Wisconsin Highway Research Program

Wet Pavements Crash Study of Longitudinal and Transverse Tined PCC Pavements

SPR # 0092-00-08

Alex Drakopoulos and David A. Kuemmel
Center for Highway and Traffic Engineering
Marquette University

June 2007

WHRP 07-04

Acknowledgments

This report was compiled by Alex Drakopoulos and Dave Kuemmel of Marquette University, Milwaukee, Wisconsin. The authors gratefully acknowledge the help of a great number of individuals, without whom this volume would have not been possible: From the Wisconsin Department of Transportation-Steve Krebbs, Dave Larson, Dick Lange, Brad Javenkoski, Mike Schumacher, Peter Amakobe, Laura Fenley; from the Turner-Fairbank Highway Research Center, Yusuf Mohamedshah; from the Midwest Research Institute Doug Harwood; from NOAA William Brown; from the Wisconsin State Climatologist Office Lyle Anderson; and all individuals mentioned in **Appendix I**. Any errors or omissions are solely the responsibility of the authors.

Disclaimer

This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project # 0092-01-06. 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 of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

Technical Report Documentation Page

1. Report No. WHRP 07-04	2. Government Accession No	3. Recipient's Catalog No

4. Title and Subtitle Wet Pavements Crash Study of Longitudinal and Transverse Tined PCC Pavements	5. Report Date June 2007
	6. Performing Organization Code Univ. of Wisconsin - Madison
7. Authors Alex Drakopoulos and David A. Kuemmel	8. Performing Organization Report No.
9. Performing Organization Name and Address Center for Highway and Traffic Engineering Marquette University	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. WisDOT SPR# 0092-00-08
12. Sponsoring Agency Name and Address Wisconsin Department of Transportation Division of Business Services Research Coordination Section 4802 Sheboygan Ave. Rm 104 Madison, WI 53707	13. Type of Report and Period Covered Final Report, 2000-2007
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report provides crash statistics for Longitudinally Tined (LT) Portland Cement Concrete (PCC) and Transversely Tined (TT) PCC pavement surfaces. The statistics were compiled for urban and rural freeways, classified in two Average Daily Traffic (ADT) categories: pavements carrying less than 60,000 vehicles per day (VPD) and those carrying an ADT in excess of 60,000 VPD.

Crash experience on California longitudinally tined PCC pavements was compared to that of Wisconsin transversely tined PCC pavements. Safety performance of wet pavements was the focus of the analysis. Rural freeways were considered to be ideal for this study, given the prevailing high speeds, absence of extraneous influences on safety (e.g., cross streets, on-street parking, pedestrians, traffic signals), and consistent design standards between the comparison states. Rainfall differences were accounted for with the use of hourly precipitation data, and terrain differences were taken into account by using level and rolling terrain California freeways (excluding mountainous terrain ones).

Statistics were based on eight years of crash and hourly weather data (1991-1998). Crash rates were computed based on hundred-million-vehicle-miles of travel--more than 72 HMVM for Wisconsin and more than 500 HMVM for California.

No statistically significant differences in safety performance were found between rural longitudinally tined freeways (California) and rural transversely tined freeways (Wisconsin) with ADT less than 60,000 vpd.

It is recommended that safety comparisons between the two pavement textures be expanded to include winter pavement surface conditions when snow or ice are present on the roadway surface. If no significant safety performance differences are found under such conditions, longitudinally tined PCC pavements may be preferred over transversely tined ones, since they generate lower levels of tire-pavement noise.

17. Key Words Concrete Pavement, Crash Rate, Pavement Texture, Pavement Safety, Wisconsin, California, Wet Pavement, Precipitation, Rural Freeway, Longitudinal, Transverse, Traffic Safety	18. Distribution Statement No restriction. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield VA 22161

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

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

WET PAVEMENT CRASH STUDY OF LONGITUDINALLY AND TRANSVERSELY TINED PCC PAVEMENTS

Presented To:

Wisconsin Department of Transportation
Division of Transportation Infrastructure Development
3502 Kinsman Boulevard
Madison, Wisconsin 53704

Prepared By:

Alex Drakopoulos
and
David A. Kuemmel
Department of Civil and Environmental Engineering
Marquette University
P.O. Box 1881
Milwaukee, Wisconsin 53201-1881

June 2007

EXECUTIVE SUMMARY

This report provides crash statistics for Longitudinally Tined (LT) Portland Cement Concrete (PCC) and Transversely Tined (TT) PCC pavement surfaces. The statistics were compiled for urban and rural freeways, classified in two Average Daily Traffic (ADT) categories: pavements carrying less than 60,000 vehicles per day (VPD) and those carrying an ADT in excess of 60,000 VPD.

The absence of significant mileage of longitudinally tined PCC surfaces in Mid-Western states lead to the decision to analyze California pavements where longitudinal texture has been the standard during the past several decades on all PCC pavements, except on bridge decks.

Crash experience on California longitudinally tined PCC pavements was compared to that of Wisconsin transversely tined PCC pavements. Safety performance of wet pavements was the focus of the analysis. Rural freeways were considered to be ideal for this study, given the prevailing high speeds, absence of extraneous influences on safety (e.g., cross streets, on-street parking, pedestrians, traffic signals), and consistent design standards between the comparison states. Rainfall differences were accounted for with the use of hourly precipitation data, and terrain differences were taken into account by using level and rolling terrain California freeways (excluding mountainous terrain ones).

Statistics were based on eight years of crash and hourly weather data (1991-1998). A total of more than 3,000 Wisconsin and 21,000 California rural freeway crashes and more than 500,000 urban California freeway crashes were analyzed in the present report. Crash rates were computed based on hundred-million-vehicle-miles of travel--more than 72 HMVM for Wisconsin and more than 500 HMVM for California rural freeways and more than five hundred billion miles of travel for California urban freeways.

Thus, statistics are based on sufficiently large databases to provide confidence in the findings. The fundamental calculated statistic was the ratio of wet pavement crash rate to dry pavement crash rate within each state. Eight such ratios were computed for each state (one for each year) and the two sets of eight observations were compared for statistically significant differences.

No statistically significant differences in safety performance were found between rural longitudinally tined freeways (California) and rural transversely tined freeways (Wisconsin) with ADT less than 60,000 vpd.

It is recommended that safety comparisons between the two pavement textures be expanded to include winter pavement surface conditions when snow or ice are present on the roadway surface. If no significant safety performance differences are found under such conditions, longitudinally tined PCC pavements may be preferred over transversely tined ones, since they generate lower levels of tire-pavement noise.

ACRONYMS AND ABBREVIATIONS USED IN THE REPORT

100MVMT = Hundred-Million Vehicle Miles of Travel

ADT = Average Daily Traffic

CalTrans = California Department of Transportation

FC = Friction Coefficient

FHWA = Federal Highway Administration

FN = Friction Number

HMVMT = Hundred-Million Vehicle Miles of Travel

Long PCC = Longitudinally tined PCC surface

LT = Longitudinally Tined

MOE = Measures of Effectiveness

MPH = Miles per Hour

MHVP = Million Heavy Vehicle Passes

MVMT = Million Vehicle Miles of Travel

PCC = Portland Cement Concrete

Trns PCC = Transversely tined PCC surface

TT = Transversely Tined

TWG = Technical Working Group

WisDOT = Wisconsin Department of Transportation

VPD = Vehicles Per Day

LSR = Liquid precipitation (rain) Safety Ratio

HSIS = Highway Safety Information System

TABLE OF CONTENTS

Appendix A

PCC Pavement Surface Textures in Use and PCC Pavement Surface Texture Specifications

TABLE OF CONTENTS

TABLE OF CONTENTS

Page

Appendix I

Agency Contacts

Appendix J

Statistical Tests

LIST OF TABLES

Appendix B

Appendix C

Appendix D

LIST OF TABLES

Page

Appendix E

Appendix F

Appendix J

LIST OF FIGURES

LIST OF FIGURES

Page

Appendix D (Continued)

INTRODUCTION

During the last few decades Transverse Tining (TT) was the surface texture predominantly used on high-speed Portland Cement Concrete (PCC) pavements. A number of studies pointed to definitive advantages of Longitudinally Tined (LT) PCC surface textures over TT ones in terms of traffic-generated noise. These studies provided a motivation for Departments of Transportation to adopt LT pavement surfaces; however, the fundamental issue of safety performance differences between the two types of surface textures needed to be addressed with a definitive study before LT surfaces were officially adopted in pavement design guidelines.

Lack of sufficient mileage of different types of pavement surface textures within the confines of any given State, necessitated an inter-State effort in order to create a substantial crash experience database. A number of states have sporadically applied LT texture on a small number of highway segments; only the state of California has adopted LT surface texture as the standard for all high-speed PCC pavements (with the exception of bridge decks where TT surfaces are used).

The present effort addresses the question whether LT pavement surfaces would be expected to perform at least equally well with the currently used TT pavement surfaces in Wisconsin. A definitive answer to this question was elicited through a safety performance comparison between TT Wisconsin pavements and LT California pavements.

At the outset of this investigation, safety differences between the two pavement surface textures were expected to emerge mainly when pavements were wet. Extensive hourly weather data were used in order to account for the dramatically different rainfall conditions between Wisconsin and California and year-to-year rainfall variations. Weather information was used to estimate the number of hours that pavements were wet in the two states, and thus estimate wet and dry pavement conditions exposure for crashes in each state.

PCC pavements are typically used in high-volume facilities, such as major arterials and freeways. Surface texture guidelines are provided by many agencies for PCC pavements where operating speeds are expected to be 45 mph or higher, in recognition of a need for better pavement friction performance. The present safety analysis was limited to freeways, the predominant high-volume, high-speed facilities in order to minimize, as much as practical, the safety influence of many extraneous factors that would be present in non-limited access facilities, such as intersections and driveways, intersection traffic control, pedestrians, on-street parking etc. In addition, freeway design standards are uniform across states and the influence of highway geometry on safety performance would be minimized, given the requirements for large radii and gentle vertical curvature on such facilities.

A total of eight years of statewide crash statistics were analyzed for each state, providing adequate temporal and spatial coverage. Database size allowed inclusion of thousands of crashes in each analyzed category.

Crash characteristics are quite different between urban and rural freeways: most crashes in urban freeways occur during peak traffic periods, two or more multiple vehicles and, because they occur at the lower speeds present during these periods, have lower severity outcomes. Crash rates on rural freeways, which typically operate at much lower congestion levels (higher Level of Service) and higher operating speeds, are lower; single-vehicle crashes are a higher percentage of all crashes, due to higher operating speeds, and more severe crash outcomes are more prevalent. For these reasons, urban and rural freeways were analyzed separately. In addition, freeways were classified by Average Daily Traffic (ADT) level. Because Wisconsin terrain is mainly level or rolling, only level and rolling terrain California data were used for comparisons with Wisconsin pavements. Mountainous terrain California data are available for the interested reader in **Appendix C**.

TT and LT pavement surface textures were expected to exhibit similar safety performance under dry conditions. The motivation for the current study was to determine whether one of the pavement surface textures had superior safety performance compared to the other when both pavements were wet. Any such differences were expected to be exacerbated on facilities with high operating speeds, since for any pavement, skidding resistance deteriorates with both pavement wetness and higher operating speeds.

Thus, crashes on rural freeways presented an ideal database on which to base a comparison between the two pavement textures, given their prevailing high operating speeds.

One concern about TT pavements in urban areas is a relatively high traffic-generated noise. LT pavements produce significantly lower noise levels. If they were proven to be equally safe (or safer) than TT pavements, they would be ideally suited for urban applications.

Thus, crashes on rural freeways were used to provide a comprehensive safety comparison between Wisconsin TT and California LT textures. Very few urban TT freeway miles were constructed in Wisconsin, thus a direct safety comparison between urban TT Wisconsin freeways and urban LT California freeways was not possible. The extensive database on urban California LT pavements was used to provide a predictor for expected safety performance, should LT pavements be applied in urban Wisconsin freeways some time in the future.

REPORT ORGANIZATION

Information presented in the body of the report is supported by self-contained Appendices that address specific issues. Appendix tables and figures are addressed by alphanumeric reference, for example, Figure D6 will be found in Appendix D; page C15 is in Appendix C.

The body of the report contains a **Literature Review**, followed by a description of the **Fundamental Issue Addressed in the Report**. **Database Considerations** are addressed next, pertaining to the types of data that were critical for this effort. ***The reader is encouraged to review the* Methodology *section that provides detailed definitions and explanations about the fundamental statistics used in this report.*** The **Findings** section presents the core findings about rural freeways in detailed and summarized format, followed by the **Conclusions** section where findings are discussed. **Recommendations** conclude the body of the report.

Appendix A presents the **PCC pavement textures** that were **in use** in the nine contacted states (California, Colorado, Illinois, Maine, Michigan, Utah, Virginia, Washington and Wisconsin), as well as PCC **pavement texture specifications** from California, Illinois, Michigan, Utah and Washington.

Appendix B is a self-contained discussion on Wisconsin Friction Number data. The Appendix provides support for the **Database Considerations** part of the report.

Appendix C provides a self-contained description of the crash, pavement and analysis databases. A crash rate summary for Wisconsin and California is provided in **Table C1. Table C2** provides a detailed listing of annual crash rates for 1991-1998 and other crash statistics for California and Wisconsin rural freeways as well as California urban freeways. Mountainous terrain California data are presented separately from rolling/level terrain data. This information supports the **Findings** part of the report.

Appendix D provides crash statistics for the **Findings** section of the report. The information is provided in tables and figures. **Important cautions for data presented in Appendix D are listed on page D2.**

Appendix E addresses the need for weather and precipitation data, the reasoning for choosing particular first order weather stations, and the reasoning for the chosen weather analysis methodology. Percentages of time that pavements were dry or covered with liquid precipitation are presented in **Tables E3 and E4**.

Appendix F provides a **mileage summary** of yearly constructed new TT PCC pavements along **analyzed rural Wisconsin freeways**.

Appendix G presents detailed information about the analyzed Highway Safety Information System California database.

Appendix H provides a summary of information acquired from the twelve state Departments of Transportation that were contacted during the data collection effort.

Appendix I is a listing of persons contacted during the data collection effort at various Agencies.

Appendix J provides details on the **statistical tests** performed **to compare wet pavement safety performance** between TT Wisconsin and LT California PCC pavements, and among LT urban and rural California PCC pavements.

LITERATURE REVIEW

This literature review focuses on the following issues related to PCC pavement surface textures: federal and state policy evolution, pavement textures in use today, safety performance and friction number issues.

Federal and State PCC texture policy evolution

Portland Cement Concrete (PCC) pavements have been used extensively for many decades in the U.S., especially on high-volume high-speed highways. The Federal Highway Administration (FHWA) policy on surface finishing of PCC pavements, established in the late 1960s, stated that pavement surfaces provided on federally-aided highway projects should have a skid-resistant surface. FHWA favored an almost exclusive use of Transversely Tined (TT) with equally-spaced tines on highways with speed limits of 65 km/hr (45 mph) or greater.

The California Department of Transportation, concerned with wet pavement crash experience, increased the minimum requirement for friction coefficient (FC) of new PCC pavements from 0.25 to 0.30 [1]. At the time, the most common texturing method was burlap drag, which typically satisfied the 0.25 FC requirement on new pavements. However the FC fell below the minimum even after very little traffic had used a new pavement. With the new requirement for a 0.30 FC, California was in urgent need to come up with a surface texturing technique that would produce long-lasting high FC. The concern with PCC textures that needed surface texture rehabilitation in order to obtain a satisfactory FC extended to other States as well.

Thus, a number of States (GA, TX, CA) embarked, in cooperation with FHWA, in various pilot projects to construct and test short highway segments using different pavement surface finishing techniques to produce a variety of textures, and choose those textures that seemed promising in terms of maintaining a high FC, while still being economically feasible. Most States decided to use TT texture, with the most notable exception of the State of California which started using Longitudinally Tined (LT) texture exclusively (except on bridge decks where it used TT).

After the intense research activity on PCC surface textures in the seventies, most State DOT and FHWA pavement research activity concentrated on pavement structures, until the 1990s when the issue of pavement noise came to the forefront.

A Technical Working Group (TWG) representing State Highway Agencies, Industry, Academia and the FHWA convened on September 27, 1993 to address the issue of tire/pavement noise generated by TT pavements that generated complaints from motorists and property owners. The TWG published a comprehensive report [2] addressing the issues of: i) the basis for surface texture selection; ii) safety considerations; iii) the need for quality mix designs on heavily traveled high-speed-speed highways; iv) general PCC surface texture considerations; v) profile considerations; vi) alternative surface treatments to improve friction properties of existing PCC surfaces; and vii) research needs. The final meeting of the TWG was held on January 31, 1996.

The original FHWA policy favoring TT was modified in a Policy Memorandum authored by

William A. Weseman, Director, Office of Engineering, dated November 1, 1995, to allow State highway agencies to select TT or LT or other surface texture techniques which meet the policy, if such decisions are supported by quantifiable data. The Policy Memorandum acknowledged the work of the TWG and referred readers to the preliminary summary of its findings.

A subsequent FHWA Policy Memorandum, issued on November the 12th, 1996, signed by Joseph S.Toole, Director, Office of Engineering , and Gerald L.Eller, Director, Office of Technology Applications, acknowledged the TWG final report and suggested that State highway agencies immediately update TT specifications for highways with design speeds of 80 km/h (55 mph) or higher to those suggested in Section 4 of the TWG final report Executive Summary. The recommended PCC surface textures were: i) transverse tining (with random tine spacing), preceded by a longitudinal artificial carpet or burlap drag; ii) longitudinal tining; iii) longitudinal plastic brushing; iv) exposed aggregate surface and other premium surface treatments (open-graded, two-layer construction, chip sprinkling). These recommendations were based on findings of reduced lower noise levels for the recommended pavement surface textures, from a study performed for WisDOT and FHWA by the Marquette University Center for Highway and Traffic Engineering [3, 4, 5].

Most common PCC pavement textures in use today

Since Federal guidelines had favored TT pavements for almost three decades, States have had an incentive to gravitate toward this surface treatment.

Indeed, most States, with the notable exception of California, have long adopted policies that parallel FHWA recommendations. For example, WisDOT Standard Specifications [6] require that all PCC pavements with design speeds of 60 km/h (40 mph) or higher receive an artificial turf (longitudinal) drag finish, followed by a transverse tined finish (WisDOT Standard Specifications Subsection 415.5.9.6.3).[1] However, CalTrans Standard Specifications require longitudinal texturing performed with a burlap drag or a broom, followed by the application of spring steel tine which will produce grooves parallel with the centerline (CalTrans Highway Design Manual [7] subsection 607.7).[1]

Safety performance of PCC pavement textures

Although LT surface texture offers measurable traffic noise reduction, which is an important input in choosing PCC surface treatments for state-wide application, both FHWA and AASHTO recommended that safety not be compromised to obtain a slight, or short-term, initial reduction in noise levels [8, 9]. Safety performance remains the paramount consideration in Federal and State design guidelines. Quoting the TWG final report, **"The purpose of surface texture is to reduce the number and severity of wet weather accidents."**

Skid surveys and crash data in the late 1960s provided the motivation for California Department of Transportation engineers to seek PCC pavement surface treatments that would produce a higher FC. The most common treatment for PCC pavements with low FC used in California,

---

[1] See Appendix A.

was longitudinal grooving by diamond saws. In the late 1970s, a number of studies identified that wet pavement crash experience on such longitudinal surfaces was much lower. Crash reductions of 85% at 14 different Los Angeles locations and 75% at 77 locations across 13 states were noted [10]. Thus, California DOT was not concerned with the safety performance of longitudinal texture created with the use of diamond saws. Diamond sawing was only applied as a FC restoration measure on pavements that were typically six or more years old and was very costly (nearly $8 million spent between 1967 and 1973). A method to create a longitudinal texture during construction using a “steel runner sled groover” proved to be easy to use during construction, but was discarded when the California Highway Patrol concluded that the texture was very hazardous to motorcyclists, and probably to compact cars as well [11]. This was due to texture configuration and the fact that grooves did not run perfectly straight.

A LT texture created during another research effort (1972-1976) [12] using steel tines was judged to create only minor discomfort to light motorcycles with certain tire treads and occasionally slight lateral drift for light passenger cars and was adopted for all new concrete pavement construction. The texture was tested using three different motorcycle sizes at slow and highway speeds by representatives of the Transportation Laboratory and the California Highway Patrol.

LT texturing was thought to impart a “tracking” effect by providing resistance to lateral movement. Longitudinal diamond grooving was thought to reduce crashes, especially on curving highways [1].

Very few crash experience comparisons between different types of concrete pavement textures have been performed in the U.S. as of this writing [13]. A recent analysis was performed in Australia [14]. The TWG report cites a Minnesota study comparing crash experience on four types of concrete pavements in urban areas, based on crash experience between 1991 and 1993. The study provides Wet / (Wet+ Dry) crash ratios which are shown to be lower for TT pavements compared to diamond ground, burlap drag and “worn” PCC pavements. The TWG recommended that all States conduct similar types of analyses to verify that the surface textures being constructed result in low wet weather crash rates. The lack of crash experience comparisons was recognized at an international level at the PIARC 20th World Congress in September of 1995.

A crash rate comparison based on six years of crash experience (1988-1993) was conducted by the Marquette University Center for Highway and Traffic Engineering for WisDOT as part of a project to evaluate the effects of spot diamond grinding on the performance of PCC pavements [15] and the results were published in 1998 [16]. Longitudinally ground pavements were found to have lower crash rates than TT ones; six-year crash rate trends (similar to those recommended in the TWG report) did not reveal any detectable changes in crash rates for either texture type. FC information was not available for the analyzed highway segments.

Friction Number as a safety performance proxy

The lack of substantial mileage of different types of pavement textures within close proximity to each-other, and the need to introduce surface textures that promise noise and/or safety benefits in parts of the country where their presence is currently very limited or non-existent, has turned investigators' attention to the study of pavement skid resistance properties. Most commonly, Friction Number (FN), measured using either a ribbed or smooth tire (using ASTM Method E 274, tire E 501 or E 524) is used as the metric of a pavement's skid resistance. Benefits of using FN to assess pavement skid resistance properties include: i) ability to evaluate a texture based on very short pavement segments (crash rate-based safety evaluations require significant vehicle-miles of travel for reliable results); ii) transferability of findings across the country (however, FHWA recognizes that similar textures may yield different FN due to wide variations in climate, materials quality and variability); and, iii) ability to monitor FN variations with time.

Substantial FN differences between different pavement textures, and a general deterioration of FN with pavement age (with the exception of exposed aggregate surface treatment that shows an initial increase in FN after construction), and cumulative vehicle passes since construction have been documented in the literature [17, 18, 19]. Despite the general usefulness of FN in assessing pavement friction properties, and the transferability of results between different parts of the country, the final TWG report recognizes that: "Available information supports only a general correlation between friction numbers and wet weather crash rates." The report recommends that additional multi-year studies are necessary to establish FN relations with crash occurrence.

FUNDAMENTAL ISSUE ADDRESSED

The present effort is a comparison of transversely tined (TT) Wisconsin PCC pavements with longitudinally tined (LT) PCC pavements. The focus of this comparison is differences in wet pavement crashes on high-speed facilities. Motivation is provided by findings of lower highway noise levels generated by longitudinally tined surfaces vis-à-vis concerns for the safety performance of these pavements when compared to the widely used transversely tined surfaces.

Departments of Transportation would use a quieter pavement surface texture, especially in urban areas, if it is shown not to be detrimental to safety; inferior safety performance will immediately disqualify a surface texture from further consideration.

DATABASE CONSIDERATIONS

As indicated in the literature review, the most prevalent PCC pavement surface texture in use today on high-speed (speeds over 40 mph) high-volume pavements is transverse tining, which is also the prevalent PCC pavement texture in use by the Wisconsin Department of Transportation. Various studies that indicated that longitudinal textures have traffic noise reduction benefits motivated a comprehensive review of various pavement surface textures. States currently applying TT texture are hesitant to experiment with longitudinal textures without proof that they are at least equally safe.

Issues needed to be addressed

The critical issue that needed to be addressed was whether differences existed in the safety performance of TT and LT pavement surface textures on high-speed, high-volume facilities. If any such differences existed, they were expected to be evident under wet pavement conditions, rather than on dry pavements.

The fundamental shortcomings of safety analyses conducted thus far had been their limited spatial and/or temporal scope, limitations that the present analysis attempts to overcome. Ideally, a direct comparison of crash performance of different types of surface treatments should be conducted within a limited geographic area (a State or a part of a State), in order to control for factors not related to pavement texture such as: environment (e.g., weather, daylight hours), driver characteristics (e.g., aggressive driving habits, driver education), speed limits (maximums differ by State), access control policies, design and construction parameters (e.g., allowable maximum superelevation values, minimum radii, construction materials). However, at the outset of the present study, it was very improbable that adequate mileage of different PCC surface texture treatments could be found within a limited geographic area, since it was more economical for State governments to limit PCC pavement texture choices in order to simplify the design, bidding and construction processes.

