. speed gradient for different site categories.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

Figure C-28. Rear end crash rate vs. IRI for different site categories.
Figure C-29. Rear end crash rate vs. average daily traffic for different site categories.
Figure C-30. Total and directional crashes per year vs. FN40 for different site categories.
Figure C-31. Total crashes per year in test direction vs. FN at posted speed limit for different site categories.
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Figure C-34. Total crashes per year in test direction vs. IRI for different site categories.
Figure C-35. Total crashes per year in test direction vs. average daily traffic for different site categories.
Figure C-36. FN20 statistics vs. MTD average for different site categories.
Figure C-37. FN20 statistics vs. MTD minimum for different site categories.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

**FN40 Statistics vs. MTD Avg. for Congested Freeways**
(Ribbed and Smooth Tires)

- FN40R Avg: \( y = 10.974 \ln(x) + 41.579 \)
  \( R^2 = 0.0784 \)
- FN40R Min: \( y = 10.795 \ln(x) + 39.202 \)
  \( R^2 = 0.0738 \)
- FN40S Avg: \( y = 19.077 \ln(x) + 32.570 \)
  \( R^2 = 0.3433 \)
- FN40S Min: \( y = 16.791 \ln(x) + 29.168 \)
  \( R^2 = 0.3261 \)

**FN40 Statistics vs. MTD Avg. for Signalized Intersections**
(Ribbed and Smooth Tires)

- FN40R Avg: \( y = -0.437 \ln(x) + 34.377 \)
  \( R^2 = 0.0001 \)
- FN40R Min: \( y = 0.1228 \ln(x) + 32.526 \)
  \( R^2 = 1 \times 10^{-5} \)
- FN40S Avg: \( y = 2.3806 \ln(x) + 24.582 \)
  \( R^2 = 0.0052 \)
- FN40S Min: \( y = 3.2642 \ln(x) + 22.705 \)
  \( R^2 = 0.01 \)

**FN40 Statistics vs. MTD Avg. for Unsignalized Intersections**
(Ribbed and Smooth Tires)

- FN40R Avg: \( y = -2.8306 \ln(x) + 39.450 \)
  \( R^2 = 0.0058 \)
- FN40R Min: \( y = -2.1081 \ln(x) + 37.344 \)
  \( R^2 = 0.0035 \)
- FN40S Avg: \( y = 12.298 \ln(x) + 31.651 \)
  \( R^2 = 0.1783 \)
- FN40S Min: \( y = 12.083 \ln(x) + 29.202 \)
  \( R^2 = 0.1735 \)

Figure C-38. FN40 statistics vs. MTD average for different site categories.
Figure C-39. FN40 statistics vs. MTD minimum for different site categories.
Figure C-40. FN60 statistics vs. MTD average and minimum for congested freeways.
Figure C-41. FN at posted speed limit vs. MTD average for different site categories.
Figure C-42. FN at posted speed limit vs. MTD minimum for different site categories.
Figure C-43. FN40 vs. temperature at time of testing for different site categories.
Figure C-44. FN at posted speed limit vs. temperature at time of testing for different site categories.
Figure C-45. Speed gradient vs. temperature at time of testing for different site categories.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

Figure C-46. FN vs. testing speed for different site categories.
Figure C-47. FN ribbed vs. FN smooth at different testing speeds for different site categories.

Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations
Figure C-48. Total crashes in test direction for different FN40 ranges on congested freeways.

Figure C-49. Cumulative percentage of all crashes (in test direction) observed on congested freeways vs. FN40 for ribbed and smooth tires.
Figure C-50. Total crashes in test direction for different FN60 ranges on congested freeways.

Figure C-51. Cumulative percentage of all crashes (in test direction) observed on congested freeways vs. FN60 for ribbed and smooth tires.
Figure C-52. Total crashes in test direction for different FN20 ranges on signalized intersections.

Figure C-53. Cumulative percentage of all crashes (in test direction) observed on signalized intersections vs. FN20 for ribbed and smooth tires.
Figure C-54. Total crashes in test direction for different FN40 ranges on signalized intersections.

Figure C-55. Cumulative percentage of all crashes (in test direction) observed on signalized intersections vs. FN40 for ribbed and smooth tires.
Figure C-56. Total crashes in test direction for different FN20 ranges on unsignalized intersections.

Figure C-57. Cumulative percentage of all crashes (in test direction) observed on unsignalized intersections vs. FN20 for ribbed and smooth tires.
Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet-Accident Locations

**Figure C-58.** Total crashes in test direction for different FN40 ranges on unsignalized intersections.

**Figure C-59.** Cumulative percentage of all crashes (in test direction) observed on unsignalized intersections vs. FN40 for ribbed and smooth tires.