Database: variables and spatial extent

Crash data

Given the above observations, an inter-state safety performance comparison would be necessary. With an emphasis on a safety performance comparison with Wisconsin TT pavements, the first preference for the present study would be a comparison with Mid-Western states. The closest states known to have used LT texture were Minnesota, Iowa, Colorado, and Virginia. Although these states had used LT texture, its application was either recent and very limited or had been discontinued (Virginia), creating a research challenge because: 1) where limited mileage was available it would have not been adequate to accumulate a substantial number of crashes for a valid statistical analysis; 2) pavement construction and reconstruction dates would be difficult to determine; 3) exact project limits would be difficult to determine. Where LT texture was employed sporadically, crash experience would be very difficult to analyze, given the difficulty of temporally and spatially matching it with pavement surface texture data.

The literature review indicated that California had used LT texture on high-speed PCC pavements exclusively for the last few decades. Application of LT texture statewide for an extensive period of time guaranteed that LT texture would be present in all analyzed PCC pavements.

Weather data

Climate differences between California, the best identified LT pavement crash experience source, and TT Wisconsin pavements, necessitated the use of detailed and accurate weather information, in order to account for the effect of weather differences between the two states on crash experience. This information could be used to calculate an approximation of the hours during which pavements were wet in each analyzed state during each analysis year, and calculate state-specific wet pavement crash rates (crashes divided by hundred-million vehicle miles of travel on wet pavements).

Friction data

The explanatory variable most commonly used to establish a relationship between safety performance and pavement surface texture has been Friction Number (FN). Use of FN as a surrogate for wet pavement safety performance would allow transferability of results between different parts of the country, under the assumption that similar textures would produce similar FNs. However, FN measurements have a great variability; their correlation with crash experience was found to be weak.[2]

The final TWG report states that: "Available information supports only a general correlation between friction numbers and wet weather crash rates." Appendix D of the same report states: "While friction properties are a convenient way to estimate the safety characteristics of various pavement types and surface textures, the real test is whether the pavement texture reduces the number and severity of wet weather accidents." The report recommended that analyses over consecutive 3- to 5-year periods were needed to determine (1) the wet weather accident rates of different textures and pavement types and (2) the change in friction numbers and accident rates over time for the different textures and pavement types."

Availability of extensive FN databases was investigated during the data collection effort (see **Appendix H** for a list of collected data).

Database emphasis

The main focus of the data collection effort was on identifying multi-year state-wide crash databases that could readily be linked to travel and roadway information (pavement surface material and texture, highway classification, Average Daily Traffic, pavement condition at the time of the crash). Weather information was also necessary in order to estimate the number of hours pavements had been wet during each year and thus calculate estimates of the relative risk of a crash occurring on a wet versus a dry pavement surface. The FN data collection effort was given secondary importance for reasons explained in **Appendix B**.

METHODOLOGY

If safety differences existed between LT and TT pavement surfaces, these differences were expected to be the greatest under wet conditions, and especially where high operating speeds prevailed. Rural freeways were chosen as the ideal facilities for the desired comparison for a number of reasons:

1. They are typically not congested, thus free-flow speeds are likely to prevail.
2. No intersections are present—intersections introduce a large number of variables

---

[2] A discussion based on a brief analysis of Wisconsin FN information is presented in Appendix B.

affecting safety performance (number of approach lanes, lane designation, traffic control parameters, cross-street volumes, etc.)
3. There is no friction with on-street parking, pedestrians and bicyclists.
4. Good quality crash data and other highway information is available.
5. High geometric design standards eliminate to a large extent the influence of sharp horizontal and vertical curves on crashes.
6. Uniform geometric design standards eliminate the influence of differences in state-specific geometric design practices.
7. A large number of crashes is typically available for analysis.

The facilities chosen for analysis also met the following criteria:

- Design speed of 50 mph or higher;
- Level or Rolling terrain.

Deer crashes were eliminated from analysis.[3]

Extensive data were available in California for LT pavement surfaces. Wisconsin had information on TT pavement surfaces.

The following safety performance Measures of Effectiveness (MOE) were calculated for each year for each of the two states (definitions and interpretations of these MOE are presented in the following section):

- Crash rate
- Wet-to-Dry ratio
- Liquid precipitation Safety Ratio

MOE Definitions and Interpretations

This section presents the meaning and interpretation of statistics used in this report. Information presented in the **Findings** section[4] was calculated using eight significant digits; tabulated information was rounded in the interest of presentation economy thus some small discrepancies may be noted between the presented rounded figures. Multiple interpretations of the fundamental Liquid precipitation Safety Ratio statistics are provided herein, for the benefit of the interested reader.

Crash rates were calculated as total crashes per one hundred million vehicle miles of travel (HMVMT OR 100 MVMT) and rounded to integer values. A higher crash rate indicates that a higher number of crashes occurred per vehicle-mile of travel, and is an indication of poorer safety performance.

---

[3] Detailed information on crashes included in the analysis is presented in Appendix C.
[4] A complete listing can be found in Appendix D.

$$Crash\ Rate = \frac{Total\ crashes}{100\ MVMT} \qquad Equation\ (1)$$

The **wet-to-dry ratio** (**Wet to Dry crashes**) is the number of crashes that occurred on wet pavement, divided by the number of crashes that occurred on dry pavement.

$$Wet-to-Dry\ ratio = \frac{Tot\_Wet}{Tot\_Dry} \qquad Equation\ (2)$$

Where:

Tot_Wet is the number of crashes on wet pavement
Tot_Dry is the number of crashes on dry pavement

This ratio is affected by the amount of wet precipitation in a given area. For example, a wet-to-dry ratio of 0.50 indicates that half as many crashes occurred on wet pavements as did on dry pavements.

Discussion: If the region where this ratio was observed had half as many rain days as it had dry days, then the risk of being involved in a crash on a wet pavement would be equal to the risk of being involved in a crash on a dry pavement. However, the same wet-to-dry ratio (0.50) would indicate that the risk of a wet pavement crash is twice as high as the risk of a crash on dry pavement, if pavements were wet only 25% of the time. Thus, the wet-to-dry ratio is mainly useful in comparisons between facilities that experience similar rainfall patterns. Under similar rainfall patterns, a high wet-to-dry ratio would indicate facilities that are more prone to wet pavement crashes.

Liquid precipitation **Safety Ratios (LSR)** were defined based on the following formula:

$$LSR = \frac{\left(\dfrac{Tot\_Wet}{\%\ time\ wet\ pavement}\right)}{\left(\dfrac{Tot\_Dry}{\%\ time\ dry\ pavement}\right)} \qquad Equation\ (3)$$

Where:

Tot_Wet is the number of crashes on wet pavement
Tot_Dry is the number of crashes on dry pavement
% time wet pavement is the percent of time a pavement is wet
% time dry pavement is the percent of time a pavement is dry

Discussion: The LSR can be thought of as the ratio of the *wet pavement crash rate* (number of crashes on wet pavement divided by 100 MVMT on wet pavement—see equation *(1)*)divided by the *dry pavement crash rate* (number of crashes on dry pavement divided by 100 MVMT on dry pavement).

$$LSR = \frac{\left(\dfrac{Tot\_Wet}{travel\ on\ wet\ pavement}\right)}{\left(\dfrac{Tot\_Dry}{travel\ on\ dry\ pavement}\right)} = \frac{\left(\dfrac{Tot\_Wet}{total\ travel \times percent\ time\ wet\ pavement}\right)}{\left(\dfrac{Tot\_Dry}{total\ travel \times percent\ time\ dry\ pavement}\right)} \qquad Equation\ (4)$$

Since travel on wet (dry) pavement is calculated by multiplying the total vehicular travel in a year by the percent time that a pavement is wet (dry), total travel is eliminated on the right-hand-side of equation *(4)*, and the result is the right-hand-side of equation *(3)*.

The LSR can also be expressed as:

$$LSR = \frac{\left(\dfrac{Tot\_Wet}{Tot\_Dry}\right)}{\left(\dfrac{\%\ time\ wet\ pavement}{\%\ time\ dry\ pavement}\right)} = \frac{(wet-to-dry\ ratio)}{\left(\dfrac{\%\ time\ wet\ pavement}{\%\ time\ dry\ pavement}\right)} \qquad Equation\ (5)$$

Interpretation: That is, LSR is the wet-to-dry ratio divided by an adjustment factor that indicates how much more frequently pavements are wet than dry. If the wet-to-dry ratio is equal to the proportion of time pavements are wet to the time they are dry, then LSR = 1.00 and a motorist has an equal chance to be involved in a crash when a pavement is wet as when the pavement is dry. If the wet-to-dry ratio is greater than the denominator, then LSR > 1.00 and the chances of being involved in a crash are greater on wet pavements than dry pavements.

This way, ***LSR allows comparisons of wet pavement performance across areas with different rainfall patterns***. In other words, it provides a measure of how many times more likely one is to be involved in a wet pavement crash, relative to being involved in a dry pavement crash if equal mileage is driven under each of these two pavement conditions. Calculation of LSR requires weather and precipitation information, as well as information of how long pavements remain wet after precipitation accumulation on the pavement. Details of how weather and precipitation data were used are provided in **Appendix E**.

Analyzed freeway length is presented in *directional miles* for Wisconsin freeways, and *centerline miles* for California freeways; Average Daily Traffic (ADT) volume thresholds used in presented summaries are bi-directional. Traffic volumes were appropriately adjusted to provide the correct vehicular travel in each database.

FINDINGS

Essential background

The following presentation of findings is based on safety performance statistics listed in the Appendices: **Appendix C** contains comprehensive tables of findings; **Appendix D** presents information (tables and figures) focused on:

- Wisconsin rural freeways with less than 60,000 ADT.
- California rural freeways with less than 60,000 ADT.
- California urban freeways with less than 60,000 ADT.
- California urban freeways with more than 60,000 ADT.

The focus of the present evaluation was a safety comparison of wet TT and LT high-speed pavements. Rural freeways were chosen as the ideal representatives of such pavements for reasons explained in the **Introduction** part of this report. The majority of available mileage is on rural freeways with an ADT less than 60,000 VPD.

The section concludes with a presentation of urban California freeway statistics which are of secondary importance to the present analysis (since lower speeds prevail on such pavements), but still quite useful: LT texture is desired in the urban environment because it generates a lower noise level. Very limited information was available for TT Wisconsin urban freeways; it is not analyzed in this report. All available information can be found in **Appendices C and D**.

Rural Freeways

Table 1 below presents statistics extracted from **Tables D1 and D2** for TT Wisconsin and LT California[5] rural freeway pavements with ADT less than 60,000 VPD. **Figures D1-D6** provide a visualization of this information. The two pavement surface types had identical crash rates, when crashes over the entire 1991-1998 period were analyzed (42 crashes per hundred million vehicle miles of travel). During these years, crash rates were in the 35-50 crashes/100MVMT range for TT Wisconsin pavements; those for LT California pavements were in the 41-45 crashes/100MVMT range.

The database included approximately 1,460 directional miles of California freeways (730 centerline miles) and 230 directional miles of Wisconsin freeways, a ratio of approximately 6:1. Approximately seven times as much travel occurred on the analyzed California freeways as did on the analyzed Wisconsin freeways over the eight study years (510 vs. 72.6 100 MVMT, respectively). The same ratio held in terms of total analyzed crashes in the two states (21,645 vs. 3,048 crashes, respectively).

When the percent time that pavements were wet in each state is taken into account, TT surfaces outperform LT surfaces, since the average LSR value was lower for TT pavements at 2.25 vs. 2.39 for LT pavements. However, this difference was not significant at the 0.99 level of confidence

---

[5] Rolling and flat terrain California freeways were used for comparisons with Wisconsin freeways.

(see **Appendix J** for details).

Table 1. Wisconsin (Trns PCC) and California (Long PCC) Rural Freeway Statistics 1991-1998. Less than 60K VPD.

Year	Wear Surface	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Liq Safety Ratio	Length miles	100 MVMT
1991	Trns PCC	47	.19	267	2.21	119.7	5.6
	Long PCC	42	.08	2668	1.62	733.5	63.4
1992	Trns PCC	40	.28	233	3.18	121.4	5.8
	Long PCC	41	.11	2608	2.42	733.5	63.4
1993	Trns PCC	46	.20	391	2.16	166.8	8.5
	Long PCC	42	.09	2663	1.71	733.5	63.4
1994	Trns PCC	40	.08	345	1.21	166.8	8.6
	Long PCC	42	.09	2646	2.60	731.6	63.6
1995	Trns PCC	40	.12	382	1.51	185.6	9.6
	Long PCC	44	.14	2720	2.27	730.1	62.5
1996	Trns PCC	50	.23	522	4.07	196.8	10.4
	Long PCC	45	.14	2922	2.93	730.8	64.5
1997	Trns PCC	35	.13	411	2.39	219.7	11.6
	Long PCC	42	.09	2726	2.66	719.8	64.6
1998	Trns PCC	40	.14	497	2.16	233.7	12.5
	Long PCC	42	.19	2692	3.06	715.4	64.4
Overall Statistics							
	Trns PCC	42	.16	3048	2.25	233.7	72.6
	Long PCC	42	.12	21645	2.39	728.5	509.7

California Urban Freeways

Aggregate eight-year statistics for all California Urban freeways with an **ADT of less than 60,000 VPD** are presented in **Table 2** below. Annual summaries are presented in **Tables C1** and **D3** and **Figures D7-D9**. Crash rates for LT surfaces had minor year-to-year fluctuations throughout the analyzed period (**Figure D7**).

Table 2. California Urban Freeway Statistics 1991-1998. Less than 60K VPD.

Wear Surface	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Liq Safety Ratio	Length miles	100 MVMT
Long PCC	76	.17	23132	3.45	278.4	304.2

Eight-year statistics for urban freeways with an **ADT of more than 60,000 VPD** are presented in **Table 3**. Annual statistics are presented in **Tables C1** and **D4** and **Figures D10-D12**. A very substantial database supported these findings, with approximately 490 thousand crashes. Crash rate statistics were exceptionally stable through the analyzed time period (**Figure D10**).

Table 3. California Urban Freeway Statistics 1991-1998. More than 60K VPD.

Wear Surface	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Liq Safety Ratio	Length miles	100 MVMT
Long PCC	100	.16	486892	3.22	1114.6	4863.0

DISCUSSION

Although the number of analyzed rural Wisconsin crashes was substantial, its much smaller size than the California database (ratio 1:7) , contributed to the observed broader Wisconsin crash rate range.

Crash rates are invaluable in comparing safety performance comparisons between facilities exposed to similar weather conditions, however, direct crash rate comparisons between California and Wisconsin pavements are not particularly useful, given the substantially different percentage of time pavements are not dry in the two states,. Wisconsin freeways operate under snow and ice conditions that are nearly non-existent on the analyzed rolling and flat terrain California freeways.

The most appropriate comparison of wet pavement safety performance, one that takes into account the mileage driven on wet pavements in each state, is the Liquid Safety Ratio (LSR).

Although TT pavements had a lower LSR of 2.25 vs. 2.39 for LT pavements, this difference was not found to be statistically significant at the 0.99 level of confidence[6] based on the eight analyzed years.

California LT pavements had higher crash rates than rural ones, a finding consistent with expectations for urban freeways. Urban LT freeway pavements with ADT grater than 60,000 VPD had much higher crash rates than those with lower ADT (76 vs. 100 crashes/ 100 MVMT, respectively), however, they had lower LSR (3.22 vs. 3.45). A statistical test performed on LSR differences between these two urban freeway categories indicated that lower volume urban freeways had statistically significantly higher LSR values at the 0.90 level of confidence. This finding indicates that ADT is an important factor affecting wet pavement safety experience; its inclusion in analyzing urban freeway crash experience on wet pavements was appropriate.

CONCLUSIONS

Essential background

A Technical Working Group (TWG) representing State Highway Agencies, Industry, Academia and the FHWA convened in the early 1990s to address tire/pavement noise generated by TT pavements. The TWG published a comprehensive report that stated that "… **the purpose of surface texture is to reduce the number and severity of wet weather accidents**." Analyses over consecutive 3-to-5-year periods were recommended to determine the wet weather accident rates of different textures and pavement types and the change of accident rates over time for the different textures and pavement types. Reliance on Friction Number (FN) as a traffic safety surrogate was discounted by the TWG which stated that "…Available information supports only a general correlation between friction numbers and wet weather crash rates."

The focus of the present effort was a comparison between Longitudinally Tined (LT) and Wisconsin Transversely Tined (TT) PCC pavement surface textures. It was desired to compare wet pavement safety performance of these two pavement textures, based on extensive crash data spanning multiple years, as recommended in the TWG final report.

Since Wisconsin did not have LT pavements, this effort would necessarily have to rely on an inter-state data comparison. Data from neighboring states were desirable, but after an extensive search, the only identified state with adequate LT pavement mileage, crash and vehicular travel information was California. This information came from the well-documented FHWA-supported HSIS database. Hourly precipitation information was used to calculate the number of hours Wisconsin and California pavements were wet and vehicular miles of travel during these hours. This information was used to provide a fair comparison of TT and LT wet pavement performance across the two states, despite their rainfall pattern differences.

Eight years of data were analyzed, in accordance with TWG recommendations in order to provide stable statistics based on the largest available database. Reduced friction under wet

---

[6] See Appendix J

pavement conditions was the major TWG safety concern. This concern was addressed by focusing the analysis on rural Wisconsin and California freeways with ADT lower than 60,000 vehicles per day. Lower congestion levels and higher operating speeds are typically present at such facilities, conditions that result in lower friction numbers for any given pavement. If TT and LT pavements differed in safety performance under wet pavement conditions, their differences would be most clearly demonstrated where higher speeds were present. In addition, the freeway environment eliminated the safety influences of intersecting facilities, parked vehicles, pedestrians, intersection right of way control devices, and severe geometry.

Conclusions

1. Use of Friction Number (FN) as a freeway pavement safety performance surrogate was shown to be impractical due to wide FN seasonal and spatial variations for similar age pavements experiencing similar levels of traffic (**Appendix B**).

2. Among rural freeways, Wisconsin TT freeway pavements were found to have similar safety performance to California LT pavements when pavements were wet. This finding was supported by a very substantial database spanning eight years and took into account vehicle miles of travel on wet pavements in each analyzed state. The comparison between high-speed facilities of high design standards provided evidence that the two pavement textures provided similar safety performance under the most adverse conditions—the combination of high operating speeds and wet pavement.

California data on urban freeways were analyzed in order to provide baseline statistics for LT PCC pavement surface applications, should LT pavements be applied in Wisconsin in the future.

3. Among California LT PCC pavements, urban freeways with ADT less than 60,000 VPD had statistically significantly higher crash rates than rural freeways. This finding is consistent with findings across the U.S. for urban freeways, regardless of pavement texture.

4. Urban LT California freeways with ADT higher than 60,000 VPD had statistically significantly higher crash rates than similar freeways with lower ADT. Traffic volume should be taken into account when analyzing crash rates for a given pavement surface texture.

5. The risk of being involved in a crash on wet pavements based on the Liquid precipitation Safety Ratio (LSR) were higher on urban LT freeways than rural LT freeways, however, urban freeways with lower ADT had the highest chances of wet pavement accident involvement. Traffic volume should be taken into account when analyzing the risk of being involved in a wet pavement crash on a given pavement surface texture.

Primary conclusion summary

1. Longitudinally Tined (LT) PCC pavements are expected to display similar wet pavement safety performance to Transversely Tined (TT) PCC pavements on high-speed, high-

design standard facilities (rural freeways), with an Average Daily Traffic (ADT) less than 60,000 vehicles per day (VPD).

2. The chances of being involved in a crash on wet LT pavements is higher for urban than rural freeways, a result consistent with crash experience across the U.S.
   - The chances of being involved in a crash on wet urban LT freeways are higher when the ADT is lower than 60,000 VPD.

RECOMMENDATIONS

1. Based on the findings of no significant wet pavement safety performance differences between Longitudinally Tined (LT) and Transversely Tined (TT) pavement textures on rural freeways, it is recommended that the comparison between the two types of pavements is extended to include safety performance under winter pavement conditions (when snow or ice are present on the pavement). If no differences are found between the two pavement textures under winter weather conditions, the construction of LT pavements would be recommended for rural Wisconsin freeways, given the benefit of lower levels of traffic-generated noise.

2. LT texture is used extensively by CalTrans District 3, which is in charge of an extensive network of snow routes. Contacts with the District 3 Office of Maintenance Equipment and Emergency Operations are recommended in order to address any winter maintenance concerns related to LT surfaces. Such contacts will identify the types of winter maintenance equipment, materials and policies in force by CalTrans.

3. It was indicated in the literature search that initial attempts at constructing LT textures in California were abandoned due to concerns about the quality of ride for motorcycles and light vehicles. It is recommended that extensive communications are exchanged with Departments of Transportation that are currently constructing LT textures (especially CalTrans) in order to avoid similar pavement surface construction pitfalls when/if they are first introduced in Wisconsin.

4. The main motivation for the introduction of LT freeway pavements in Wisconsin is their applicability where noise concerns exist, for example in the urban environment. The safety performance of California LT pavements has been addressed herein. Safety performance should be the paramount criterion in choosing a pavement surface texture. Therefore, a comprehensive comparison with the safety performance of pavement textures currently in use in urban Wisconsin freeways is recommended. If one surface texture is shown to be clearly superior in terms of safety, that surface texture should be chosen for application in the urban environment. If LT pavement surfaces are on par with their counterparts, construction of urban freeway LT pavements may be recommended based on noise, durability, material availability or other pertinent considerations.

ACKNOWLEDGMENTS

This report was compiled by Alex Drakopoulos and Dave Kuemmel of Marquette University, Milwaukee, Wisconsin. The authors gratefully acknowledge the help of a great number of individuals, without whose help this volume would have not been possible: From the Wisconsin Department of Transportation-Steve Krebbs, Dave Larson, Dick Lange, Brad Javenkoski, Mike Schumacher, Peter Amakobe, Laura Fenley; from the Turner-Fairbank Highway Research Center, Yusuf Mohamedshah; from the Midwest Research Institute Doug Harwood; from NOAA William Brown; from the Wisconsin State Climatologist Office Lyle Anderson; and all individuals mentioned in **Appendix I**. Any errors or omissions are solely the responsibility of the authors.

REFERENCES

1. B.F. Neal, *An Evaluation of PCC Pavement Tine Texturing Patterns*, FHWA/CA/TL-85/05, CalTrans, November 1985.
2. Hibbs, B. and Larson, R. *Tire Pavement Noise and Safety Performance*. PCC Pavement Surface Texture Technical Working Group, FHWA-SA-96-068, May, 1996.
3. Kuemmel, D.A. *Noise Characteristics of Pavement Surface Texture in Wisconsin*. Transportation Research Record. No. 1544, TRB, National Research Council, Washington, D.C., 1996.
4. Kuemmel, D.A. *Impacts Related to Pavement Texture Selection*. Wisconsin Dept. of Transportation, Report WI/SPR-06-96, Bureau of Highway Construction, Pavement Section, January, 1997.
5. Kuemmel, D. A. et al. *Noise and Texture on PCC Pavements - Results of a Multi-State Study*. Wisconsin Dept. of Transportation, Bureau of Highway Construction, Pavement Section, Draft Report, April, 1999.
6. *Standard Specifications for Highway and Structure Construction*. State of Wisconsin, Department of Transportation, 1996 Edition.
7. *Highway Design Manual*. California Department of Transportation, Fifth Edition, Metric, July 1, 1995.
8. *Highway Traffic Noise Guidance and Policies and Written Noise Policies*. Tony Kanes's June 12, 1995, Memorandum to FHWA Regional Administrators 86 pp.
9. *Guide on Evaluation and Abatement of Traffic Noise*. American Association of State Highway and Transportation Officials, AASHTO, 1993, 40 pp.
10. Society of Automotive Engineering, *Grooved Pavement Causes Tire Reaction,* Automotive Engineering, Vol 85, Issue 10, October 1977, pp. 50-52.
11. B.F. Neal, D.E. Peck, J.H. Woodstrom, D.L. Spellman, *PCC Pavement Texture Quality Investigation*, CA-DOT-TL-3126-10-75-07, CalTrans, January, 1975.
12. B.F. Neal, D.E. Peck, J.H. Woodstrom, D.L. Spellman, *Surface Textures for PCC Pavement*, FHWA-CA-TL-78-14, CalTrans, April 1978.
13. Holbrook, L. F. *Accident Rates and Surface Properties : An Investigation of Relationships*. Michigan Dept. of State Highways and Transportation, Testing and Research Division, Lansing, Michigan State Highway Commission Report no. FHWA-MI-76-994, 1976.
14. Cairney, P. *Skid Resistance and Crashes : A Review of the Literature*. Research report ARR no. 311. Vermont South, Vic., ARRB Transport Research, Ltd., 1997.
15. Wenzel, T.H. et al. *Effects of Spot Diamond Grinding on Performance of Portland Cement Concrete Pavements*. In Transportation Research Record 1629, TRB, National Research Council, Washington, D.C., 1998, pp. 197-207.
16. Drakopoulos A., et al. *Crash Experience on Tined and Continuously Ground Portland Cement Concrete Pavements*. Transportation Research Record 1639, TRB, National Research Council, Washington, D.C., 1998, pp 140-146.
17. *Measurement of Runway Friction Characteristics on Wet, Icy, or Snow-Covered Runways*. Report FS-160-65-68-1. FAA, U.S. Department of Transportation, 1971.

REFERENCES (continued)

18. Law, S. M., and Rasoulian, M. *Texturing of Concrete Pavements*. Louisiana Department of Transportation and Development, Aug. 1979.
19. How Effective is CPR? *Better Roads*, Vol. 58, No.12, Dec. 1988, pp 23-24, 26.

APPENDIX A

PCC PAVEMENT SURFACE TEXTURES IN USE
AND
PCC PAVEMENT SURFACE TEXTURE SPECIFICATIONS

INTRODUCTION

Page A3 presents a summary of pavement surface textures in use in nine contacted states (California, Colorado, Illinois, Maine, Michigan, Utah, Virginia, Washington and Wisconsin).

The remainder of the Appendix presents more detailed information on pavement surface treatment specifications based on either direct quotes from specification manuals (California, Illinois, Michigan, Washington) or information provided via e-mail contact (Michigan for transversely tined pavements and Utah).

PAVEMENT SURFACE TEXTURES IN USE

CALIFORNIA
Longitudinally tined texture was used since the 1970s on all high-speed PCC pavements, except bridge decks where transversely tined texture was used.

COLORADO
Longitudinal texture: uniformly spaced longitudinal tining at 3/4 of an inch intervals with the depth and width of 1/8 of an inch is currently specified. Transversely tined texture: tines every 1” .

ILLINOIS
Two types of surface textures in use on PCC pavements: Type A (transversely grooved) and Type B (single artificial turf drag). Type A used on pavements with a posted speed greater than 40 mph; Type B texture used on pavements with lower posted speeds.

MAINE
Asphaltic concrete used exclusively since 1975-1976; about 72 lane miles of PCC were slated to be overlaid with asphalt; bridge decks transversely tined PCC.

MICHIGAN
Prior to 1969 no tining was used. Transverse tining used since 1975. Michigan has used very little longitudinal tining on a trial basis.

UTAH
Transverse tining for high-speed PCC pavements. No tining for urban highways with speeds less than 65 km/hr (45 mph).

VIRGINIA
Two tining processes in the Road and Bridge Specifications - longitudinal tining and transverse tining. Up until the early 1980s most of VDOT's PCC pavements were tined in the longitudinal direction. As concerns for hydroplaning increased, VDOT moved to uniform transverse tining.

WASHINGTON STATE
PCC is primarily used on interstates, but densely graded asphalt is also used. Only transversely tined pavement surface texture is used for PCC. The state has approximately 700 miles of interstate highways, 250 miles of which have been rehabbed. In the majority of the rehabbed pavements, the right lane has been continuously ground.

WISCONSIN
Transverse tining used on PCC pavements since 1978. Asphalt pavements used as well.

PCC PAVEMENT SURFACE TEXTURE SPECIFICATIONS

CALIFORNIA

STANDARD SPECIFICATIONS

STATE OF CALIFORNIA

BUSINESS, TRANSPORTATION AND HOUSING AGENCY

DEPARTMENT OF TRANSPORTATION

JULY, 1999

ISSUED BY

DEPARTMENT OF TRANSPORTATION
STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
PUBLICATION DISTRIBUTION UNIT
1900 Royal Oaks Drive
Sacramento, California 95815
Telephone (916) 445-3520

40-1.09 PRELIMINARY FINISHING

- In each day's work the Contractor shall mark the pavement with an approved stamp. This stamp shall be approximately 0.3-m by 0.6-m in size and shall be furnished by the Contractor at the Contractor's expense. The stamp mark shall be located 6 m ± 1.5 m from the transverse contact joint formed at the start of each day's work and 0.3-m± 0.1-m from the outside edge of pavement. The stamp mark shall show month, day and year of placement, and Engineer's station for the transverse contact joint and shall be oriented so that the stamp mark can be read from a position at the outside edge of pavement.
- Prior to completion of float finishing and texturing, water shall not be applied to the pavement surface in excess of the amount lost by evaporation.
- Placement of concrete shall cease at such time that finishing operations can be completed during daylight hours, unless lighting facilities provided by the Contractor are determined by the Engineer to be adequate for allowing later placement and finishing.

40-1.09A Stationary Side Form Finishing

- After spreading and compacting, concrete shall be given a preliminary finish by one of the following methods:

40-1.09A(1) Machine Float Method

- Self-propelled machine floats shall be used to finish pavement smooth and true to grade.
- The number and capacity of machine floats furnished shall be adequate to perform all work required at a rate equal to that at which concrete is delivered. Any delay exceeding 30 minutes in performing preliminary finishing shall constitute cause for stopping delivery of concrete until machines performing the work are again in proper position to continue without delay.

- Machine floats shall be capable of running either on side forms or on adjacent lanes of pavement. When machine floats run on adjacent pavement, its surface shall be protected as specified in Section 40-1.07, "Spreading, Compacting and Shaping."
- Floats shall be constructed of hardwood, steel or steel-shod wood. They shall be equipped with devices to permit adjusting the under side to a true flat surface.

40-1.09A(2) Hand Method

- Pavement shall be finished smooth and true to grade with suitable manually operated floats or powered finishing machines.
- Finishing shall take place as far back of concrete spreading operations as concrete remains workable, and the number of passes shall be sufficient to remove all perceptible inequalities.

40-1.09B Slip-Form Finishing

- Pavement shall be given a preliminary float finish by means of devices incorporated in the slip-form paver. These may be supplemented, at the Contractor's option, with suitable machine floats.
- Any edge slump of pavement, exclusive of edge rounding, in excess of 6 mm shall be corrected before concrete has hardened.

40-1.10 FINAL FINISHING

- After preliminary finishing has been completed, edges of initial paving widths shall be rounded to 12 mm radius. Transverse contact joints and the edge of longitudinal contact joints adjacent to hardened concrete pavement shall be rounded to 6 mm radius.
- In advance of curing operations, pavement shall be given an initial and a final texturing. Initial texturing shall be performed with a burlap drag or broom device which will produce striations parallel with centerline. Final texturing shall be performed with a spring steel tine device which will produce grooves parallel with centerline. The spring steel tine device shall be operated within 130 mm, but not closer than 75 mm, of pavement edges.
- Except when texturing areas of pavement finished in conformance with the provisions in Section 40-1.09A(2), "Hand Method," burlap drags, brooms and tine devices shall be installed on self-propelled equipment having external alignment control. The installation shall be such that when texturing, the area of burlap in contact with the pavement surface shall be maintained constant at all times. Broom and tine devices shall be provided with positive elevation control. Down pressure on pavement surface shall be maintained at all times during texturing so as to achieve uniform texturing without measurable variations in pavement profile. Self-propelled texturing machines shall be operated so that travel speed when texturing is maintained constant. Failure of equipment to conform to all provisions in this paragraph shall constitute cause for stopping placement of concrete until the equipment deficiency or malfunction is corrected.
- Spring steel tines of the final texturing device shall be rectangular in cross-section, 2.4 to 3.2 mm wide, on 19-mm centers, and of sufficient length, thickness and resilience to form grooves approximately 5 mm deep in the fresh concrete surface. Final texture shall be uniform in appearance with substantially all of the grooves having a depth between 1.5 and 8 mm.
- Initial and final texturing shall produce a surface having a coefficient of friction not less than 0.30 as determined by California Test 342.

- Tests to determine coefficient of friction will be made before pavement is opened to public traffic, but not sooner than 7 days after concrete placement. Pavement containing areas that have a coefficient of friction less than 0.30 shall be grooved as directed by the Engineer before opening it to public traffic.
- Finished pavement shall conform to the following provisions in not more than 10 days following placement of concrete:

> The surface will be straightedged, at locations to be determined by the Engineer, with a straightedge 3.6 m ± 0.06-m long. When the straightedge is laid on finished pavement in a direction parallel with centerline or normal to centerline, the surface shall not vary more than 6 mm from the lower edge.
>
> Any high points that cause the surface to exceed these tolerances shall be removed by grinding as provided in this Section 40-1.10.
>
> The surface shall be profiled, by the Contractor in the presence of the Engineer, using a California Profilograph or equivalent in conformance with the requirements in California Test 526 and these provisions. Prior to beginning profiles, the profilograph shall be calibrated in the presence of the Engineer. Profiles shall be made 1.0 m from and parallel with each edge of pavement and at the approximate location of each longitudinal joint for all pavement areas except those specified herein.
>
> Pavement so profiled shall conform to the following Profile Index requirements:
>
> 1. Pavement on tangent alignment and pavement on horizontal curves having a centerline radius of curve 600 m or more shall have a Profile Index of 11 mm or less for each 0.1-km.
> 2. Pavement on horizontal curves having a centerline radius of curve 300 m or more but less than 600 m and pavement within the superelevation transition of those curves shall have a Profile Index of 19 mm or less for each 0.1-km.
>
> Pavement within 15 m of a transverse joint that separates the pavement from a structure deck or an approach slab shall meet the profile requirements of Section 51-1.17, "Finishing Bridge Decks."
>
> Checking the following areas of pavement surface with the California Profilograph or equivalent will not be required:
>
> 1. Pavement on horizontal curves having a centerline radius of curve less than 300 m and pavement within the superelevation transition of those curves.
> 2. Pavement within 15 m of a transverse joint that separates the pavement from an existing pavement not constructed under the contract.
> 3. Pavement for exit ramp termini, truck weigh stations, ramps and connectors with steep grades and high rates of superelevation and short sections of city or county streets and roads.
>
> Individual high points in excess of 7.5 mm, as determined by measurements of the profilogram in conformance with the requirements in California Test 526, shall be reduced by grinding as provided in this Section 40-1.10, until the high points as indicated by reruns of the profilograph do not exceed 7.5 mm.

After grinding has been completed to reduce individual high points in excess of 7.5 mm, additional grinding shall be performed as necessary to reduce the Profile Index to values specified above in any 0.1-km section along any line parallel with the pavement edge.

Additional grinding shall be performed as necessary to extend the area ground in each lateral direction so that the lateral limits of grinding are at a constant offset from, and parallel with, the nearest lane line or pavement edge, and in each longitudinal direction so that the grinding begins and ends at lines normal to the pavement centerline, within any one ground area. All ground areas shall be neat rectangular areas of uniform surface appearance.

When pavement is ground or grooved as specified herein, the work shall be performed in conformance with the provisions in Section 42, "Groove and Grind Pavement," except that residue from grinding or grooving operations shall be disposed of outside the highway right of way in conformance with the provisions in Section 7-1.13.

The original of final profilograms that indicate the pavement surface is within the Profile Index specified shall become the property of the State and shall be delivered to the Engineer prior to acceptance of the contract.

ILLINOIS

Standard Specifications for Road and Bridge Construction
Adopted January 1, 2002.

SECTION 420. PORTLAND CEMENT CONCRETE PAVEMENT
420.11 Final Strike Off, Consolidation, and Finishing.

(e) Final Finish. Type A final finish shall be used unless Type B is specified.
(1) Type A. Type A final finish shall be obtained by the use of a carpet drag composed of an artificial turf approved by the Engineer followed immediately by a mechanically operated metal comb transverse grooving device. The artificial turf shall be made of molded polyethylene with synthetic turf blades approximately 20 mm (0.85 in.) long and contain approximately 7,200 individual blades per 0.1 sq m (sq ft).

The artificial turf shall be suitably attached to an approved device that will permit control of the time and rate of texturing. The artificial turf carpet shall be full pavement width and of sufficient size that during the finishing operation, approximately 600 mm (2 ft) of carpet parallel to the pavement centerline will be in contact with the pavement surface. The drag shall be operated in a longitudinal direction so as to produce a uniform appearing finish meeting the approval of the Engineer. If necessary for maintaining intimate contact with the pavement surface, the carpet may be weighted.

The metal comb shall consist of a single line of tempered spring steel tines spaced at 20 mm (3/4 in.) centers and securely mounted in a suitable head. The tines shall be flat and of a size and stiffness sufficient to produce a groove of the specified dimensions in the plastic concrete without tearing of the pavement edge or surface. The Contractor shall modify the equipment or operations if an acceptable pavement edge or surface is not produced. The mechanically operated metal comb shall be attached to an exclusive piece of equipment which is mechanically self-propelled and capable of traversing the entire pavement width being placed in a single pass. The artificial turf carpet drag may be attached to this piece of equipment provided a surface texture is produced satisfactory to the Engineer. The tining device shall be operated so as to produce a relatively uniform pattern of grooves perpendicular to the pavement centerline spaced at approximately 20 mm (3/4 in.) centers, 3 to 5 mm (1/8 to 3/16 in.) deep and 2.5 to 3.2 mm (0.100 to 0.125 in.) wide. No other operation will be permitted with this equipment. Separate passes will be required for the turf dragging operation and the tining operation.

Hand tining or tining with a mechanically operated comb combined with the curing equipment specified in Article 1101.09 will be permitted where the Specifications permit hand finishing or vibratory screeds, one lane construction up to 5 m (16 ft) wide, gaps, projects with a net length of 800 m (1/2 mile) or less, and where the production rate on any paving day will be less than 1200 cu m (1,500 cu yd) per day. A foot bridge shall be provided for the hand tining operation for all pavement over 3.6 m (12 ft) wide, unless it can be demonstrated to the satisfaction of the Engineer that an alternate texturing operation produces satisfactory results.

Pavement texture not meeting the above spacing and depth requirements shall be corrected by the Contractor at his/her own expense. Regrooving in either plastic or hardened concrete shall be done transversely meeting the spacing and depth requirements as stated above.

(2) Type B. Type B final finish shall be obtained by the use of a single artificial turf drag. The artificial turf shall conform and be operated according to the requirements for Type A finish, except this device shall not be attached to other pieces of equipment in the paving train but shall be a separate piece of equipment used expressly for the texturing operation. Pavement texture damaged by rain may be restored by retexturing the concrete while in the plastic state.

MICHIGAN

Current specification:

Transverse tining: 3/4" nominal spacing between grooves with some desired random spacing for noise mitigation. The grooves are approximately 1/8" wide by 1/8" deep. A burlap drag precedes the tinning. The timing of the grooving is specified to prevent excessive tearing of the concrete.

Few short applications of longitudinal tining on a trial basis are based on the following specification:

MICHIGAN
DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION
FOR
LONGITUDINAL TINNING SURFACE TEXTURE

a. Description- This work shall consist of texturing concrete pavement with longitudinal tinning. Replace the second paragraph in section 6.02.03K, 1996 Standard Specifications for Construction, with the following :

Immediately after dragging, all surfaces other than concrete base courses, shoulders and gore areas shall be tinned longitudinally with a track machine. The tinning process shall produce grooves of 2.5 mm (± 0.5 mm) width, by 3mm (± 0.5 mm) depth, spaced on 19 mm (± 2 mm) centers. The grooves shall be parallel to the longitudinal joint(s) without noticeable wander, overlap, or a wave pattern. The grooves shall be formed in the plastic concrete without either slumping of the edges or severe tearing of the surface. Prior to paving, the Contractor shall provide a written description of the intended tinning process for the Engineer's approval to ensure that the grooves will be parallel and uniformly spaced.

If surface corrections are made to the hardened concrete, the amount of macro-texture shall be verified in accordance with ASTM E965, “Test Method for Measuring Surface Macrotexture Depth Using a Sand Volumetric Technique,” to ensure the texture is adequate for skid resistance and does not cause excessive tire noise. A minimum mean texture depth (MTD) of 1.0 mm is required, but it shall not exceed 2.50 mm to assure noise mitigation. If the specified MTD is not being achieved, the Contractor shall suspend operations until a revised procedure is approved by the Engineer. In lieu of re-correcting the surface, a MTD between 0.80 mm and 1.0 mm is acceptable with a contract pay adjustment equal to ten percent of the unit cost of the concrete pavement. A MTD of less than 0.80 mm is unacceptable and shall be corrected to achieve the desired macro-texture.

Any areas represented by a single test with a texture depth of less than 0.50 mm or greater than 2.50 mm will require additional correction. The limits for correction shall be determined by performing additional test measurements at a maximum 30 meter interval along the wheel path from the original failing test location. Additional testing shall continue until a minimum 0.80 mm texture depth is achieved. The Engineer will then use the results to determine the limits for texture correction.

b. Measurement and Payment - All costs associated with this special provision will not be paid for separately, but shall be included in the pay item for concrete pavement.

UTAH

Current Standard Specification for Portland Cement Concrete Pavement states:

Texture the pavement by burlap drag and transverse tining.

1. Use at least three piles of wet burlap and drag parallel to the centerline without tearing.
2. Complete the drag finish with one pass.
3. Form depressions in the plastic concrete surface with the tining comb:
    a. Randomly spaced (15mm to 25mm)
    b. 2 mm to 4 mm deep normal to centerline.
    c. Do not tear or remove excess mortar in the tining process.
4. Do not tine Category 5 highways (i.e., Urban highways with design speed < 65 km/hr).

WASHINGTON STATE

From the 2000 Standard Specifications-English units, pp. 5-44 and 5-45 (these specifications remain unchanged in the 2004 edition)
http://www.wsdot.wa.gov/fasc/EngineeringPublications/Manuals/SS2000English.pdf

5-05.3(11) Finishing

After the concrete has been given a preliminary finish by means of finishing devices incorporated in the slip-form paving equipment, the surface of the fresh concrete shall be checked by the Contractor with a straightedge device not less than 10 feet in length. High areas indicated by the straightedge device shall be removed by the hand-float method.

Each successive check with the straightedge device shall lap the previous check path by at least one half of the length of the straightedge. The requirements of this paragraph may be waived if it is successfully demonstrated that other means will consistently produce a surface with a satisfactory profile index and meeting the 10-foot straightedge requirement specified in Section 5-05.3(12).

Any edge slump of the pavement, exclusive of specified edging, in excess of 1/4 inch shall be corrected before the concrete has hardened. If edge slump on any 1foot or greater length of hardened concrete exceeds 1 inch, the concrete shall be repaired as provided in section 5-05.3(22).

The pavement shall be given a final finish surface by texturing with a comb perpendicular to the center line of the pavement. The comb shall produce striations approximately 1/8 inch to 3/16 inch in depth. Randomly space the striations from 1/2 inch to 11/4 inch. The comb shall be operated mechanically either singly or in gangs with several placed end to end. Finishing shall take place with the elements of the comb as nearly perpendicular to the concrete surface as is practical, to eliminate dragging the mortar. If the striation equipment has not been previously approved, a test section shall be constructed prior to approval of the equipment. If the pavement has a raised curb without a formed concrete gutter, the texturing shall end 2 feet from the curb line.
At the beginning and end of paving each day, the Contractor shall, with an approved stamp, indent the concrete surface near the right hand edge of the panel to indicate the date, month, and year of placement.

At approximate 500-foot intervals where designated by the Engineer the Contractor shall, with an approved stamp, indent the concrete surface near the right hand edge of the pavement with the stationing of the roadway.

APPENDIX B

WISCONSIN PCC PAVEMENT FRICTION NUMBER DISCUSSION

INTRODUCTION

The explanatory variable most commonly used to establish a relationship between safety performance and pavement surface texture has been Friction Number (FN). The method used to obtain the FN for a given pavement simulates pavement performance under wet pavement conditions. Thus, a typical operating assumption for a number of previous research efforts was that low FNs would be associated with a higher number of wet pavement crashes; conversely, higher FNs would be associated with fewer wet pavement crashes.

Benefits and disadvantages of FN as pavement safety performance explanatory variable

FN allowed transferability of results between different parts of the country, under the assumption that similar textures would produce similar FNs when tested using the same FN-testing standard. As indicated in the literature search part of the report, both assumptions were not universally true:

1. Although a general correlation has been identified between low FN and inferior safety performance, this correlation was not found to be very strong; and,
2. Quite different FNs can be obtained for the same pavement surface texture due to materials quality and variability, among other factors.

In other words, FN was not found to be a good explanatory variable for safety performance, and FN-based findings were not guaranteed exact transferability across the country.

FN varies depending on when measurements were taken (for example, after a long dry period, or after a strong rain), and the locations at which they were taken. It should also be noted that data are typically collected at 40-50 mph speeds, which are much lower than typical freeway free-flow operating speeds, thus FNs at freeway operating speeds are typically extrapolated; any correlations with safety performance are subject to errors related to the accuracy of such extrapolations.

FN data are collected on one lane and in one wheel path at a time. Under typical highway traffic conditions, FN is lower for the shoulder lane than for the median lane, due to a heavier lane usage that results in exacerbated aggregate polishing; FN values also vary among wheel paths. Thus, a single FN cannot meaningfully characterize a freeway segment friction performance. Although a lower FN can be expected on the shoulder lane (as a result of higher pavement wear due to heavier traffic), the lower speeds present in this lane may more than compensate for this deficiency—wet pavement crashes may be due to higher vehicle speeds in the median lane, despite its higher FN, but information on the lane in which a crash occurred is not typically available, thus this issue cannot be resolved satisfactorily with currently available FN and crash data.

Ideal FN database attributes

The final TWG report states that: “Available information supports only a general correlation between friction numbers and wet weather crash rates.” Appendix D of the same report states: “While friction properties are a convenient way to estimate the safety characteristics of various pavement types and surface textures, the real test is whether the pavement texture reduces the number and severity of wet weather accidents.” The report recommended that “additional analyses over consecutive 3- to 5-year periods were needed to determine (1) the wet weather accident rates of different textures and pavement types and (2) the change in friction numbers and accident rates over time for the different textures and pavement types."

A large, multi-year FN database would be necessary to address the issue of FN deterioration with pavement age/cumulative vehicle passes. An ideal FN database would contain information collected at the same locations for a large number of pavement sections, over a number of years.

DISCUSSION BASED ON WISCONSIN FN DATA

This Appendix presents a discussion of FN data collected during the period 1975-1994 in Wisconsin for a variety of pavement surface textures. The discussion focuses on some of the FN fluctuations mentioned above. A complete listing of the database is accompanied by figures demonstrating FN fluctuation along a single direction of travel and between directions of travel for a specific highway, and year-to-year FN fluctuations at a specific location. The Appendix also presents FN correlations with the number of years a pavement had been in service and with cumulative heavy vehicle passes since construction.

The database comprises of 534 Friction Number (FN) observations. **Table B1** presents a comprehensive listing of the recorded FN organized by pavement surface texture treatment, highway, location (from reference point, to reference point), lane in which the data were collected and the data collection year and month. Data from **Table B1** were used to create **figures B1–B4**.

Figure B1 presents data collected in both directions of Interstate 90 (Eastbound - 90E and Westbound – 90W on the figure) in September of 1981. FN on the vertical axis is plotted against reference point[1] on the horizontal axis for all FN tests along 182 freeway centerline miles. The figure demonstrates that substantial FN variations exist within and between travel directions. The tested pavement was constructed between 1959 and 1973 (**Table B2**). It is thus to be expected that substantial differences exist in cumulative vehicle passes between freeway segments. However, FN varies substantially within pavement sections in a given travel direction constructed during the same year and experiencing similar traffic volume levels.

For example, the segment between reference points 39T and 79K (approximately 40 miles long) was constructed in 1964. A range of FN were measured for each travel direction: Westbound FN was in the 35-42 range; eastbound FN was in the 36-41 range.

If an even daily directional split is assumed for I-90, FN differences between directions of travel for the same freeway segment cannot easily be explained, since both directions experience equal traffic volumes and all FN tests were conducted on the same month. FN differences exceeding four FN units between travel directions are present at reference point 79K. Similar observations can be made at other milepoints along the entire 182-mile corridor shown in **Figure B1**.

---

[1] Numeric part of horizontal axis codes indicates approximate freeway mile.

Figure B2 presents FN variations between lanes on a three-lane Eastbound segment of Interstate 90 for the period 1985-1994. As expected, the shoulder lane (lane 1), carrying the heaviest traffic volumes consistently displays the lowest FN. FN change from year-to-year for each of the three lanes does not show a consistent FN deterioration; furthermore, the direction of change from year-to-year is not consistent among the three lanes.

The most comprehensive FN database was for transversely tined PCC pavements, with a total of 291 observations. FN relations with pavement age are summarized in **figure B3**, where information is presented separately for the shoulder lane (square markers) and the passing lane (triangular markers). No clear FN pattern emerges in that figure, perhaps due to the substantially different traffic volumes carried on the pavements in the database. In order to account for the effect of traffic on FN, **figure B4** presents FN information as a function of cumulative Million Heavy Vehicle Passes (MHVP) for tined PCC pavement surfaces. Heavy vehicle volume information was only available for the shoulder lane, thus the sample size used in **figure B4** is 170 observations. There is a very broad range of FN values at each level of MHVP, thus the correlation between the two analyzed variables was not strong. Among the best fitting simple regression models used to explain FN as a function of MHVP,[2] the power model:

$$FN = 49.33 * MHVP^{-0.37569}$$

provided the best fit with an $R^2 = 0.123$ (the regression line for the model is shown on **Figure B4**). Similar results ($R^2 = 0.152$) were obtained from a simple regression model using Accumulated Vehicle Passes in the shoulder lane.

DISCUSSION

Given the variability of FN values present in the analyzed database, using FN as a proxy for the likelihood of wet pavement crashes was given a much lower priority than a comprehensive crash experience analysis. Still, FN data availability was investigated with each of the contacted state Departments of Transportation, in order to assess the following issues:

1. Whether FN measurements could readily be “mapped” to crash locations.
2. Whether a large number of observations was available in order to correlate FN with crashes as close as possible to the location where FN measurements were obtained. Ideally, a representative FN would be available for each of a large number of short freeway segments.
3. Whether a large number of observations was available in order to correlate FN with crashes that occurred during the same year FN information was obtained.
4. Whether FN variability similar to that presented in the preceding discussion, based on Wisconsin data, existed in other states.

---

[2] The following regression models were calibrated: Linear, logarithmic, inverse, compound, power, growth, exponential, logistic.

Table B1. FN data 1975-1994 Part 1

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
ASTRO-TURF DRAG	43N	95D	99K	N/B Shoulder lane	75	Dec.	45
			99M	N/B Shoulder lane	76	Oct.	51
					77	May	54
					78	May	50
					79	Jun.	43
					80	Jun.	49
						Sep.	44
					81	Jun.	40
						Oct.	47
					82	Jul.	44
					83	Jul.	36
					84	Aug.	36
		99M	101D	N/B Shoulder lane	75	Dec.	49
					76	Oct.	60
					77	May	63
					78	May	57
					79	Jun.	51
					80	Jun.	55
						Sep.	53
					81	Jun.	46
						Oct.	49
					82	Jul.	49

Table B1. FN data 1975-1994 Part 2

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
ASTRO-TURF DRAG	43N	99M	101D	N/B Shoulder lane	83	Jul.	41
					84	Aug.	42
	Mean						48
	43S	95D	99M	S/B Shoulder lane	75	Dec.	46
					76	Oct.	53
					77	May	57
					78	May	53
					79	Jun.	47
		99M	101D	S/B Shoulder lane	75	Dec.	47
					76	Oct.	62
					77	May	64
					78	May	55
					79	Jun.	50
	Mean						53
Mean							50

Table B1. FN data 1975-1994 Part 3

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
BURLAP DRAG	15E	70K	70K	E/B Shoulder lane	82	Sep.	35
					84	Jul.	33
	Mean						34
	15W	70K	70K	W/B Shoulder lane	82	Sep.	36
					84	Jul.	34
			73	W/B lane 2	82	Sep.	37
					84	Jul.	36
	Mean						36
	41N	14	15K	N/B lane 2	82	Sep.	30
					84	Jul.	28
	Mean						29
	41S	14	15K	S/B lane 2	82	Sep.	30
					84	Jul.	28
	Mean						29
	45N	49	50	N/B lane 2	82	Sep.	29
					84	Jul.	28
		50	53	N/B lane 2	82	Sep.	30
					84	Jul.	28
	Mean						29
	45S	49	50	S/B lane 2	82	Sep.	28
					84	Jul.	26
		50	53	S/B lane 2	82	Sep.	28
					84	Jul.	27
	Mean						27
	81E	99B	112B	-E-	80	Jun.	53

Table B1. FN data 1975-1994 Part 4

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
BURLAP DRAG	81E	99B	112B	-E-	80	Aug.	49
					81	Jun.	44
						Oct.	50
					82	Aug.	49
					83	Aug.	46
					84	Aug.	47
					90	Aug.	53
					92	Sep.	54
					94	Jul.	54
				E&W	76	Nov.	54
					77	May	60
					78	May	54
					79	May	46
	Mean						51
	90E	1C	3K	E/B Shoulder lane	81	Sep.	38
		3K	5T	E/B Shoulder lane	81	Sep.	40
		10D	13G	E/B Shoulder lane	81	Sep.	38
		13G	20K	E/B Shoulder lane	81	Sep.	37
		20K	28K	E/B Shoulder lane	81	Sep.	41
		28K	34D	E/B Shoulder lane	81	Sep.	39
		34D	39T	E/B Shoulder lane	81	Sep.	36
		39T	43M	E/B Shoulder lane	81	Sep.	37

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
BURLAP DRAG	90E	45T	52K	E/B Shoulder lane	81	Sep.	40
		52K	55G	E/B Shoulder lane	81	Sep.	39
		55G	60G	E/B Shoulder lane	81	Sep.	40
		61K	68D	E/B Shoulder lane	81	Sep.	41
		69K	74G	E/B Shoulder lane	81	Sep.	37
		79K	85T	E/B Shoulder lane	81	Sep.	38
		86K	89M	E/B Shoulder lane	81	Sep.	36
		89M	92M	E/B Shoulder lane	81	Sep.	39
		106M	111M	E/B Shoulder lane	81	Sep.	32
		111M	118K	E/B Shoulder lane	81	Sep.	34
		118K	123D	E/B Shoulder lane	81	Sep.	34
		123D	126G	E/B Shoulder lane	81	Sep.	34
		129K	133M	E/B Shoulder lane	81	Sep.	33
		134M	137D	E/B Shoulder lane	81	Sep.	33
		138D	142G	E/B Shoulder lane	81	Sep.	37
						Nov.	36
					82	Sep.	34
					83	Sep.	30
					84	Aug.	31
					85	Aug.	32
					86	Aug.	32

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
BURLAP DRAG	90E	138D	142G	E/B Passing lane	81	Nov.	43
					82	Sep.	47
					83	Sep.	42
					84	Aug.	39
					85	Aug.	44
					86	Aug.	43
		142G	145K	E/B Shoulder lane	81	Sep.	35
		145K	150D	E/B Shoulder lane	81	Sep.	37
		150D	154G	E/B Shoulder lane	81	Sep.	36
		155M	159K	E/B Shoulder lane	81	Sep.	37
		159K	163G	E/B Shoulder lane	81	Sep.	37
		163G	167T	E/B Shoulder lane	81	Sep.	38
		168T	172G	E/B Shoulder lane	81	Sep.	38
		172G	174K	E/B Shoulder lane	81	Sep.	36
		174K	177K	E/B Shoulder lane	81	Sep.	36
		177K	182K	E/B Shoulder lane	81	Sep.	38
		182K	187T	E/B Shoulder lane	81	Sep.	36
	Mean						37
	90W	1C	3K	W/B Shoulder lane	81	Sep.	38
		3K	5T	W/B Shoulder lane	81	Sep.	42
		10D	13G	W/B Shoulder lane	81	Sep.	38
		13G	20K	W/B Shoulder lane	81	Sep.	38

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
BURLAP DRAG	90W	20K	28K	W/B Shoulder lane	81	Sep.	42
		28K	34D	W/B Shoulder lane	81	Sep.	39
		34D	39T	W/B Shoulder lane	81	Sep.	36
		39T	43M	W/B Shoulder lane	81	Sep.	35
		45T	52K	W/B Shoulder lane	81	Sep.	39
		52K	55G	W/B Shoulder lane	81	Sep.	38
		55G	60G	W/B Shoulder lane	81	Sep.	37
		61K	68D	W/B Shoulder lane	81	Sep.	38
		69K	74G	W/B Shoulder lane	81	Sep.	36
		79K	85T	W/B Shoulder lane	81	Sep.	42
		86K	89M	W/B Shoulder lane	81	Sep.	37
		89M	92M	W/B Shoulder lane	81	Sep.	39
		94M	97K	W/B Shoulder lane	81	Sep.	40
		98M	101T	W/B Shoulder lane	81	Sep.	41
		101T	106M	W/B Shoulder lane	81	Sep.	43
		106M	111M	W/B Shoulder lane	81	Sep.	34
		111M	118K	W/B Shoulder lane	81	Sep.	36
		118K	123D	W/B Shoulder lane	81	Sep.	34
		123D	126G	W/B Shoulder lane	81	Sep.	33
		129K	133M	W/B Shoulder lane	81	Sep.	32
		134M	137D	W/B Shoulder lane	81	Sep.	32

Table B1. FN data 1975-1994 Part 8

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
BURLAP DRAG	90W	138D	142G	W/B Shoulder lane	81	Sep.	46
		142G	145K	W/B Shoulder lane	81	Sep.	35
		145K	150D	W/B Shoulder lane	81	Sep.	36
		150D	154G	W/B Shoulder lane	81	Sep.	39
		155M	159K	W/B Shoulder lane	81	Sep.	38
		159K	163G	W/B Shoulder lane	81	Sep.	39
		163G	167T	W/B Shoulder lane	81	Sep.	39
		168T	172G	W/B Shoulder lane	81	Sep.	38
		172G	174K	W/B Shoulder lane	81	Sep.	37
		174K	177K	W/B Shoulder lane	81	Sep.	39
		177K	182K	W/B Shoulder lane	81	Sep.	39
		182K	187T	W/B Shoulder lane	81	Sep.	38
	Mean						38
	94E	311D	312D	E/B lane 2	82	Sep.	28
					84	Jul.	26
		312M	314K	E/B lane 2	82	Sep.	31
					84	Jul.	28
		314K	315D	E/B lane 2	82	Sep.	28
					84	Jul.	26
		315D	315G	E/B lane 2	82	Sep.	31
					84	Jul.	28
		318G	323T	E/B lane 2	82	Sep.	35

Table B1. FN data 1975-1994 Part 9

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
BURLAP DRAG	94E	318G	323T	E/B lane 2	84	Jul.	32
		323T	325D	E/B lane 2	82	Sep.	37
	Mean						30
	94W	311D	312D	W/B lane 2	82	Sep.	29
					84	Jul.	28
		312M	314K	W/B lane 2	82	Sep.	30
					84	Jul.	29
		314K	315D	W/B lane 2	82	Sep.	28
					84	Jul.	26
		315D	315G	W/B lane 2	82	Sep.	30
					84	Jul.	27
		318G	323T	W/B lane 2	82	Sep.	33
					84	Jul.	30
		323T	325D	W/B lane 2	82	Sep.	35
	Mean						30
	119E	3	5	E/B Shoulder lane	82	Jul.	53
					84	Jul.	50
	Mean						51
	119W	3	5	W/B Shoulder lane	82	Jul.	47
					84	Jul.	45
	Mean						46
	145N	3	6	N/B lane 2	82	Sep.	40
					84	Jul.	38
	Mean						39

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
BURLAP DRAG	145S	3	6	S/B lane 2	82	Sep.	41
					84	Jul.	38
	Mean						40
	894E	4T	4T	E/B lane 2	82	Sep.	30
			7D	E/B lane 2	82	Sep.	32
		7D	8D	E/B lane 2	82	Sep.	28
		8D	9D	E/B lane 2	82	Sep.	30
				W/B lane 2	82	Sep.	30
	Mean						30
	894W	4T	4T	W/B lane 2	82	Sep.	31
			7D	W/B lane 2	82	Sep.	33
		7D	8D	W/B lane 2	82	Sep.	28
	Mean						31
Mean							37

Table B1. FN data 1975-1994 Part 11

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
CONTINUOUS GRINDING	41N	61	66	N/B Shoulder lane	80	Jun.	42
						Sep.	42
					81	Jun.	38
						Oct.	38
					82	Jul.	41
					83	Jul.	30
					84	Jul.	36
					85	Jul.	35
					86	Jul.	32
					87	Jul.	34
					88	Jul.	35
				N/B Passing lane	80	Jun.	49
						Sep.	48
					81	Jun.	43
						Oct.	46
					82	Jul.	48
					83	Jul.	39
					84	Jul.	45
					85	Jul.	44
					86	Jul.	43
					87	Jul.	42

Table B1. FN data 1975-1994 Part 12

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
CONTINUOUS GRINDING	41N	61	66	N/B Passing lane	88	Jul.	45
	Mean						41
	90W	138D	142G	W/B Shoulder lane	81	Nov.	43
					82	Sep.	37
					83	Sep.	31
					84	Aug.	33
					85	Aug.	33
					86	Aug.	32
				W/B Passing lane	81	Nov.	46
					82	Sep.	44
					83	Sep.	40
					84	Aug.	39
					85	Aug.	42
					86	Aug.	40
	Mean						38
Mean							40

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
GROOVED SURFACE	43S	75K	76T	S/B lane 2	76	Jun.	25
					77	May	27
					78	May	29
					79	Jun.	26
						Oct.	26
					80	May	25
						Aug.	24
					81	Jul.	24
						Oct.	24
					82	Jul.	26
	Mean						26
Mean							26

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
SKIP-GRINDING	90E	138D	142G	E/B Shoulder lane	81	Nov.	37
					82	Sep.	35
					83	Sep.	30
					84	Aug.	30
					85	Aug.	34
					86	Aug.	32
				E/B Passing lane	81	Nov.	45
					82	Sep.	48
					83	Sep.	42
					84	Aug.	42
					85	Aug.	45
					86	Aug.	43
	Mean						39
Mean							39

Table B1. FN data 1975-1994 Part 15

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	10E	304	309	E&W	81	Jun.	50
						Nov.	52
					82	Aug.	51
					83	Aug.	46
					84	Sep.	46
					86	Aug.	43
					88	Sep.	43
					90	Aug.	47
					92	Aug.	47
					94	Aug.	47
	Mean						47
	11E	83B	86B	E/B Shoulder lane	79	May	48
					80	Jun.	50
						Aug.	50
					81	Jun.	43
						Oct.	47
					82	Aug.	48
					83	Aug.	45
					84	Aug.	47
					86	Jul.	46
					88	Aug.	49
					90	Sep.	53

Table B1. FN data 1975-1994 Part 16

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	11E	83B	86B	E/B Shoulder lane	92	Sep.	54
					94	Jul.	55
	Mean						49
	12E	361B	362B	E&W	79	May	47
					80	Jun.	48
						Oct.	47
					81	Jun.	44
						Oct.	44
					82	Sep.	43
					83	Sep.	41
					84	Sep.	41
					86	Sep.	41
					88	Sep.	42
					92	Sep.	49
	Mean						44
	14E	211B	216B	E/B Shoulder lane	79	May	51
					80	Jun.	53
						Aug.	51
					81	Jun.	50
						Sep.	51
					82	Sep.	52
					83	Sep.	48

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	14E	211B	216B	E/B Shoulder lane	84	Sep.	49
					86	Sep.	51
					88	Sep.	53
					90	Sep.	59
					92	Sep.	60
					94	Jul.	56
	Mean						52
	14W	211B	216B	W/B Shoulder lane	79	May	49
					81	Jun.	50
						Sep.	49
					82	Sep.	51
					83	Sep.	45
					84	Sep.	48
					86	Sep.	48
					88	Sep.	53
					90	Sep.	57
					92	Sep.	57
					94	Sep.	55
	Mean						51
	18W	99D	101K	W/B Shoulder lane	81	Jun.	52
						Sep.	55
					82	Sep.	54

Table B1. FN data 1975-1994 Part 18

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	18W	99D	101K	W/B Shoulder lane	83	Sep.	50
					84	Sep.	47
					86	Sep.	50
					88	Sep.	47
					89	Oct.	43
					90	Sep.	56
					92	Oct.	54
					94	Aug.	52
	Mean						51
	19E	24E	27M	E&W	81	Jun.	45
						Oct.	48
					82	Aug.	49
					83	Sep.	44
					84	Aug.	44
					86	Aug.	46
					88	Aug.	42
					90	Aug.	45
					92	Aug.	45
					94	Aug.	41
	Mean						45
	43N	4K	9M	N/B Shoulder lane	76	Nov.	54
					77	May	56

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	43N	4K	9M	N/B Shoulder lane	78	May	51
					79	May	46
					80	Jun.	52
						Aug.	49
					81	Jun.	45
						Oct.	50
					82	Aug.	49
					83	Aug.	47
					84	Aug.	47
					86	Aug.	46
					88	Aug.	50
					90	Aug.	57
					92	Sep.	56
		11D	15B	N/B Shoulder lane	76	Nov.	60
					77	May	61
					78	May	56
					79	May	51
					80	Jun.	55
						Aug.	52
					81	Jun.	48
						Oct.	52

Table B1. FN data 1975-1994 Part 20

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	43N	11D	15B	N/B Shoulder lane	82	Aug.	50
					83	Aug.	48
					84	Aug.	49
					86	Aug.	49
					88	Aug.	53
					90	Aug.	59
					92	Sep.	59
		25D	30K	N/B Shoulder lane	76	Nov.	60
					77	May	60
					78	May	56
					79	May	49
					80	Jun.	57
						Aug.	50
					81	Jun.	46
						Oct.	52
					82	Aug.	51
					83	Aug.	48
					84	Aug.	48
					86	Aug.	47
					88	Aug.	40
					90	Aug.	45

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	43N	102D	107K	N/B Shoulder lane	75	Dec.	46
					76	Oct.	62
					77	May	62
					78	May	54
					79	Jun.	47
					80	Jun.	52
						Sep.	47
					81	Jun.	43
						Oct.	44
					82	Jul.	43
					83	Jul.	37
					84	Aug.	37
					86	Aug.	37
					88	Jul.	38
					90	Jul.	47
		108D	113T	N/B Shoulder lane	75	Dec.	47
					76	Oct.	63
					77	May	64
					78	May	57
					79	Jun.	50
					80	Jun.	53

Table B1. FN data 1975-1994 Part 22

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	43N	108D	113T	N/B Shoulder lane	80	Sep.	47
					81	Jun.	43
						Oct.	46
					82	Jul.	46
					83	Jul.	38
					84	Aug.	39
					86	Aug.	38
					88	Jul.	40
					90	Jul.	44
	Mean						50
	43S	4K	9M	S/B Shoulder lane	76	Nov.	61
					77	May	58
					78	May	57
					79	May	49
		11D	15B	S/B Shoulder lane	76	Nov.	60
					77	May	64
					78	May	60
					79	May	52
		25D	30K	S/B Shoulder lane	76	Nov.	64
					77	May	61
					78	May	59
					79	May	51

Table B1. FN data 1975-1994 Part 23

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	43S	102D	107K	S/B Shoulder lane	75	Dec.	51
					76	Oct.	59
					77	May	61
					78	May	55
					79	Jun.	48
					86	Aug.	38
		108D	113T	S/B Shoulder lane	75	Dec.	47
					76	Oct.	58
					77	May	61
					78	May	52
					79	Jun.	46
					86	Aug.	39
	Mean						55
	51S	176	185	S/B Shoulder lane	81	Jun.	48
						Oct.	52
					82	Aug.	54
					83	Aug.	49
					84	Aug.	50
					86	Aug.	50
					88	Aug.	54
					90	Aug.	59
					92	Sep.	56

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	51S	176	185	S/B Shoulder lane	94	Jul.	52
	Mean						52
	81E	112B	121	-E-	76	Nov.	53
					77	May	61
					78	May	59
					79	May	49
					80	Jun.	57
						Aug.	53
					81	Jun.	49
						Oct.	54
					82	Aug.	52
					83	Aug.	48
					84	Aug.	41
					86	Aug.	47
					88	Aug.	52
					90	Aug.	59
					92	Sep.	57
					94	Jul.	57
	Mean						53
	90E	92M	106G	E/B Shoulder lane	75	Sep.	47
					76	Jun.	50
						Oct.	51

Table B1. FN data 1975-1994 Part 25

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	90E	92M	106G	E/B Shoulder lane	77	Apr.	51
					78	May	44
					79	May	45
					80	Jun.	48
						Sep.	50
					81	Jun.	46
						Sep.	48
					82	Sep.	49
					83	Aug.	46
					84	Sep.	47
					86	Sep.	48
					88	Sep.	49
					90	Sep.	55
					93	Aug.	55
					94	Aug.	50
		119M	123D	E/B lane 1	85	Aug.	47
					86	Aug.	43
					87	Aug.	48
					88	Aug.	46
					89	Aug.	53
					90	Aug.	47

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	90E	119M	123D	E/B lane 1	91	Aug.	50
					92	Aug.	48
					93	Aug.	51
					94	Aug.	46
				E/B lane 2	85	Aug.	49
					86	Aug.	46
					87	Aug.	50
					88	Aug.	48
					89	Aug.	55
					90	Aug.	50
					91	Aug.	52
					92	Aug.	51
					93	Aug.	54
					94	Aug.	48
				E/B lane 3	85	Aug.	53
					86	Aug.	51
					87	Aug.	53
					88	Aug.	55
					89	Aug.	61
					90	Aug.	57
					91	Aug.	56

Table B1. FN data 1975-1994 Part 27

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	90E	119M	123D	E/B lane 3	92	Aug.	58
					93	Aug.	57
					94	Aug.	53
		123D	126T	E/B lane 1	85	Aug.	47
					86	Aug.	46
					87	Aug.	47
					88	Aug.	46
					89	Aug.	53
					90	Aug.	51
					91	Aug.	50
					92	Aug.	48
					93	Sep.	39
					94	Aug.	49
				E/B lane 2	85	Aug.	49
					86	Aug.	45
					87	Aug.	49
					88	Aug.	50
					89	Aug.	57
					90	Aug.	54
					91	Aug.	53
					92	Aug.	52

Table B1. FN data 1975-1994 Part 28

PCC Surface Texture	Highway	From Ref Point	To Ref Point	Lane	Test Year	Test Month	FN value
TINED SURFACE	90E	123D	126T	E/B lane 2	93	Sep.	51
					94	Aug.	49
				E/B lane 3	85	Aug.	53
					86	Aug.	52
					87	Aug.	53
					88	Aug.	55
					89	Aug.	64
					90	Aug.	59
					91	Aug.	58
					92	Aug.	59
					93	Sep.	49
					94	Aug.	57
	Mean						51
	138E	11T	19B	E&W	81	Sep.	47
					82	Sep.	48
					83	Sep.	45
					84	Sep.	45
							46
					88	Sep.	48
					90	Sep.	55
					92	Sep.	52
					94	Jul.	52
	Mean						49
Mean							50

Table 2. Construction year and Design Lane Average Daily Traffic information for figure B1.

I-90 Segment Construction Year

Year	From Ref Point	To Ref Point
1959	172G	187T
1961	86K	92M
	106M	142G
1962	142G	172G
1964	39T	85T
1967	1C	5T
1969	10D	34D
1973	94M	106M

I-90 Segment Design Lane Volume

Lane ADT (VPD)	From Ref Point	To Ref Point
0.8K - 2.3K	28K	39T
2.3K - 3.7K	3K	5T
	10D	28K
	39T	52K
3.7K - 7.0K	1C	3K
	52K	74G
7.0K - 21.0K	79K	187T

Notes:

- Reference points are highway features located within the milepoint indicated by the numeric part of the Reference Point code.
- This information was extracted from the WisDOT Metamanager database.
- Segment extent is approximate.
- Short Transversely tined pavement segments were also present on I-90 in 1981.
- Data in figure B1 are for Burlap Drag segments only.
- Design Lane = Shoulder lane.

Figure B1. Friction Number Variation Along Interstate 90. (Burlap Drag Surface Texture).

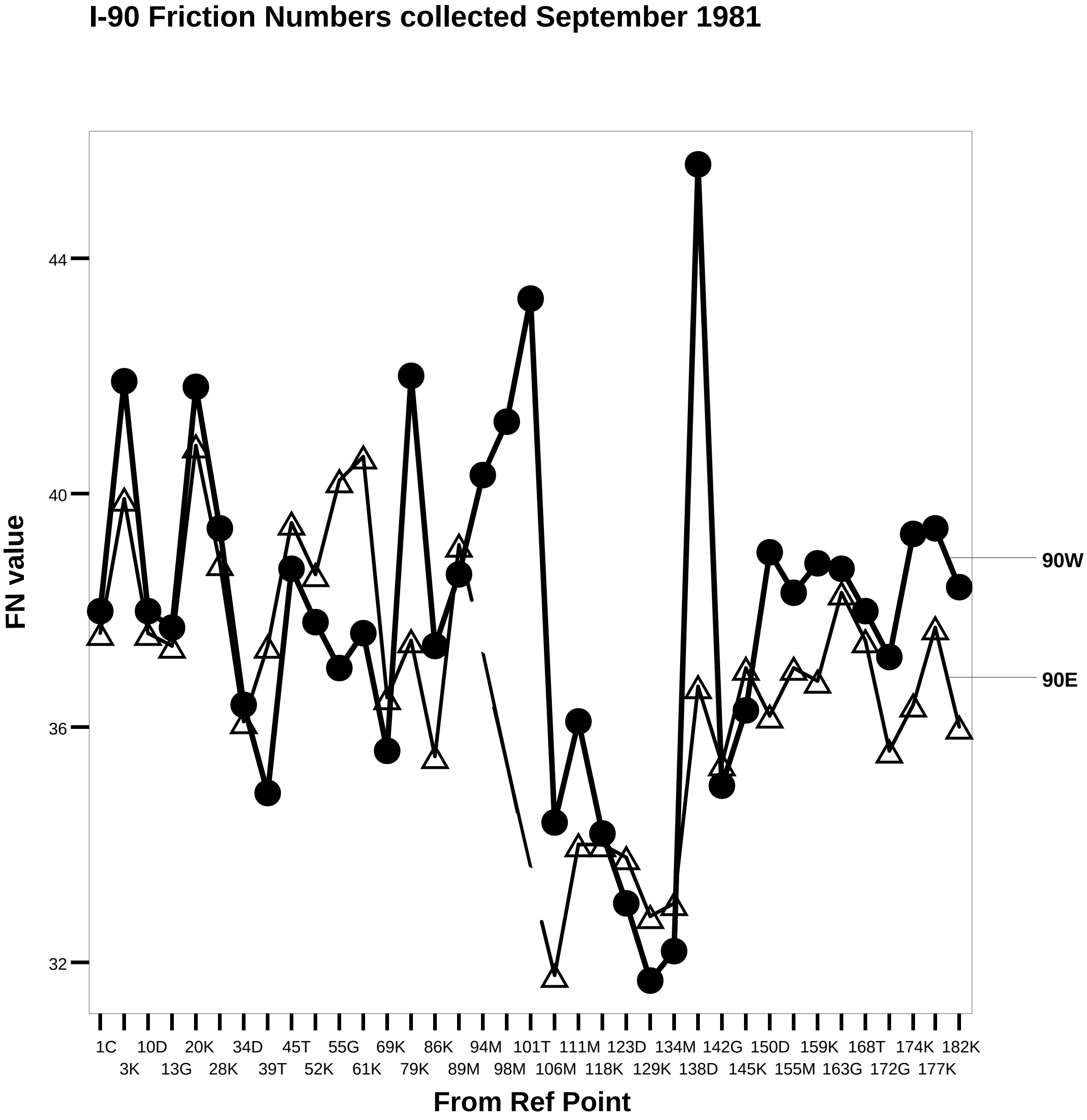


Figure B2. Friction Number Variation Between Lanes Interstate 90. (Tined Surface Texture).

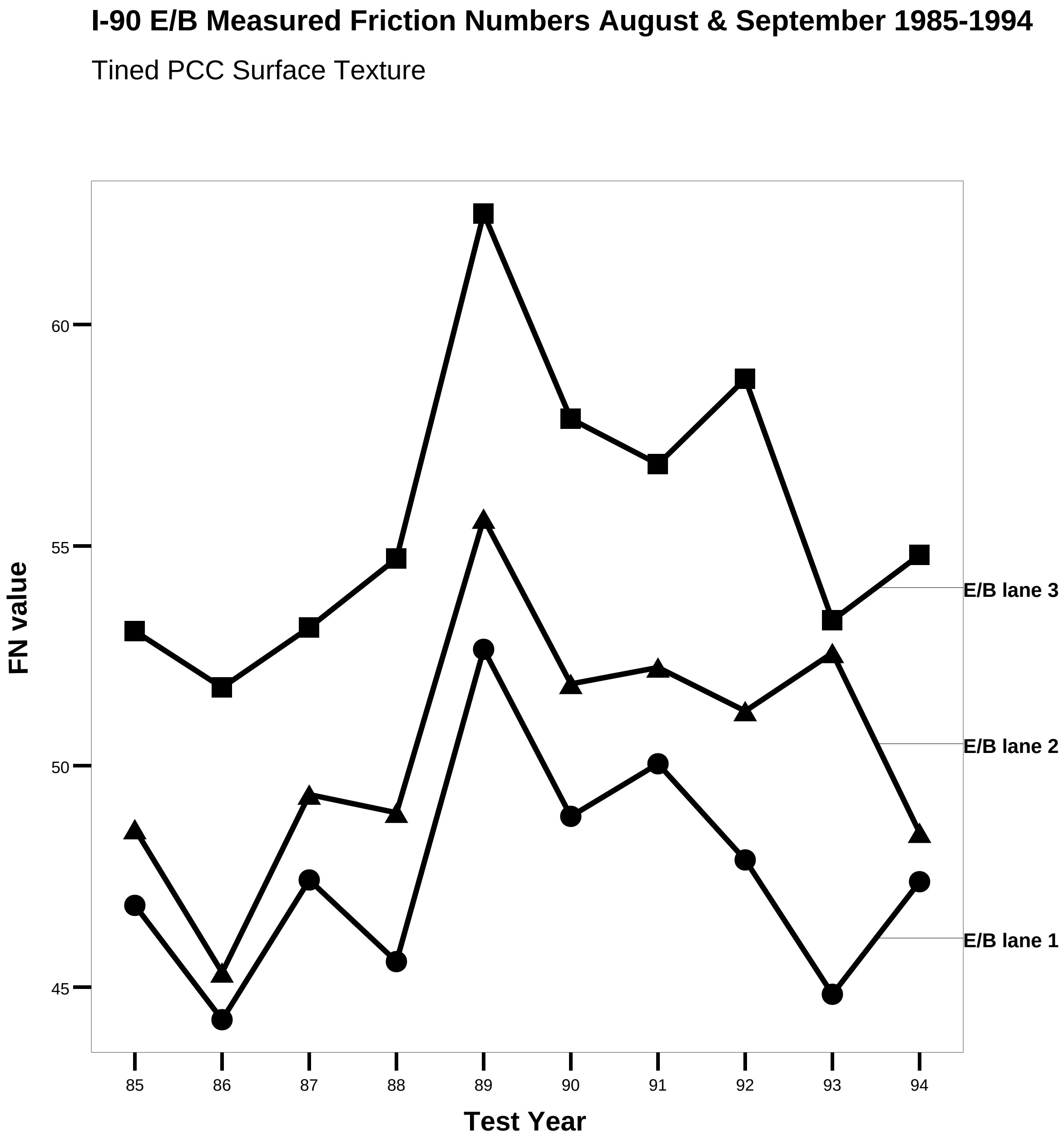
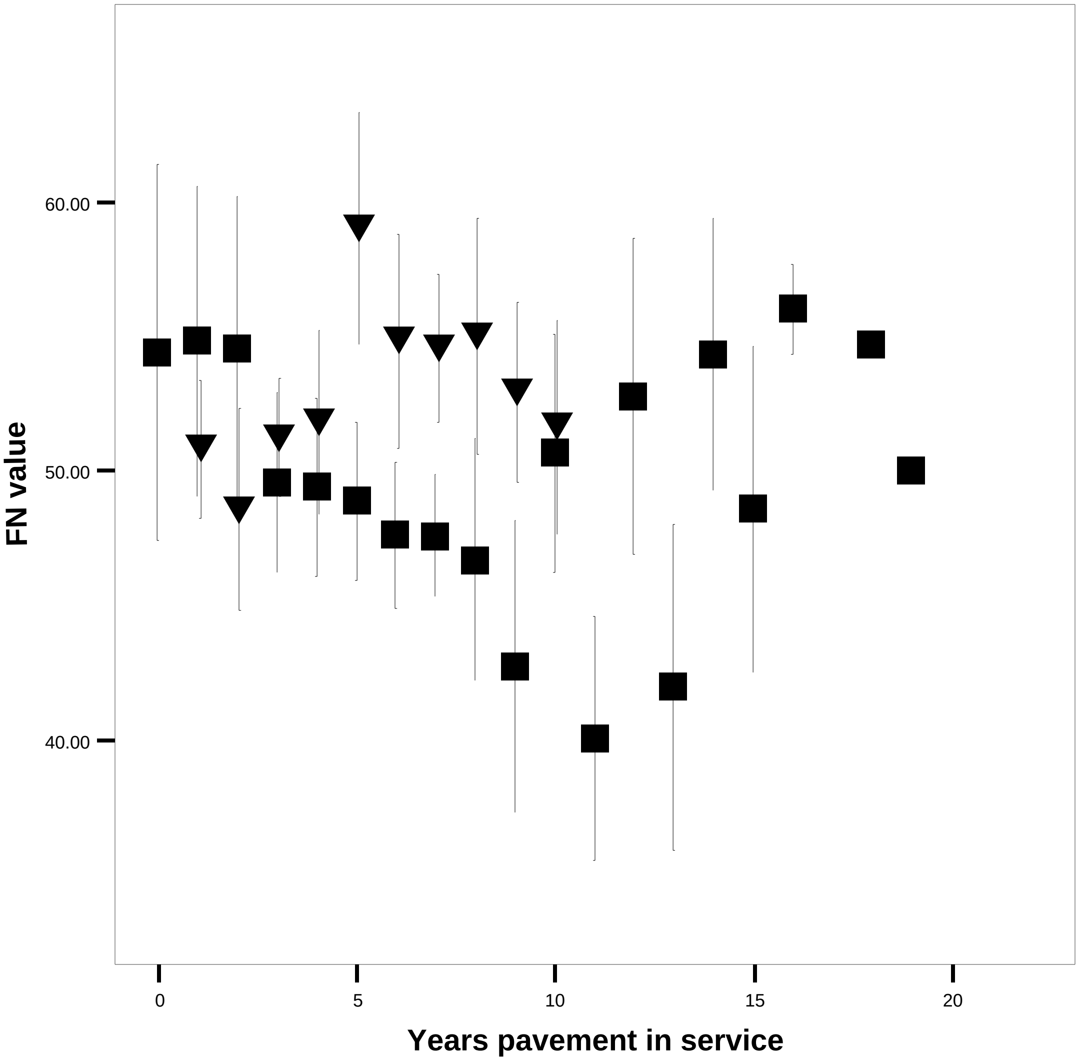


Figure B3. Friction Number Variation with Pavement Age. (Tined Surface Texture).
(Square markers-Shoulder lane, Triangular markers-Passing lane)

FN relation with Pavement Age

Tined PCC Surface Texture



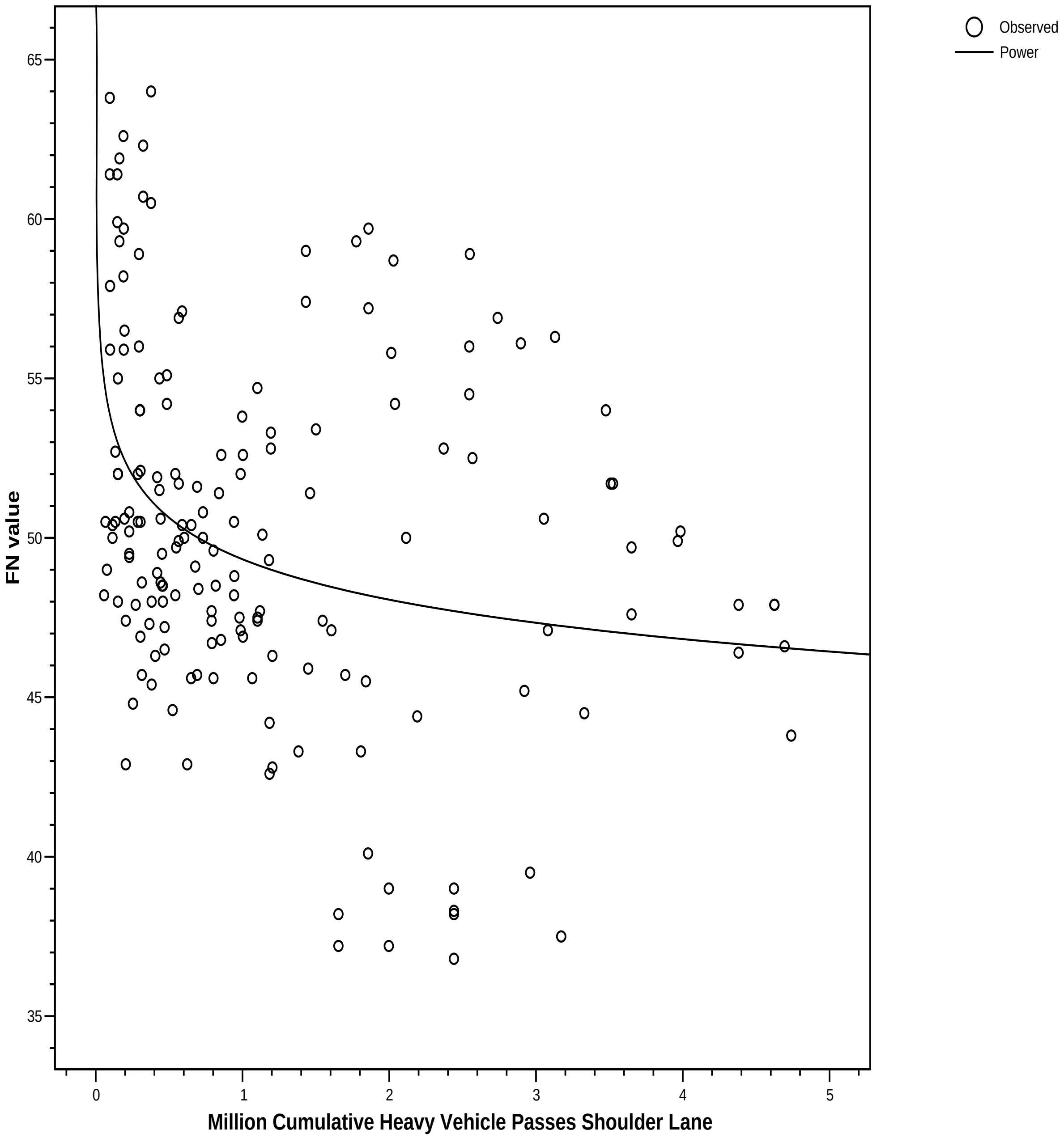
Error Bars show Mean +/- 1.0 SD

Friction Number differences between lanes

Figure B4. Friction Number Variation with Vehicle Passes. Shoulder Lane.

FN relation with Cumulative Vehicle Passes

Tined PCC Surface Texture



APPENDIX C

CRASH STATISTICS

INTRODUCTION

A description of the crash and pavement selection process is provided for Wisconsin and California data. The description is followed by **Table C1** summarizing annual crash rates for Wisconsin and California. **Table C2** provides more detailed annual and cumulative findings for Wisconsin and California freeways (refer to the **Methodology** section of the report for detailed descriptions of the *wet-to-dry ratio* and the *Liquid Safety Ratio–LSR* statistics presented herein).

Wisconsin data listings are followed by California data for level and rolling terrain; listings for mountainous California terrain data conclude the Appendix. ***Important cautions about information provided in Table C2 are presented on page C4.*** Tables and figures specific to the crash statistics discussion in the Findings section of the report are presented in **Appendix D**.

Use of weather and precipitation information in producing the Liquid precipitation Safety Ratio (LSR) is described in **Appendix E**.

CRASH AND PAVEMENT SELECTION PROCESS

The analyzed database consists of crashes that occurred between 1991 and 1998 (inclusive). A detailed description of the analyzed databases for each state is provided below:

WISCONSIN

Crash database

All freeway crashes on all sections of I-90, I-94, I-894 and I-794 with a speed limit greater or equal to 50 mph, that occurred on pavements constructed between 1978 and the year before a crash occurred. Deer crashes were excluded from consideration. Out of a state-wide total of approximately 69,000 crashes, 34,635 freeway crashes fit the above criteria.

Pavement database

Pavement data were extracted from the “Metamanager” WisDOT database. The database provided pavement materials information (PCC-analyzed herein or asphalt-not included in this analysis), the date a pavement surface was constructed, travel information (freeway segment length and Average Daily Traffic-ADT) and freeway type (urban or rural). The 1999 database was used in order to include the pavement surface construction dates relevant to all analyzed segments; travel information was based on extrapolations of annual traffic growth to each analyzed year.

Analysis database

The pavement database was queried for pavements constructed between 1978 (the first year that all new PCC pavements were required to have transversely tined-TT surfaces) and 1990. Crashes that occurred during 1991 were then matched with 1991 travel information on the pavement on which they occurred. The pavement selection method guaranteed that any selected PCC freeway pavement would be transversely tined. Any new PCC pavement mileage constructed during 1991 was added to the database, and 1992 crashes were matched to the corresponding 1992 travel information. This process was repeated for each analyzed year, up to and including the 1998 crash data. Thus the analyzed mileage increased from 1991 to 1998. Details on the pavements analyzed each year are provided in **Appendix F**. The total number of crashes matched to analyzed freeway segments was 11,887. Most, (7,838) occurred on rural freeways and the remainder (4,049) on urban freeways. Thus, the analyzed database included approximately 34% (11,887 / 34,635) of the crashes that occurred on I-90, I-94, I-794, and I-894, which approximately correspond to 17% (11,887 / 69,000) of all Wisconsin freeway crashes, in all analysis years.

It should be noted that the emphasis of the present analysis was on rural freeways. Most urban pavements constructed on the analyzed freeways were asphalt; very few PCC pavement miles were constructed in urban areas, thus reliable statistics are not available for these pavements.

CALIFORNIA

Crash database

The Highway Safety Information System (HSIS) California database (see **Appendix G** for details) was utilized to provide freeway crashes. All 832,129 reported freeway crashes that occurred between 1991 and 1998 were analyzed.

Pavement databases

The HSIS Roadway Inventory and the Traffic Volume databases were used to provide urban/rural freeway designation, travel information (based on ADT and freeway segment length), and terrain information (Level, Rolling or Mountainous). Information was available for every year from 1993 to 1998. Travel information for years 1991 and 1992 was extracted from the 1993 data.

Analysis database

The crash and pavement databases were merged for each analysis year. Each crash was matched to a freeway section. There were 74,548 crashes on rural freeways and 757,581 crashes on urban freeways during all analysis years. Very small freeway mileage changes occurred during the analyzed years.

California PCC pavements were Longitudinally Tined-LT, except for bridge decks, that were TT, and were excluded from further consideration.

California freeways were analyzed in two terrain groups: level or rolling terrain, and mountainous terrain. This grouping allowed comparisons with Wisconsin, where no mountainous terrain is present. Mountainous terrain statistics are listed in the present Appendix for the interested reader, but are not discussed in the body of the report.

INTRODUCTION TO CRASH STATISTICS TABLE C2

Statistics were calculated for freeways with less than 60,000 VPD and those with 60,000+ VPD. The focus of this effort is on rural freeways, where free-flow speeds prevail, crash rates are lower, but crash outcomes are more severe. The majority of rural freeways are in the lower ADT range. These freeways are addressed extensively in the Findings section of the report; abbreviated tables and figures relating to the Findings section are presented in **Appendix D**.

Separate statistics are provided for level/rolling terrain and for mountainous terrain California freeways. Level/rolling terrain summaries are more appropriate for comparisons with Wisconsin, which has a similar terrain.

Urban freeway statistics are provided in the interest of a comprehensive presentation of findings, and are briefly discussed in the **Findings** section of the report. Summary statistics (tables and figures) relating to that discussion are presented in **Appendix D**. The majority of wet pavement crashes on urban freeways occur during peak traffic periods when speeds are substantially below free-flow speed levels. Congestion (traffic shock waves), tailgating, driver impatience, and inattention may play a more significant role than pavement surface frictional properties in such crashes.

<u>The following cautions should be kept in mind when interpreting table C2 information:</u>

- Wisconsin mileage represents directional miles.
- California mileage represents centerline miles (both directions).
- 100% of California freeway crashes were analyzed (the remainder occurred on TT bridge decks and were excluded from further consideration).
- 34% of Wisconsin freeway crashes were analyzed.
- Statistics based on very few freeway miles are not reliable and are presented as preliminary information. It is recommended to consult statistics based on more than 100 miles of freeway.

Table C1. Crash Rate (Crashes per 100MVMT) Summary Wisconsin and California 1991 - 1998.

Year	Wisconsin	California Statewide Rolling & Level Terrain		
	Analyzed Rural <60K ADT	Rural <60K ADT	Urban <60K ADT	Urban 60K+ ADT
	TT PCC	LT PCC	LT PCC	LT PCC
1991	47	42	72	97
1992	40	41	70	95
1993	46	42	74	94
1994	40	42	76	99
1995	40	44	76	98
1996	50	45	80	105
1997	35	42	78	104
1998	40	42	84	108
	n = 3,048 crashes	n = 21,645 crashes	n = 23,132 crashes	n = 486,892 crashes

Note:
Statewide CA data from the HSIS database (see Appendix G).

Table C2. Annual Wisconsin and California Crash Statistics by Pavement Surface Type.

Wisconsin

Year	Freeway	Wear Surface	AADT vpd	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Dry pvt crashes	Wet pvt crashes	Liq Safety Ratio	Length miles	100 MVMT
1991	Rural	Trns PCC	<60K	47	.19	267	95	18	2.21	120	5.6
1992				40	.28	233	96	27	3.18	121	5.8
1993				46	.20	391	162	32	2.16	167	8.5
1994				40	.08	345	131	10	1.21	167	8.6
1995				40	.12	382	180	21	1.51	186	9.6
1996				50	.23	522	160	37	4.07	197	10.4
1997				35	.13	411	149	20	2.39	220	11.6
1998				40	.14	497	233	32	2.16	234	12.5
Overall				42	.16	3048	1206	197	2.25	234	72.6

Table C2. Annual Wisconsin and California Crash Statistics by Pavement Surface Type. (continued)

California

Rolling and Level Terrain

Year	Freeway	Wear Surface	AADT vpd	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Dry pvt crashes	Wet pvt crashes	Liq Safety Ratio	Length miles	100 MVMT
1991	Rural	Long PCC	<60K	42	.08	2668	2429	188	1.62	733.5	63.4
			60K+	42	.15	1202	1040	152	3.07	91.9	28.7
		All		42	.10	3870	3469	340	2.06	825.4	92.1
	Urban	Long PCC	<60K	72	.12	2888	2571	309	2.52	299.1	40.2
			60K+	97	.12	56825	50761	6036	2.50	1054.2	586.9
		All		95	.12	59713	53332	6345	2.50	1353.3	627.1
1992	Rural	Long PCC	<60K	41	.11	2608	2315	249	2.42	733.5	63.4
			60K+	45	.22	1298	1058	237	5.04	91.9	28.7
		All		42	.14	3906	3373	487	3.24	825.4	92.1
	Urban	Long PCC	<60K	70	.18	2807	2380	418	3.95	299.1	40.2
			60K+	95	.16	55581	47715	7852	3.70	1054.2	586.9
		All		93	.17	58388	50095	8270	3.71	1353.3	627.1

Table C2. Annual Wisconsin and California Crash Statistics by Pavement Surface Type. (continued)

California — Rolling and Level Terrain

Year	Freeway	Wear Surface	AADT vpd	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Dry pvt crashes	Wet pvt crashes	Liq Safety Ratio	Length miles	100 MVMT
1993	Rural	Long PCC	<60K	42	.09	2663	2390	215	1.71	733.5	63.4
			60K+	47	.20	1359	1131	224	3.76	91.9	28.7
		All		44	.12	4022	3521	439	2.37	825.4	92.1
	Urban	Long PCC	<60K	74	.17	2990	2556	425	3.15	299.1	40.2
			60K+	94	.16	54986	47464	7505	3.00	1054.2	586.9
		All		92	.16	57976	50020	7930	3.01	1353.3	627.1
1994	Rural	Long PCC	<60K	42	.09	2646	2370	223	2.60	731.6	63.6
			60K+	42	.15	1212	1052	155	4.06	90.5	28.7
		All		42	.11	3858	3422	378	3.05	822.0	92.3
	Urban	Long PCC	<60K	76	.14	2923	2568	353	3.80	282.3	38.7
			60K+	99	.13	58699	52144	6534	3.46	1071.8	591.5
		All		98	.13	61622	54712	6887	3.48	1354.2	630.1

Table C2. Annual Wisconsin and California Crash Statistics by Pavement Surface Type. (continued)

California

Rolling and Level Terrain

Year	Freeway	Wear Surface	AADT vpd	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Dry pvt crashes	Wet pvt crashes	Liq Safety Ratio	Length miles	100 MVMT
1995	Rural	Long PCC	<60K	44	.14	2720	2339	330	2.27	730.1	62.5
			60K+	49	.27	1516	1191	320	4.34	92.6	30.7
		All		45	.18	4236	3530	650	2.97	822.7	93.2
	Urban	Long PCC	<60K	76	.18	2824	2392	424	2.86	269.8	37.0
			60K+	98	.19	59490	50062	9405	3.03	1092.6	606.1
		All		97	.19	62314	52454	9828	3.02	1362.4	643.1
1996	Rural	Long PCC	<60K	45	.14	2922	2492	356	2.93	730.8	64.5
			60K+	53	.26	1644	1303	339	5.32	92.0	30.7
		All		48	.18	4566	3795	695	3.75	822.7	95.2
	Urban	Long PCC	<60K	80	.18	2970	2517	443	3.61	265.2	37.0
			60K+	105	.16	65031	55957	9044	3.31	1096.2	618.7
		All		104	.16	68001	58474	9487	3.32	1361.5	655.7

Table C2. Annual Wisconsin and California Crash Statistics by Pavement Surface Type. (continued)

California

Rolling and Level Terrain

Year	Freeway	Wear Surface	AADT vpd	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Dry pvt crashes	Wet pvt crashes	Liq Safety Ratio	Length miles	100 MVMT
1997	Rural	Long PCC	<60K	42	.09	2726	2460	214	2.66	719.8	64.6
			60K+	52	.16	1683	1455	227	4.79	96.4	32.5
		All		45	.11	4409	3915	441	3.45	816.3	97.1
	Urban	Long PCC	<60K	78	.13	2701	2385	311	3.99	252.2	34.8
			60K+	104	.12	66491	59488	6990	3.60	1112.2	637.0
		All		103	.12	69192	61873	7301	3.61	1364.4	671.8
1998	Rural	Long PCC	<60K	42	.19	2692	2172	411	3.06	715.4	64.4
			60K+	50	.32	1734	1305	413	5.13	102.6	34.4
		All		45	.24	4426	3477	824	3.84	818.0	98.9
	Urban	Long PCC	<60K	84	.25	3029	2387	601	4.08	260.3	36.0
			60K+	108	.21	69789	57739	12014	3.37	1114.6	649.0
		All		106	.21	72818	60126	12615	3.40	1374.9	685.0

Table C2. Annual Wisconsin and California Crash Statistics by Pavement Surface Type. (continued)

California Mountainous Terrain

Year	Freeway	Wear Surface	AADT vpd	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Dry pvt crashes	Wet pvt crashes	Liq Safety Ratio	Length miles	100 MVMT
1991	Rural	Long PCC	<60K	48	.14	625	481	67	2.90	125.3	13.1
			60K+	39	.10	378	340	34	2.08	35.3	9.6
		All		44	.12	1003	822	100	2.56	160.6	22.7
	Urban	Long PCC	<60K	230	1.00	70	35	35	20.65	2.0	.3
			60K+	86	.12	1026	915	111	2.56	25.9	11.9
		All		90	.15	1096	950	146	3.23	28.0	12.2
1992	Rural	Long PCC	<60K	46	.24	604	443	106	5.35	125.3	13.1
			60K+	47	.17	452	384	65	3.82	35.3	9.6
		All		47	.21	1056	827	171	4.64	160.6	22.7
	Urban	Long PCC	<60K	167	.70	51	30	21	15.72	2.0	.3
			60K+	89	.18	1063	901	162	4.05	25.9	11.9
		All		91	.20	1114	931	183	4.43	28.0	12.2

Table C2. Annual Wisconsin and California Crash Statistics by Pavement Surface Type. (continued)

California Mountainous Terrain

Year	Freeway	Wear Surface	AADT vpd	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Dry pvt crashes	Wet pvt crashes	Liq Safety Ratio	Length miles	100 MVMT
1993	Rural	Long PCC	<60K	49	.23	642	459	107	4.45	125.3	13.1
			60K+	52	.13	503	444	56	2.41	35.3	9.6
		All		50	.18	1145	903	164	3.44	160.6	22.7
	Urban	Long PCC	<60K	177	1.00	54	27	27	18.46	2.0	.3
			60K+	81	.18	965	819	145	3.36	25.9	11.9
		All		83	.20	1019	847	171	3.85	28.0	12.2
1994	Rural	Long PCC	<60K	54	.19	665	484	90	5.16	121.2	12.3
			60K+	54	.10	568	511	53	2.87	39.4	10.5
		All		54	.14	1233	995	143	3.98	160.6	22.8
	Urban	Long PCC	<60K	215	1.92	64	22	42	53.02	1.9	.3
			60K+	103	.11	1198	1080	118	3.01	26.1	11.7
		All		105	.14	1262	1102	160	4.00	28.0	12.0

Table C2. Annual Wisconsin and California Crash Statistics by Pavement Surface Type. (continued)

California

Mountainous Terrain

Year	Freeway	Wear Surface	AADT vpd	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Dry pvt crashes	Wet pvt crashes	Liq Safety Ratio	Length miles	100 MVMT
1995	Rural	Long PCC	<60K	54	.24	644	456	109	3.84	113.3	11.9
			60K+	59	.25	618	489	122	4.02	37.7	10.5
		All		57	.24	1262	945	231	3.93	150.9	22.3
	Urban	Long PCC	<60K	270	1.64	84	32	52	26.39	2.0	.3
			60K+	99	.21	1196	985	210	3.43	25.9	12.1
		All		103	.26	1280	1017	262	4.15	28.0	12.4
1996	Rural	Long PCC	<60K	61	.22	683	466	102	4.46	109.2	11.2
			60K+	53	.18	635	532	94	3.63	41.8	11.9
		All		57	.20	1318	998	196	4.02	150.9	23.1
	Urban	Long PCC	<60K	239	.91	74	39	35	18.63	2.0	.3
			60K+	96	.22	1245	1018	227	4.56	25.9	12.9
		All		100	.25	1319	1057	262	5.08	28.0	13.3

Table C2. Annual Wisconsin and California Crash Statistics by Pavement Surface Type. (continued)

California — Mountainous Terrain

Year	Freeway	Wear Surface	AADT vpd	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Dry pvt crashes	Wet pvt crashes	Liq Safety Ratio	Length miles	100 MVMT
1997	Rural	Long PCC	<60K	56	.20	647	484	99	6.24	109.2	11.6
			60K+	63	.15	762	663	96	4.46	41.8	12.1
		All		59	.17	1409	1146	195	5.21	150.9	23.7
	Urban	Long PCC	<60K	147	1.58	31	12	19	48.47	1.6	.2
			60K+	94	.17	1228	1047	180	5.26	26.4	13.1
		All		95	.19	1259	1059	199	5.75	28.0	13.3
1998	Rural	Long PCC	<60K	62	.54	705	365	198	8.79	109.2	11.3
			60K+	68	.29	848	653	191	4.72	41.8	12.5
		All		65	.38	1553	1019	389	6.18	150.9	23.8
	Urban	Long PCC	<60K	117	.62	14	9	5	9.97	1.1	.1
			60K+	105	.34	1384	1032	351	5.52	26.9	13.2
		All		105	.34	1398	1040	357	5.55	28.0	13.3

APPENDIX D

SUMMARY CRASH FINDINGS

INTRODUCTION

This Appendix provides background data for the **Findings** section of the report. Annual statistics are extracted from the comprehensive crash statistics in **Table C2**. Wisconsin statistics in **Tables D2, D3 and D4** are provided as preliminary findings only.

The following cautions should be kept in mind when interpreting APPENDIX D information:

- Wisconsin mileage represents directional miles.
- California mileage represents centerline miles (both directions).
- 100% of California freeway crashes were analyzed.
- 34% of Wisconsin freeway crashes were analyzed.
- Statistics based on very few freeway miles are not reliable and are presented as preliminary information. It is recommended to consult statistics based on more than 100 miles of freeway.

Table D1. Wisconsin Rural Freeway Statistics 1991-1998. Less than 60K VPD.

Year	Wear Surface	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Liq Safety Ratio	Length miles	100 MVMT
1991	Trns PCC	47	.19	267	2.21	119.7	5.6
1992		40	.28	233	3.18	121.4	5.8
1993		46	.20	391	2.16	166.8	8.5
1994		40	.08	345	1.21	166.8	8.6
1995		40	.12	382	1.51	185.6	9.6
1996		50	.23	522	4.07	196.8	10.4
1997		35	.13	411	2.39	219.7	11.6
1998		40	.14	497	2.16	233.7	12.5
Overall Statistics							
	Trns PCC	42	.16	3048	2.25	233.7	72.6

Figure D1. Wisconsin Rural Freeway Crash Rates. <60K VPD

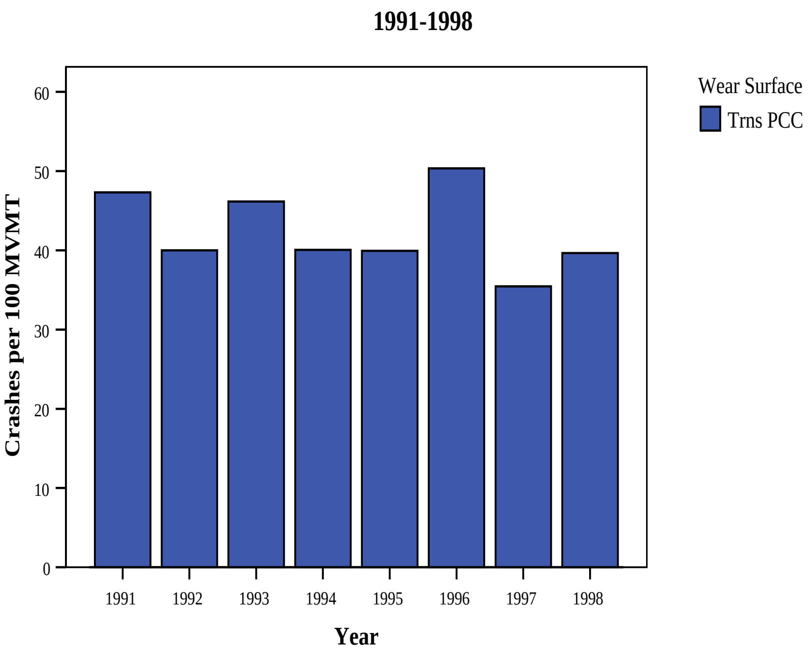


Figure D2. Wisconsin Rural Freeway Wet/Dry Ratios. <60K VPD

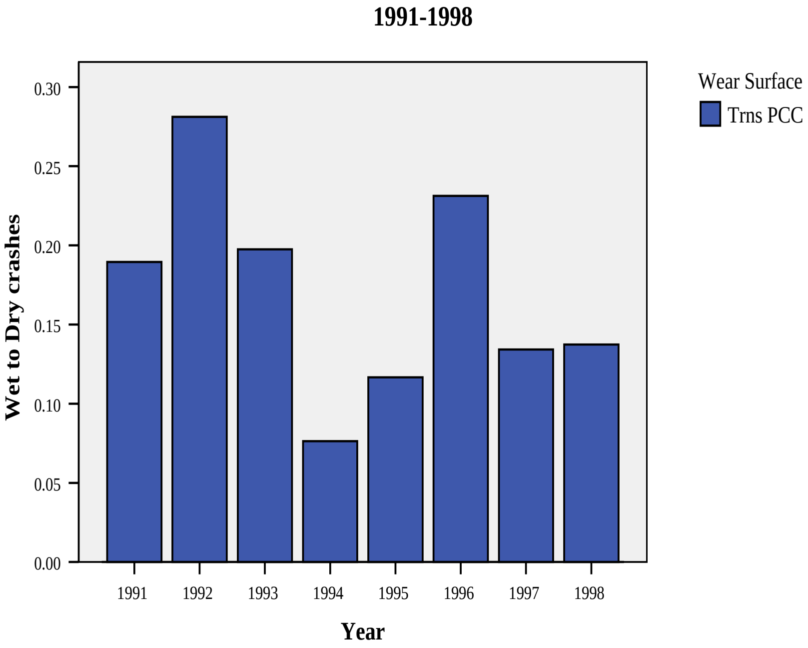


Figure D3. Wisconsin Rural Freeway Liquid Precip. Safety Ratios. <60K VPD

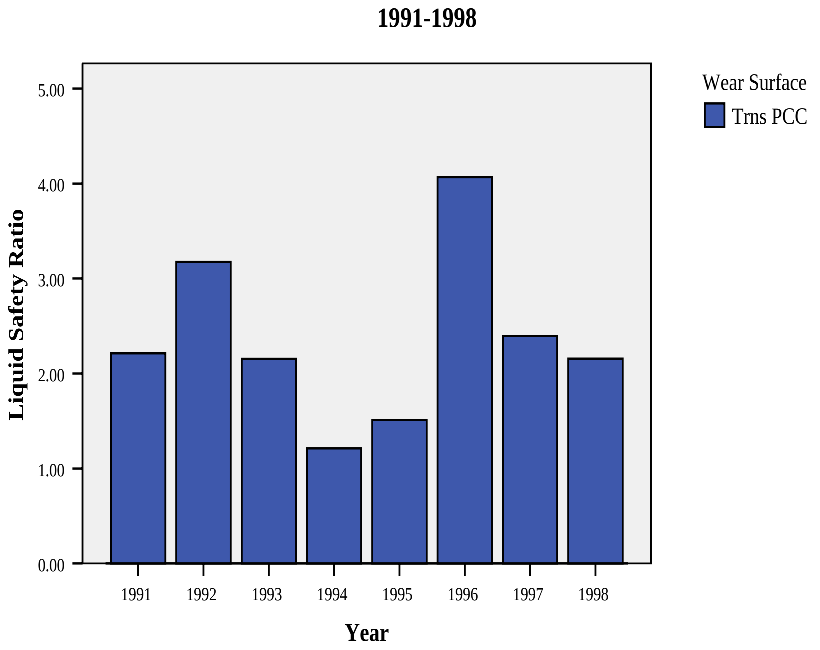


Table D2 California Rural Freeway Statistics 1991-1998. Rolling and Level Terrain. Less than 60K VPD.

Year	Wear Surface	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Wet Safety Ratio	Length miles	100 MVMT
1991	Long PCC	42	.08	2668	1.62	733.5	63.4
1992		41	.11	2608	2.42	733.5	63.4
1993		42	.09	2663	1.71	733.5	63.4
1994		42	.09	2646	2.60	731.6	63.6
1995		44	.14	2720	2.27	730.1	62.5
1996		45	.14	2922	2.93	730.8	64.5
1997		42	.09	2726	2.66	719.8	64.6
1998		42	.19	2692	3.06	715.4	64.4
Overall Statistics							
	Long PCC	42	.12	21645	2.39	715.4	509.7

Figure D4. California Rural Freeway Crash Rates. <60K VPD

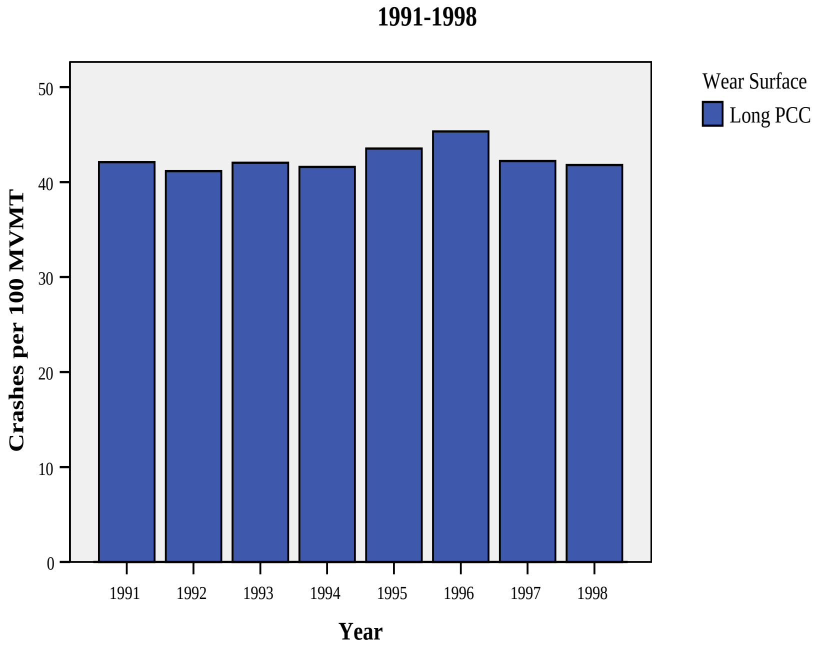
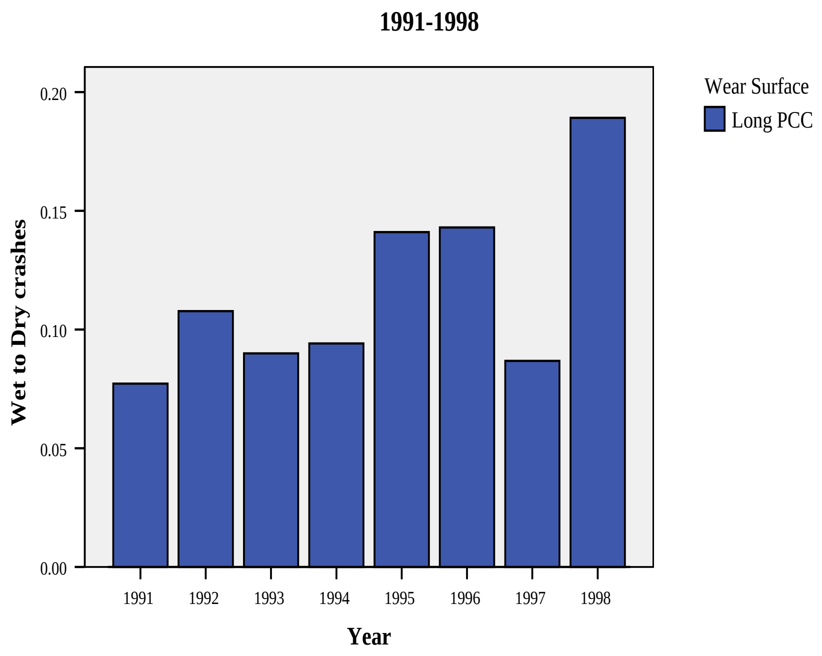


Figure D5. California Rural Freeway Wet/Dry Ratios. <60K VPD



Fiugre D6. California Rural Freeway Liquid Precip. Safety Ratios. <60K VPD

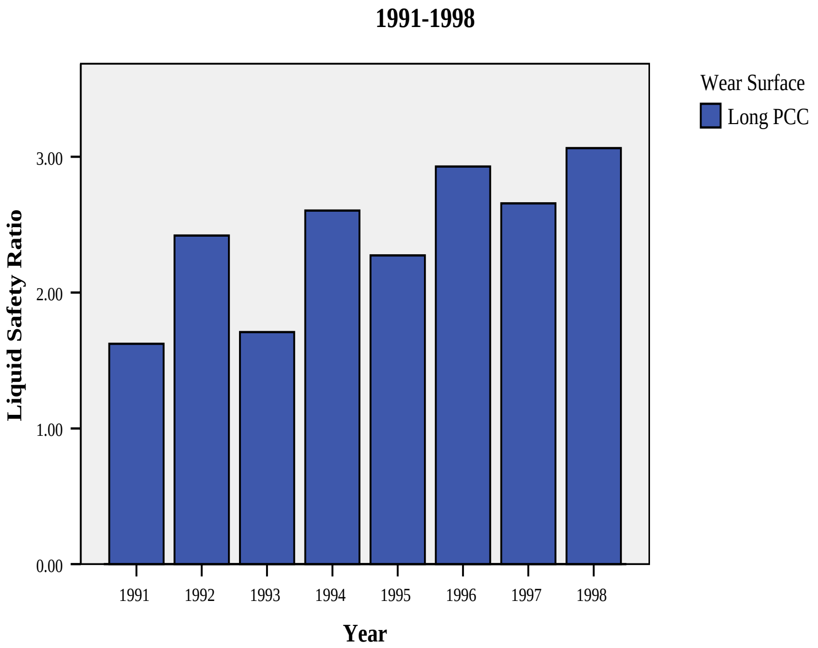


Table D3 California Urban Freeway Statistics 1991-1998. Rolling and Level Terrain. Less than 60K VPD.

Year	Wear Surface	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Wet Safety Ratio	Length miles	100 MVMT
1991	Long PCC	72	.12	2888	2.52	299.1	40.2
1992	Long PCC	70	.18	2807	3.95	299.1	40.2
1993	Long PCC	74	.17	2990	3.15	299.1	40.2
1994	Long PCC	76	.14	2923	3.80	282.3	38.7
1995	Long PCC	76	.18	2824	2.86	269.8	37.0
1996	Long PCC	80	.18	2970	3.61	265.2	37.0
1997	Long PCC	78	.13	2701	3.99	252.2	34.8
1998	Long PCC	84	.25	3029	4.08	260.3	36.0
Overall Statistics							
	Long PCC	76	.17	23132	3.45	260.3	304.2

Figure D7. California Urban Freeway Crash Rates. <60K VPD

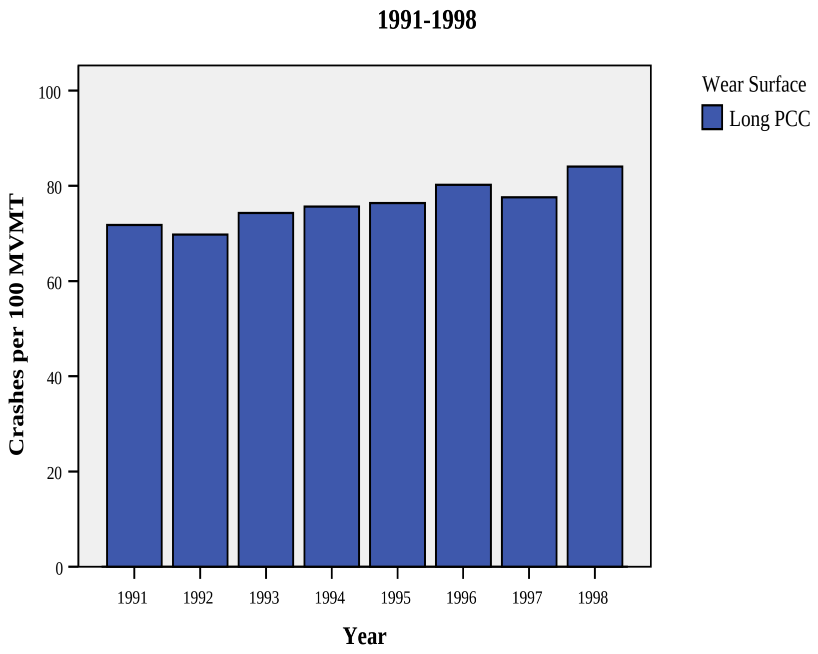


Figure D8. California Urban Freeway Wet/Dry Ratios. <60K VPD

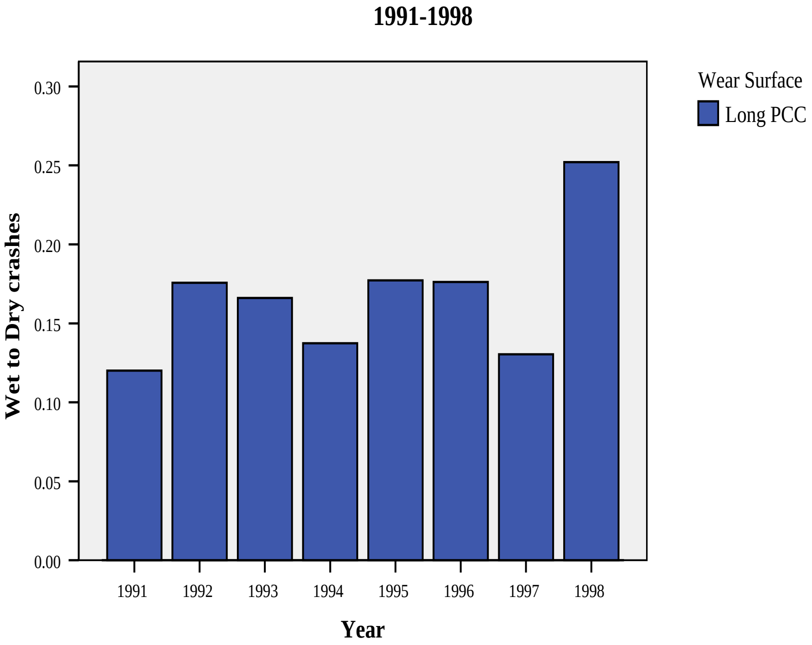


Figure D9. California Urban Freeway Liquid Precip. Safety Ratios. <60K VPD

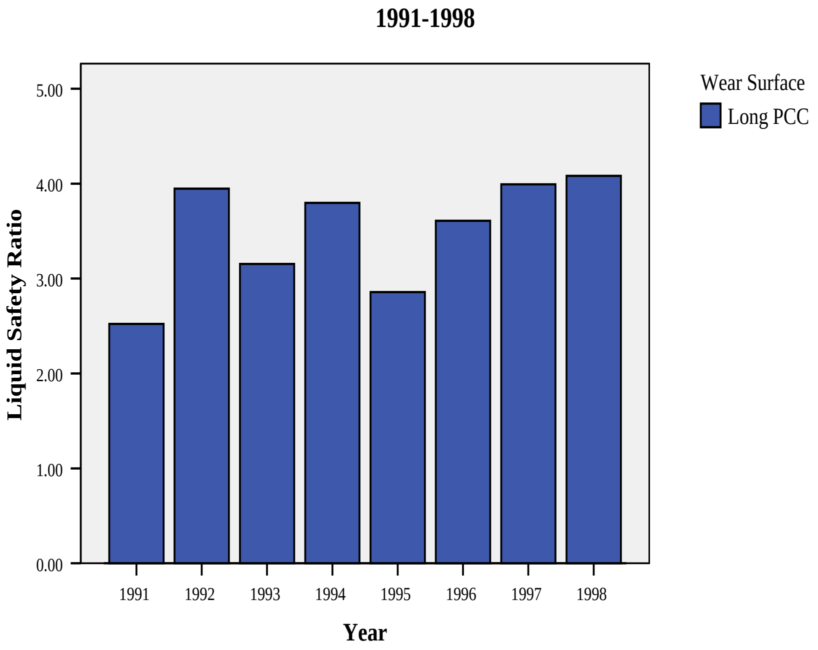


Table D4 California Urban Freeway Statistics 1991-1998. Rolling and Level Terrain. More than 60K VPD.

Year	Wear Surface	Crashes per 100 MVMT	Wet to Dry crashes	Total crashes	Wet Safety Ratio	Length miles	100 MVMT
1991	Long PCC	97	.12	56825	2.50	1054.2	586.9
1992	Long PCC	95	.16	55581	3.70	1054.2	586.9
1993	Long PCC	94	.16	54986	3.00	1054.2	586.9
1994	Long PCC	99	.13	58699	3.46	1071.8	591.5
1995	Long PCC	98	.19	59490	3.03	1092.6	606.1
1996	Long PCC	105	.16	65031	3.31	1096.2	618.7
1997	Long PCC	104	.12	66491	3.60	1112.2	637.0
1998	Long PCC	108	.21	69789	3.37	1114.6	649.0
Overall Statistics							
	Long PCC	100	.16	486892	3.22	1114.6	4863.0

Figure D10. California Urban Freeway Crash Rates. 60K+ VPD

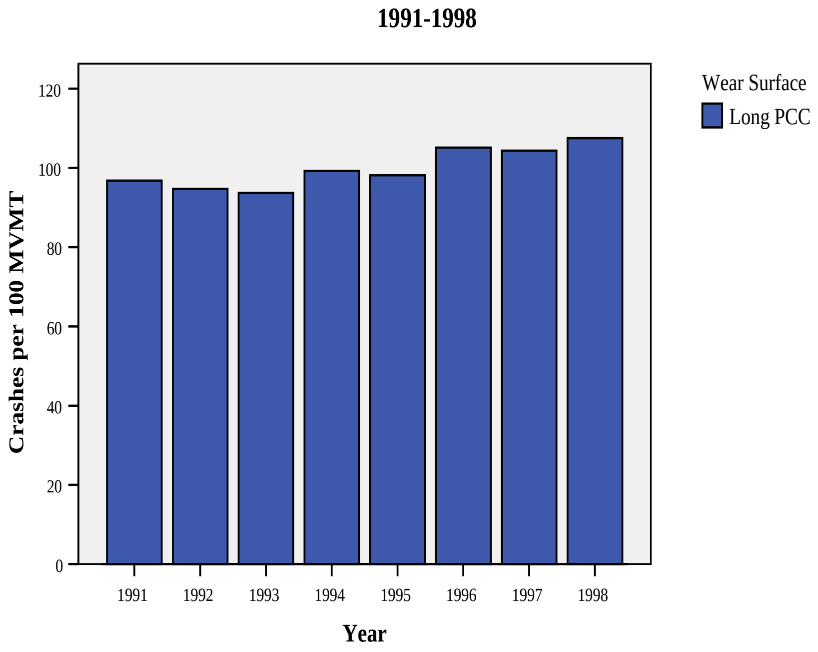


Figure D11. California Urban Freeway Wet/Dry Ratios. 60K+ VPD

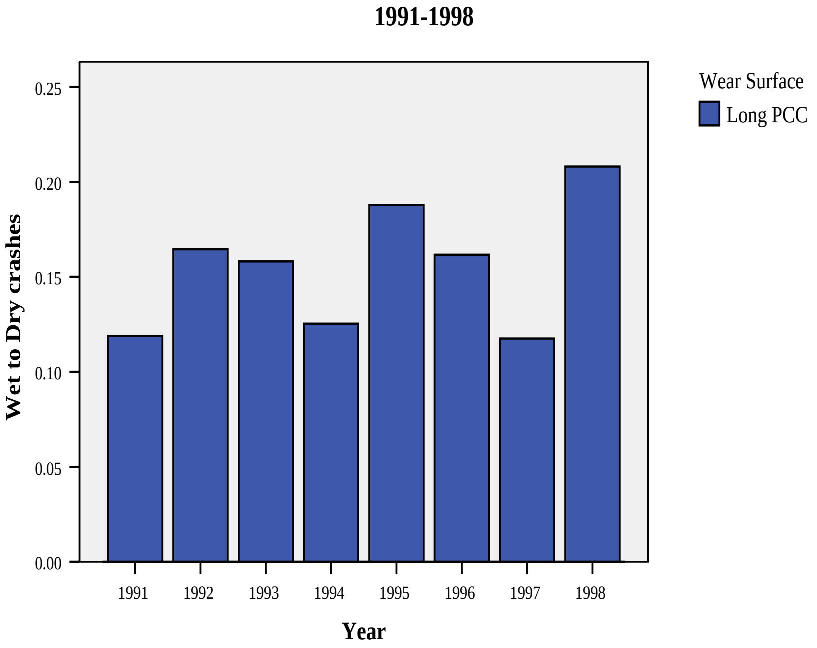
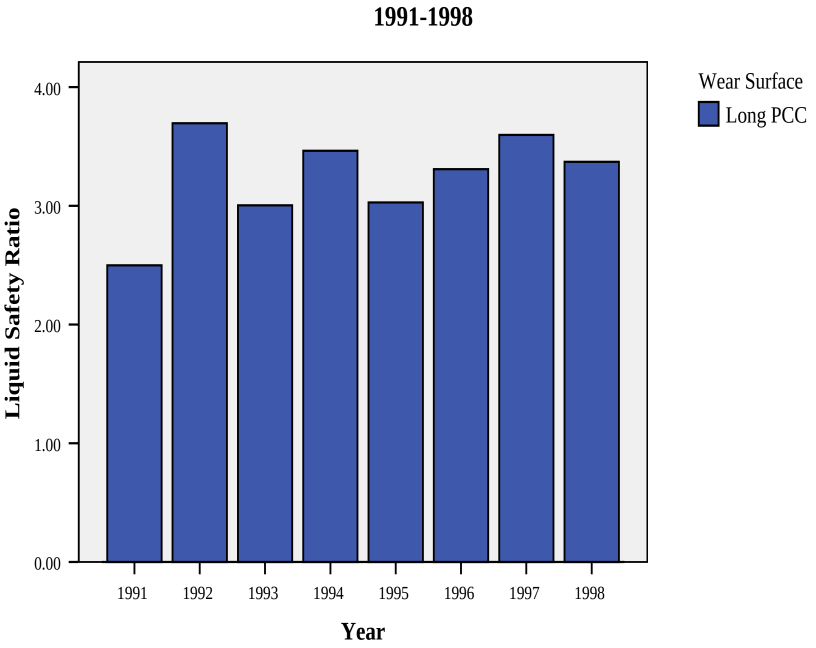


Figure D12. California Urban Freeway Liquid Precip. Safety Ratios. 60K+ VPD



APPENDIX E

WEATHER DATA

INTRODUCTION

Weather and precipitation data were needed in order to calculate the percent time pavements were dry, or covered with liquid precipitation. The present Appendix addresses a number of critical issues related to this topic. Tables and figures located at the end of the Appendix provide supporting information.

The **Weather Station Selection** section addresses the method and reasoning in choosing the first order weather stations that were used in the analysis (**table E1**).

The **Weather and Precipitation Data Analysis** section describes the attempt to use the WETTIME software, the effect of missing information (**table E2**), and the chosen method used to calculate the hours pavements were dry or covered with liquid precipitation (**Tables E3 and E4**).

WEATHER STATION SELECTION

After extensive communications with NOAA, the comprehensive list (n = 6,352) of world-wide stations providing International Station Meteorological Climate Summary (ISMCS) information was downloaded from the NOAA web site and searched through custom-made software in order to identify all first order weather stations in each state that was under consideration for the present analysis. An effort was made to select weather stations that would be as representative as possible of conditions for the majority of a state’s freeway system, using maps and comparing a station’s latitude and longitude to the orientation of a state’s freeway system. Hourly weather data were purchased for each selected station for each of the eight analysis years. Hourly precipitation data were provided to Marquette University at no cost from NOAA. Data were received for the stations listed in **Table E1**.

Only the California, Wisconsin and Minnesota stations were used in the analysis (the latter two stations were used to represent conditions on the analyzed Wisconsin freeways).

Two stations were selected among a total of 25 identified first order stations in California. San Francisco was chosen to represent coastal weather conditions in the north part of the state, and Los Angeles to represent the southern coastal part of the state.

The Milwaukee station was chosen among the four identified first order stations in Wisconsin, to represent conditions on the Southeastern part of the state, where most freeway travel is accumulated.

The Minneapolis/St. Paul station was chosen among the four identified first order Minnesota stations, to provide information for the Western part of Wisconsin. Thus, the Milwaukee and Minneapolis/St. Paul weather stations, represent conditions along the SE-to-NW main orientation of the analyzed Wisconsin freeways.

WEATHER AND PRECIPITATION DATA ANALYSIS

Weather files contained station identification, date and time information, wind speed and direction, sky cover, temperature, dew point, barometric pressure, and four weather codes describing weather conditions in the vicinity of the weather station. Although other variables were coded in the database, they typically contained no information. Precipitation files contained station identification date and time information, amount of liquid precipitation (frozen precipitation was converted to equivalent liquid precipitation) for each hour for which precipitation was recorded. The file also contained special flags indicating, among other conditions, time periods of missing information.

Information from both files was necessary to calculate how many hours liquid precipitation were present on a pavement: weather files provided the nature of any precipitation (for example “Shower(s) of snow or of rain and snow”), but the amount of this precipitation was recorded in the precipitation files.

Doug Harwood of the Midwest Research Institute was contacted and graciously agreed to provide a copy of the WETTIME software he authored, as well as the accompanying “Users Guide for the ‘Wettime’ Exposure Estimation Model.”[1]

The Wettime software estimates the percentages of time that a pavement is dry, or covered with liquid or frozen precipitation, using precipitation and surface weather data, available from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA).

Considerable effort was expended searching for weather and precipitation data in the formats used in the program, both through NOAA and commercial weather data providers. However the particular formats of the TD 3280 weather data and the TD 3240 precipitation data used in the program were abolished in 1996-7 and were no longer available. The NOAA database was extensively searched for data that could be used to re-create the variables used in the program (for example, relative humidity had to be reconstituted from other available information, cloud coverage was no longer available in the same format, etc.) Despite excellent WETTIME documentation, it was not possible to follow the program logic, which relied to a great extent to various “flags” that were coded in the particular format of the datasets used by the software author, because the original flags and their meanings were no longer available from NOAA.

Given the difficulties in correctly applying the WETTIME software, but also concerns with missing information described below, it was decided to proceed with a different method to assess the number of hours a pavement was covered with liquid precipitation. Hourly weather and precipitation information were matched. It was decided than hours during which both liquid and frozen precipitation were recorded would be considered hours of frozen precipitation and dropped from consideration. Following this decision rule, hours with liquid and frozen precipitation were tallied separately for each analysis

---

[1] Publication No. FHWA-RD-87-106, February 1988.

year; it was assumed that precipitation remained on the pavement for the entire hour during which precipitation was recorded. (WETTIME uses a variety of factors to adjust the length of time precipitation remained on the pavement. Depending on prevailing weather conditions and amount of precipitation, precipitation may be present on the pavement less than an hour or may remain on the pavement considerably longer. However, the drying effect of traffic is not taken into account. Concerns about missing precipitation data, described below would have also diminished WETTIME applicability to the present effort).

Missing data

Extensive testing of matched precipitation and weather information revealed that in many instances, although a weather database (TD 3280 data) code indicated presence of liquid precipitation, no precipitation was recorded in the precipitation database (TD 3240 data) for the same hour.

NOAA precipitation data was recorded in the following manner:

- Each record represented information for a 24-hour period and contained individual fields for each hour of the day;
- A record was produced for the first day of each month, regardless of whether or not precipitation was present during that day;
- One record was added to the database for each day during which precipitation was recorded for at least one hour;
- Special flags were used to mark the beginning and ending times of missing data. Thus, the user had to rely on the presence of missing data flags in order to identify periods with missing precipitation information.

Given the above-described database scheme, if missing data flags were not properly recorded, it would not be possible to independently verify whether days for which no record was present indeed had no precipitation or were simply missing (due to equipment failure), because in both cases no precipitation record would be present in the database.

One record was provided for each hour in the NOAA weather data, thus identification of missing weather information was straight-forward, without reliance on specially coded flags.

The noted discrepancy between the weather and precipitation information, led to a decision to use weather data exclusively, since it was apparent that precipitation data was missing for quite a number of days, when weather information reported some form of precipitation. Missing weather information would bias findings.

Available hours of weather information data are presented in **table E2** for each analyzed weather station. All stations had very few missing hours of observations (there were 259 missing hours in Milwaukee in 1996; all other years had less than 38 hours of missing observations for any one station).

It should be noted that the number of missing observations was not known until after data were purchased and analyzed.

Weather data processing

Precipitation information was averaged between the first order weather stations used to represent each state.

- For Wisconsin, Minnesota and Milwaukee data were averaged.
- For California, San Francisco and Los Angeles data were averaged for liquid precipitation.

Tables E3 and E4 present the calculated percentages of the time in a year that pavements are dry or liquid precipitation is present on pavements for Wisconsin and California, respectively. This information was used in the calculation of the Liquid precipitation Safety Ratio (LSR)[2] statistics presented in **Appendices C and D** and the Findings section of the report.

---

[2] The definition and meaning of LSR are presented in the Methodology part of the report.

Table E1. Weather Station Information.

ST	WMOID	WBAN	CALL SIGN	STATION NAME	COOP ID
CA	72 4800	23157	KBIH,	BISHOP	40822
	72 2950	23174	KLAX,	LOS ANGELES INTL	45114
	72 4940	23234	KSFO	FRISCO	47769
WA	72 7930	24233	KSEA,	SEATTLE/TACOMA	457473
	72 7850	24157	KGEG	SPOKANE	457938
IL	72 5300	94846	KORD,	OHARE	111549
	72 4390	93822	KSPI	SPRINGFIELD	118179
MN	72 6580	14922	KMSP	MINNEAPOLIS/ST PAUL	215435
MI	72 6380	94814	KHTL,	HOUGHTON LAKE	203936
	72 5390	14836	KLAN	LANSING	204641
UT	72 5720	23127	KSLC	SALT LAKE CITY	427598
NC	72 3140	13881	KCLT,	CHARLOTTE	311690
	72 3060	13722	KRDU	RALEIGH	317069
WI	72 6400	14839	KMKE	MITCHELL	475479
VA	72 4010	13740	KRIC,	RICHMOND	447201
	72 4030	93738	KIAD	DULLES	448903
WA	72 4050	13743	KDCA	WASH NATL WSCMO	448906

Table E2. Available Hourly Weather Observations (NOAA file TD 3280).

STA_ID Milwaukee

		MONTH											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
YEAR	1991	744	672	744	720	744	720	744	744	720	744	720	744
	1992	744	696	744	720	744	720	744	744	720	744	720	744
	1993	744	672	744	720	744	720	744	744	720	744	720	744
	1994	744	672	744	720	744	720	744	744	720	744	720	744
	1995	744	672	744	720	744	719	742	744	720	721	720	732
	1996	703	517	717	720	702	717	742	744	714	744	719	739
	1997	743	672	744	720	742	719	744	742	720	731	718	736
	1998	739	664	744	720	744	719	744	744	720	744	720	743

Table E2. Available Hourly Weather Observations (NOAA file TD 3280). (Continued)

STA_ID Minneapolis

		MONTH											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
YEAR	1991	744	672	744	720	744	720	744	744	720	741	720	744
	1992	744	696	744	720	744	720	744	744	720	744	720	744
	1993	744	672	742	720	744	720	744	741	720	744	720	744
	1994	744	672	744	720	744	720	744	744	720	744	720	744
	1995	744	672	744	720	744	720	744	744	720	744	720	744
	1996	742	696	744	720	744	701	744	744	720	741	714	744
	1997	743	672	744	720	744	720	743	744	720	744	719	727
	1998	744	672	744	720	744	719	744	744	720	737	718	740

Expected number of observations per month:

- Jan, Mar, May, Jul, Aug, Oct, Dec: 24 hours x 31 days = 744 hours / month.
- Apr, Jun, Sep, Nov: 24 hours x 30 days = 720 hours / month.

Feb: 24 hours x 28 days = 672 hours, except in 1992 and 1996: 696 hours.

Table E2. Available Hourly Weather Observations (NOAA file TD 3280). (Continued)

STA_ID Los Angeles CA

		MONTH											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
YEAR	1991	744	672	744	719	744	720	744	744	720	744	720	744
	1992	744	696	744	719	744	720	744	744	720	744	720	744
	1993	744	672	744	720	744	720	744	744	720	744	720	744
	1994	744	672	744	720	744	720	744	744	720	742	720	743
	1995	744	672	744	720	744	720	744	744	720	744	720	743
	1996	744	696	744	720	744	720	744	744	720	744	720	744
	1997	744	672	743	717	738	718	687	743	720	740	718	744
	1998	744	672	744	720	744	720	744	744	713	738	720	743

Table E2. Available Hourly Weather Observations (NOAA file TD 3280). (Continued)

STA_ID San Francisco CA

		MONTH											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
		Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
YEAR	1991	744	672	744	720	744	720	744	744	720	744	720	744
	1992	744	696	744	720	744	720	744	744	720	744	720	744
	1993	743	672	744	720	744	720	744	744	720	744	720	744
	1994	742	672	744	720	744	720	744	744	720	744	720	744
	1995	744	672	744	720	744	720	744	744	720	744	720	744
	1996	744	695	744	720	744	720	736	739	719	741	719	743
	1997	744	672	743	720	743	720	742	744	707	741	709	744
	1998	744	672	743	716	744	718	744	744	717	744	720	738

Expected number of observations per month:

- Jan, Mar, May, Jul, Aug, Oct, Dec: 24 hours x 31 days = 744 hours / month.
- Apr, Jun, Sep, Nov: 24 hours x 30 days = 720 hours / month.
- Feb: 24 hours x 28 days = 672 hours, except in 1992 and 1996: 696 hours.

Table E3. Wisconsin Liquid Precipitation Summary

Year	% Time Dry	% Time Liquid	Dry/Liquid
1991	0.866	0.074	11.68
1992	0.858	0.076	11.29
1993	0.848	0.078	10.91
1994	0.883	0.056	15.87
1995	0.872	0.067	12.95
1996	0.896	0.051	17.59
1997	0.899	0.050	17.83
1998	0.903	0.058	15.70

Table E4. California Liquid Precipitation Summary

Year	% Time Dry	% Time Liquid	Dry/Liquid
1991	0.952	0.045	21.01
1992	0.955	0.043	22.46
1993	0.948	0.050	19.00
1994	0.963	0.035	27.64
1995	0.940	0.058	16.12
1996	0.952	0.047	20.48
1997	0.965	0.032	30.61
1998	0.939	0.058	16.20

Note (Tables E3 and E4): Missing percentage of time: Frozen precipitation present.

APPENDIX F

ANALYZED WISCONSIN FREEWAYS

INTRODUCTION

Pavement data were extracted from the “Metamanager” WisDOT database. The database provided pavement materials information (PCC or asphalt), the date a pavement surface was constructed, travel information (freeway segment length and ADT) and freeway type (urban or rural). The mid-1999 Metamanager edition was used in order to include the pavement surface construction dates relevant to all analyzed segments.

The pavement database was queried and freeway pavement segments constructed within a range of years was identified (starting after 1978 and ending on a specific year between 1990 and 1997). Selection of pavement construction dates after 1978, the first year that all new PCC freeway pavements were required to have a TT texture, guaranteed that all identified PCC surfaces were transversely tined. Crashes were matched to travel information on the pavement section on which they occurred and crash statistics were calculated (see **Table C2**). The exact pavement selection and crash matching methodology is described in detail in **Appendix C**.

Table F1 provides pavement mileage and type for pavement for pavements constructed after 1978 along the analyzed freeways I-90, I-94, I-794 and I-894. The first such construction occurred in 1982. All rural mileage shown on **table F1** for years 1982 – 1990 adds up to 279 miles; urban mileage adds up to 33 miles; the total (based on rounded mileage) is 312 miles, shown on **page C6** that summarizes 1991 crash experience. In 1991, 55.07 rural miles and 2.49 urban miles were added to the analyzed database, as can be verified on **page C7** showing 334 rural miles, 36 urban miles and a total of 370 miles for the 1992 crash summary.

Table F1. Transversely Tined pavements constructed, after 1978 TT PCC guidelines were in place, on Analyzed Wisconsin Freeways.

		Roadway Classification	
		Rural Freeway	Urban Freeway
		Length	Length
Year	1982	.	.
	1983	13.40	.
	1984	18.97	.
	1985	13.40	.
	1986	32.16	.
	1987	14.12	.
	1988	4.73	.
	1989	16.33	.
	1990	7.14	2.20
	1991	1.66	.
	1992	45.41	.
	1993	.	.
	1994	18.76	.
	1995	11.28	3.23
	1996	22.89	4.07
	1997	13.99	.
	Total	234.24	9.50

APPENDIX G

HIGHWAY SAFETY INFORMATION SYSTEM
&
HSIS GUIDEBOOK FOR THE CALIFORNIA DATA FILES
VOLUME I

HIGHWAY SAFETY INFORMATION SYSTEM

The Highway Safety Information System is a multi-state database that contains crash, roadway inventory, and traffic volume data for a select group of States. The HSIS is operated by the University of North Carolina Highway Safety Research Center (HSRC) and LENDIS Corporation, under contract with FHWA.[1]

California database:

- First Year Available: 1991
- Average Crashes/Year: 160,000
- Roadway Mileage: ***15,300***

Available files:

Crash - Contains basic accident, vehicle, and occupant information on a case-by-case basis. Typical data include type of accident, type of vehicle, sex and age of occupants, fixed-object struck, accident severity, and weather conditions.

Roadway Inventory - Contains information on roadway cross-section and the type of roadway. Data include the number of lanes, lane width, shoulder width and type, median width, rural/urban designation, and functional classification.

Traffic Volume - Contains annual average daily traffic (AADT) data. Additional data on hourly volumes and percentage of trucks is also available in selected States and/or locations.

Intersection - Contains information on highway intersections. Data include traffic control type, intersection type, signal phasing, and turn lanes.

Interchange/Ramp - Contains information on highway interchanges. Data include interchange type and ramp characteristics.

---

[1] Source: http://www.hsisinfo.org// Friday, June 04, 2004, 2:07 AM

HIGHWAY SAFETY INFORMATION SYSTEM GUIDEBOOK

FOR THE CALIFORNIA DATA FILES

Volume I

Prepared by

Forrest M. Council
Carolyn D. Williams

University of North Carolina
Highway Safety Research Center
730 Airport Road, Suite 300
Chapel Hill, NC 27599-3430

Prepared for

Federal Highway Administration
Office of Safety and Traffic Operations Research & Development
U.S. Department of Transportation
Washington, DC 20590

November, 1995

TABLE OF CONTENTS

INTRODUCTION

The California database incorporated into the HSIS system is derived from the California TASAS (Traffic Accident Surveillance and Analysis System). The system, maintained by the Traffic Operations Office of CALTRANS, is a mainframe-based system based on COBOL programming. The Traffic Operations Office (TO) provides the data to HSIS in the form of two different data files. These contain:

Accident data (including accident, vehicle and occupant data)

Roadway inventory data (including intersection and interchange ramp data, and Average Daily Traffic counts)

Raw file data is provided to the Highway Safety Research Center where they are retained as backup information. The documentation (variable listings, definitions, etc.) for these raw files and for the SAS files that are developed from them are available at FHWA offices. The conversion programs developed by HSRC and LENDIS to convert the files into SQL and SAS formats are included in the Programmer's Guidebook, which is available at the HSIS offices at FHWA.

Beginning in 1994, the HSIS system was converted to a relational database for internal use. This database, using a SYBASE system, stores the data received from California and other states, and the data files for a given state are linked and manipulated using SQL language. However, this conversion from the original SAS-based system to the newer relational system is somewhat transparent to the end-user of the data since the output files produced by SYBASE for modelling and analysis will be SAS formatted. As in the past, we have continued to produce SAS format libraries for each of the variables in each of the files. Because it is envisioned that the majority of analyses will utilize these SAS files and formats, this Guidebook will concern these SAS files -- their formats, completeness, and quality. Single variable tables for key variables from each file will continue to be published in a separate Volume II document.

As noted above, the California SAS accident data is divided into three separate subfiles, the first containing the basic accident information on a case-by-case basis, the second containing information on up to nine vehicles in each accident (including driver information), and the third containing information on up to seventy occupants in each crash. The HSIS accident and vehicle data are extracted directly from the TASAS by the Traffic Operations staff. The occupant data, including data on the driver, are not included in TASAS, but are in the California Highway Patrol's SWITRS (Statewide Integrated Traffic Records System) file. This latter file is acquired from California by the US DOT National Highway Traffic Safety Administration (NHTSA) each year, and HSRC staff obtains copies of this file from NHTSA and merges it with the TASAS data.

Unlike the accident file which is referenced to a point on the roadway, each record in the Roadlog File contains information on a homogeneous section of roadway (i.e., a stretch of road which is consistent in terms of certain characteristics, with a new section being defined each time any of the characteristics changes). Each record contains current characteristics of the roadway system and includes such variables as traveled way width, number of lanes, paved and total shoulder width, median type, and other variables. Traffic information in the form of Average Annual Daily Traffic (AADT) and Daily Vehicle Miles of travel is included for each section. As will be noted below, unlike most other HSIS state inventories, this file also contains information on terrain, design speed, and special features such as auxiliary lanes. There is no horizontal or vertical alignment information in the files.

While intersections were included as part of the basic TASAS roadway inventory record, a separate Intersection File has been created in the HSIS system. Each record on the file contains information on both the mainline route and the crossing route. The information includes such items as intersection type, traffic control type, lighting, channelization, and ADT for both the mainline and cross street.

In similar fashion, an Interchange Ramp File has been developed which contains information on approximately 14,000 individual ramps. While there is no way to tie these ramps to one of the approximately 3000 associated interchanges in the state, the file does contain information on ramp type (e.g., diamond, slip, direct left-turn connector, etc.), ADT, and whether the crossing road is a state route or not.

DETAILS OF MAJOR FILES

The Accident Files

The state agency responsible for statewide accident data collection is the California Highway Patrol (CHP). The CHP is responsible for investigating crashes on all freeways (urban and rural) and on other state routes and county roads outside municipal areas. They are also responsible for the collection and computerization of crash data from all investigating agencies in the state. The CHP investigates approximately two-thirds of all accidents occurring on state routes. The remainder are reported by municipal police. The general accident reporting threshold used by the CHP is currently $500 or personal injury. This threshold is felt to be fairly consistently used by all CHP personnel in terms of filing crash reports. Conversations with the CHP indicated that while minor (non-towaway) crashes will be reported, they are reported on a "short form." In approximately 50 percent of these minor cases, the officer will not provide information on uninjured passengers.

However, neither the report form used nor the reporting threshold followed is consistent across the many local municipalities in the state. Unlike the other HSIS states, accident data are not collected statewide by all police departments on a standard form. While some municipalities use the standard CHP form, many have developed their own form, including major cities such as San Jose, San Diego and Los Angeles. Currently, the CHP is "recruiting" these cities to adopt the standard form, and hope that they will begin using a revised version of the form in 1996. Other cities and towns may or may not follow suit. Even though these cities use non-CHP forms, their data are "converted" to CHP format by accident coders to the extent possible. They are ultimately key-punched into the CHP's data system, known as SWITRS (Statewide Integrated Traffic Records System).

In addition to differing forms, it also appears that different municipalities follow different reporting thresholds, with some reporting only towaway crashes, many reporting crashes with damage of greater than $1000, and some not reporting PDO crashes at all. Some information on the level of PDO reporting can be gleaned from CHP's "Annual Report of Fatal and Injury Motor Vehicle Traffic Accidents." This publication, available at the FHWA HSIS office, provides a city-by-city breakdown of fatal, injury, and PDO crashes reported. In general, if reported to a moderately low threshold, 55-70 percent of the total crashes should be no-injury (PDO) crashes.

Cities which don't show such a ratio are more than likely not fully reporting these non-injury crashes.

Thus, in general, while injury and fatal data is felt to be accurate for both the CHP and most municipalities, PDO crashes (and thus total crashes) are most accurate for the Highway Patrol. Crashes investigated by the Patrol can be identified by using the variable CHP_IND. In terms of rate development, this means that rates developed for freeways (urban and rural) and for other rural roads (outside municipalities) where accidents are reported by the CHP would be accurate. Total accident rates developed for urban areas should be considered somewhat suspect, or the analyst must determine which cities should be included in the rate based on reporting ratios or other information.

It is estimated that there are over 500,000 accidents in the entire state each year. Approximately 150,000 of these are investigated by the California Highway Patrol on state routes (where TASAS inventory information is available). As noted above, all forms (regardless of form type) are sent to the CHP for processing. The CHP then separates the forms into those occurring on state routes (including the urban areas using their own forms) and those on non-state routes, and sends the state-route hard copies to the Traffic Operations Office (TO) for location coding. Of the 500,000 total accidents that occur each year, approximately 150,000 occur on the state system and are location-coded by the TO.

The location coding is done by coding staff using maps, straight line diagrams, reference marker location logs and other aids. In addition to the standard coding done by other states, all accidents which occur on interchange ramps are located to the specific interchange ramp on which they occur. (See specifics under later discussion of "Interchange ramps.")

The mile-posting of all accidents is based on the investigating officer's location-related information and on his/her narrative and sketch. Each officer is instructed to provide a distance to a reference point measured in .01 miles in rural areas or feet in urban areas. Unlike other states, the officer attempts to give distances to reference markers in both directions from the point of the crash. All routes on the state system (Interstate, US, and State numbered highways) have both regularly spaced reference markers as well as markers on many different objects along the roadway (e.g., bridges, culverts, boundary signs). By 1995, approximately 13,000 call boxes with reference numbers will be added on the suburban and urban state system.

In summary, given the reference markers, locations procedures, and coding procedures used, it is felt that the location coding for the 150,000 state-route accidents per year is probably as accurate as would be found in any state in the U.S., with over 90% of the urban and rural accidents being located to within .01 miles. TO staff estimate that there are problems in location provided by the officers in less than two percent of the accidents that the staff codes. These are sent back to the police officers for correction.

In addition to the location coding, the TO staff also code additional variables related to fixed objects struck (up to four in sequence), location of collision by lane, and movement and direction of travel prior to collision. These codes are then returned to the CHP along with the location codes and hard copies.

All codes are then keypunched by the California Highway Patrol and entered into SWITRS. Once keypunched and entered, the complete computer file is sent back to the TO office for their use. The complete annual file is "closed out" around April of the following year.

The TASAS system retains up to ten years of accident data. The HSIS system currently contains accident data for 1991-1994.

The Accident Subfile contains over 40 variables and approximately 150,000 crash records per year. It contains basic variables describing the overall crash (i.e., time and location, weather, lighting, collision severity, accident type, etc.). The file does not include a “first harmful event” variable or a "most harmful event." It also does not contain speed limit or vehicle damage or point of contact. More specific variables related to contributing factors, object struck, and vehicle movements are included in the Vehicle Subfile.

While the Accident Subfile does not contain a "sequence of events" variable, the Vehicle Subfile does contain a type of sequence for fixed-object impacts. Here, the CHP coders enter up to four fixed objects (and their locations) in the order they are struck. One of the fixed object codes is "rollover," which will allow meaningful analysis of roadside hardware and fixed object impacts.

The Vehicle Subfile contains over 30 variables and approximately 300,000 vehicle records per year. It contains information on up to nine vehicles in the crash. In addition to the fixed-object sequence, the file contains specific information on vehicle type, an indication of "direction of travel," contributing factors, vehicle maneuvers and pedestrian locations prior to the crash, and the number of injured and killed occupants. As noted above, specific driver information related to injury, restraint use, sex, and physical condition/drug use are extracted from a separate CHP file and attached to this file. (It is noted that approximately two percent of the vehicles could not be matched with the SWITRS file. This occurs because the Traffic Operations staff manually enters some city reports and some late CHP reports which are not included in the SWITRS file.) The truck information on the file contains some detail on the basic configuration -- whether van or tanker and how many trailers are being pulled. The NGA elements are not on the report form or the file, but will be collected by the CHP on a supplementary form in the future. A complete form revision which will include the NGA elements, and added variables on pedestrian accidents and traffic control devices, is expected in 1/1/96.

The HSIS Occupant Subfile contains information on up to seventy occupants per crash. As noted above, it is not part of TASAS, but is extracted from the CHP file. It contains information on occupant type, sex, age, seating position, injury class, safety equipment use, and ejection for approximately 200,000 occupants per year. Of these, approximately 140,000 are injured and uninjured passengers. However, as noted above, information on uninjured passengers is not captured in approximately 50 percent of the minor (non-towaway) crashes. If one passenger is injured, data is captured on all other passengers whether injured or not. Thus, the file is biased to some extent toward more serious (injury-producing) crashes. The remaining 60,000 records concern injured (but not uninjured) drivers. Information on uninjured (and injured) drivers is found in the Vehicle Subfile.

In order to assess the accuracy of accident variables, we both questioned the California DOT Traffic Operations staff concerning their feelings of variables that were incompletely coded or might be inaccurate, and examined a series of single-variable tables for key variables in each of the subfiles. The Operations staff indicated that virtually all variables on the Accident and Vehicle Subfiles seem to be coded correctly, especially by the Highway Patrol. (They do not use the occupant data in the CHP files, and thus have no knowledge of its accuracy.) They do feel that the information concerning whether an accident occurred in a construction zone (which is part of a "road condition" variable) is less than accurate. (Based on a recent HSIS staff analysis of work zone accident data in other HSIS and non-HSIS states, this problem is common across almost all states.)

In addition to information received from the TO staff, single variable tabulations were run to examine the questions of reporting completeness and data accuracy for these accident subfiles. (As noted earlier, single-variable tables for key variables are provided in Volume II of the Guidebook.) Here, study of percent of "unknown," "not applicable," and "not stated" values for over 50 key variables indicate that, in general, the data in the Accident and Vehicle Subfiles are coded to a high degree of completeness. With very few exceptions, these data also appear to be quite consistent across years, and similar variables appear to have similar values. The exceptions are noted under pertinent variables in the later format section.

As noted above, the major exception to this is in terms of completeness and accuracy of the Occupant Subfile data. First, the file contains data that are biased to some extent toward the more severe accidents, since some significant proportion of the uninjured occupants in non-towaway, property-damage-only crashes do not get entered into the file. Second, there are some differences in the type/seating of occupants between the two variables related to OCC_TYPE (Occupant Type) and SEATPOS (Seating Position). This is due to the fact that the Occupant Type variable combines all uninjured occupants into one code, and that while report forms used by California cities all contain some type of information on drivers, all do not contain a variable on seating position. It is again noted that the most complete information on drivers can be found in the Vehicle Subfile. Other data issues are noted with the specific variable in the later format section.

Except for these Occupant Subfile problems, based on both the interviews and the data comparisons conducted, the majority of the data appear quite accurate.

The Roadway Inventory Files

The California roadway inventory system, taken directly from TASAS, contains current characteristics of the state road system. It is divided into three files within the HSIS system. The first is a basic roadway characteristics file (i.e., the "Roadlog") containing information on the roadway mainline cross section. The second is an Intersection File which contains information on the characteristics of approximately 20,000 intersections and their approach roadways. The third is an Interchange Ramp File, describing the basic characteristics of over 14,000 separate ramps of interchanges.

All three inventory files were developed from inventory information originally collected through a series of field surveys and from construction drawings. Updates to the file is now done on a routine basis by the TO inventory staff based on new construction drawings. The only updates that would be missed by the TO staff are new intersections build at the district level when new development (e.g., a shopping center) occurs. These are sometimes reported by the district office and sometimes not. Often, during accident plotting procedures, these come to the attention of the TO staff, who then request information from the district office. In general however, the Operations staff feel that the inventory information is quite accurate.

The Roadlog File

As shown in Table 1 below, the basic Roadlog File contains information on approximately 15,200 miles of mainline (non-ramp) roadway. This includes all functional classes of roads within the state system -- Interstate, U.S. and state routes. This file contains information on approximately 2,450 miles of Interstate, 11,000 miles of other primary highway, and 1,700 miles of secondary/county/township roads. California has a higher proportion of freeway mileage than do the other HSIS states, particularly urban freeway. Currently, there are two roadway inventory files in the HSIS system, 1993 and 1994. Because a new record is generated each time any of the items on the file changes, the sections that are generated are fairly short, resulting in a large number of individual records. The 15,200 miles of basic inventory information is divided into approximately 50,000 records, resulting in an average section length of 0.3 miles.

The file contains information on route descriptors (including functional class) and general terrain, and cross-section information related to traveled way width, number of lanes, paved and total shoulder width, median type, and other variables. Unlike most state inventories, it also contains information on design speed, special features such as auxiliary lanes, and detailed information on median barriers. The original TASAS file does not contain specific information on the type of shoulder (e.g., earth, sod, gravel, paved). However, California staff note that two variables related to total shoulder width and treated shoulder width can be used to infer whether part or all of a shoulder is paved.

Table 1. HSIS roadway mileage by roadway category (1994 data).

Roadway Category	**Mileage**
Urban freeways	2,205.36
Urban freeways < 4 Lanes	43.08
Urban multilane divided non-freeways	732.55
Urban multilane undivided non-freeways	185.15
Urban 2 lane highways	640.60
Rural freeways	1,846.95
Rural freeways < 4 lns	96.42
Rural multilane divided non-freeways	589.89
Rural multilane undivided non-freeways	408.50
Rural 2 lane highways	8,496.75
Total	15,245.25

The original TASAS file contains groups of variables for "right roadbed" and "left roadbed." Since the definition of each type of roadbed can change depending on whether or not the roadway is divided, the data has been converted to more standard HSIS definitions. After conversion (and as in other HSIS states), "Road 1" is either the full roadway for undivided sections, or the right-hand roadway in the direction of inventory for divided sections. "Road 2" only exists for divided roadways, and is the left-hand roadway in the direction of inventory. There are a few variables which were left in the original "roadbed" format (e.g., right and left roadbed "special features"). These are noted in the format section of this Guidebook.

Traffic information in the form of Average Daily Traffic is included for each section, along with Daily Vehicle Miles of travel. However, truck percentages are not included in the basic inventory file. A detailed description of the basis for these traffic variables is included below.

Finally, unlike most states, the California Roadlog file contains some information concerning changes that occurred to the roadway elements. With some programming, this should allow "before/after" analysis for specific roadway changes. Unlike the Washington State HSIS file, this is not a "date of last change" for each variable. Instead, using a "history indicator" flag and an "effective date" variable, one can determine whether a change has occurred since the preceding year within a group of variables. These flag and date variables exist for groups of variables related to the access control, AADT, median, right roadbed, and left roadbed. To determine the specific variable that changed, and the change in that variable, one must compare the current group of variables to the same group in the preceding year's file. (As noted in the format section under these flag and date variables, this is somewhat difficult to do since the roadbed designations for most variables except for these "history" variables have now been converted to the more conventional "Road 1/Road 2" definitions.) It is also noted that both the history indicator and the effective-date variable must be used in identifying changes. The history indicator variable will remain "on" after the first change, and thus will not indicate whether a subsequent change has occurred. However, the effective date will indicate when the current roadway characteristics became "open to traffic."

In order to assess the accuracy of roadway inventory variables in this Roadlog file and the related files concerning intersections and ramps, we again questioned the California DOT

Traffic Operations staff and examined a series of single-variable tables for key variables in each of the files. The Operations staff feel that the overall quality of the variables in all three files is very high. As noted above, the information in the files is updated in an ongoing effort based on construction plans and maintenance effort reports.

In addition to information received from the TO staff, single variable tabulations were run to examine the questions of reporting completeness and data accuracy. (Again, single-variable tables for key variables are provided in Volume II of the Guidebook.) Here, study of percent of "unknown," "not applicable," and "not stated" values for over 40 key variables in the Roadlog File indicate that, in general, the data is coded to a high degree of completeness. For most variables, there was no missing data. For the remainder, missing data was found in less than 1.5% of the cases. The data also appear to be quite consistent across years, and similar variables appear to have similar values.

In general, from the interviews and the data comparisons conducted, the data appear quite accurate. In the limited number of cases where possible inaccuracies were found or where more detailed definitions might be critical in future analyses, they are noted in the later formats section under the specific variables.

The Intersection File

As noted earlier, intersection-related information for approximately 20,000 intersections has been extracted from the TASAS roadway inventory file and placed in a separate HSIS Intersection File. This file contains more detail on intersections than do most state inventory files, describing both the mainline route and the intersecting route.

In the development of this file, the original TASAS roadway record was used to generate an intersection record each time a state route crosses either a state or non-state route. Thus, during the development process, two (duplicate) records would be generated each time two state routes crossed. (Only one record would be generated when a state route crossed a non-state route since the non-state route would not be inventoried in the roadway file.) A given state route would appear as "mainline" in one of these records, and as "intersecting street" in the second record. To reduce computer storage requirements, the original TASAS file only carries the full set of intersection variables on the record with the lower route number. For example, for an intersection of US 100 with California State Route 2, the data would be retained on the record in which CA 2 was the mainline. The higher number route record would only contain reference data pointing to the other record. For ease of use in the HSIS file, these higher-numbered route records have been deleted from the file. The intersecting route can still be matched with other files since the location (milepost) information is retained on the intersection record, along with the mainline location information.

For each intersection record, specific inventory variables for the mainline include variables related to intersection type, whether the mainline is divided or undivided, traffic control type (with information on whether the signals are semi-actuated or fixed time) intersection lighting, presence of signal mastarm, the presence of left-turn channelization, the presence of right-turn channelization, the type of traffic flow (e.g., two way verses one way with left turns permitted or not permitted), the number of through lanes, and the mainline ADT. It is noted that the channelization and traffic flow information is in the record only once for the mainline (and once for the intersecting street), meaning that the incoming and outgoing legs of each roadway are assumed identical with respect to these variables. In addition to the general information and the information on the mainline legs, cross-street variables include information on the traffic signal mastarms, left and right turn channelization, type of traffic flow, ADT and the number of through lanes.

Finally, as with inventory variables on the Roadlog File, there are a series of "history" and "effective date" variable that will help the analyst determine whether a change has occurred to the intersection in the past year. There are separate history variables for the entire intersection, traffic control, and lighting, and separate history variables for mainline and cross street ADT, and for the groups of variables describing the mainline and cross street (including channelization, mastarm, and traffic flow type). Again, as discussed above, both variables must be used in determining when a change has occurred.

In terms of data accuracy and completeness, examination of tables for the 20 key variables in the file indicate very little missing data (i.e., less that 4% for any variable, and no missing data for most variables). The values for all variables appear logical, and no problems were indicated by California Traffic Operations staff.

The Interchange Ramp File

As with the intersection data, information on approximately 14,000 ramps has been extracted from the TASAS roadway inventory file and placed in a separate HSIS Interchange Ramp File. It is noted there is no “unifying number” which would allow one to group ramps which would be in the same interchange. Thus, an analysis can be done on a ramp basis rather than interchange basis. It is estimated that these 14,000 ramps represent approximately 3,000 interchanges statewide.

Specific variables on the file include the general type of ramp (on or off), the basic ramp design (e.g., diamond, direct, slip, loop, etc.), the ADT on the ramp, whether a median is present on the roadway where the ramp begins, and whether the crossroad on which the ramp terminates is a state or non-state ("area 4") route. Again, a separate pair of history variables are present for both the general descriptive information and for the ADT information.

As was noted earlier under the accident section, individual accidents are located to the ramps on which they occur by a unique ramp identification number. If an accident occurs in the speed change lane prior to the gore area, it is coded to the mainline rather than the ramp. If after the gore and prior to the ramp terminal, it is coded to the ramp. If the ramp terminal is an intersection (as in a diamond interchange), and the accident occurs in the crossroad/ramp intersection or is near enough to be judged as being affected by the ramp terminal (usually 150 ft), there are two different ways of locating the crash depending on the type of crossroad. If the crossroad is a state route, then the crash is coded to the state route. If, on the other hand, the crossroad is non-state route, the accident is coded to the ramp, but is designated in the accident file under INT_RMP ("Intersection/Ramp accident location") to be a "ramp area, intersecting street" location. This is referred to as "area 4" by California staff. As noted above, there is also a code on the Interchange Ramp File defining whether an "area 4" exists for a given ramp (i.e., whether the crossroad is a non-state route.) For non-state routes, "area 4" would also include any crashes occurring between the two ramp terminals (i.e., on or near the overpass).

In terms of completeness and accuracy, examination of tables for the five key variables in the file indicate missing data in less than one percent of the records. Values appear logical, and no problems were indicated by California Traffic Operations staff.

<u>Traffic Information in the Roadway Inventory Files</u>

As indicated in the preceding three sections, all three inventory files contain Annual Average Daily Traffic (AADT) information. In addition, the Roadlog File contains information on Daily Vehicle Miles, which is computed as the product of the section length and section AADT estimate.

In California, the twelve district offices have the responsibility of collecting traffic data and developing the AADT estimates for each road section within their district. The Division of Traffic Operations of CALTRANS' central office oversees the operation, and attempts to maintain consistency in the methods and data across all districts as much as possible. If requested, Traffic Operations personnel will assist a district in calculating the AADT estimates. The Division also maintains all count data on an on-line computer file for the districts' use.

There are approximately 2,100 permanent count stations on mainline highways operated by CALTRANS in California. Of these, approximately 400 are permanent, continuous counting control stations that operate continuously each day in a given year. Every major state-administered route is counted each year. The 400 permanent continuous count stations form a network that covers all major routes. The remaining control stations are permanent, quarterly counting control stations, i.e., in-pavement loops to which a counter/recorder device is attached for 7 to 14 days during each quarter. CALTRANS also collects count data at approximately 700 of these quarterly counting control stations once every three years. In a given year, there are approximately 1,000 permanent quarterly counting stations where count data are not collected. California has determined that the AADT estimates which are derived from the simple average of the four (unadjusted) quarterly counts does indeed account for seasonal fluctuations without further adjustment based on nearby permanent counters. Consequently, there are no additional adjustments or corrections applied to the AADT’s estimated from the quarterly counts.

In addition to the permanent control stations, approximately 1,000 coverage counts are collected annually. The intent is to collect coverage counts on a 3-year cycle (for a total of approximately 3000 coverage counts), although conditions may force longer intervals in certain districts at times. A coverage count is basically a 24-hour to 1-week count.

Coverage counts are expanded to AADT estimates using factors derived from the combined continuous counts and quarterly count data. For road sections which are not counted in a given year, it is the responsibility of the districts to develop these AADT estimates. In some cases, the districts reply on overall traffic growth trends within the district. However, in most cases, the AADT assigned to the section is developed by studying the traffic growth in counts falling on each side of the section.

It is also noted that 24-hour to one-week coverage counts are collected on approximately 3,200 on- and off-ramps per year. These ramp counts are manipulated through ramp balancing to reflect continuity of flow on mainline freeways.

Finally, vehicle classification data are collected at approximately 70 permanent stations across the state. Additional classification counts are collected on an as-requested basis, typically at locations where traffic count data is being collected. Since this is district-based, there is no reliable estimate on how many additional classification counts are collected across all twelve districts per year. Finally, there are approximately 45 weight-in-motion stations statewide which provide speed, volume, and the "13-bin" vehicle classification information.

Issues Related to Developing and Merging Files

As noted above, the accident data are subdivided into three subfiles -- accident, vehicle and occupant. The Accident and Vehicle Subfiles can be linked together using the accident report number (i.e., CASENO). When linking the occupant subfile, the additional linking variable related to vehicle number (i.e., VEHNO) must match so that the occupants are associated with the vehicle in which they were traveling. To link vehicles with accidents, first sort both subfiles by CASENO. To link the Occupant file with the other two subfiles, first sort both the Vehicle subfile and Occupant subfile by case number and vehicle position number. Next sort the Accident subfile by case number. Alternatively, the separate subfiles can be linked by specifying an SQL JOIN operation with the constraining condition that case number and vehicle number from each table are equal. SQL processing does not require the data to be presorted and the output will not be in any particular sort order unless ORDER BY is specified.

The Accident Subfile can be linked to Intersection and Interchange Ramp Files using the two variables related to county/route (i.e., CNTY_RTE) and MILEPOST. Using the same CNTY_RTE and MILEPOST variables, the Accident Subfile can be linked to the Roadlog File using the CNTY_RTE and BEGMP and ENDMP variables.

To prepare the Accident Subfile for linking with the Roadlog File using a SAS data step process, the analyst must sort both the Accident and the Roadway File into location order by

CNTY_RTE and MILEPOST on the Accident file and by CNTY_RTE and BEGMP on the Roadlog File. Similar sorts would be done with other files to be merged. For the alternative SQL join, the analyst must specify an exact match on CNTY_RTE and a range match where MILEPOST occurs between BEGMP and ENDMP. (Programs to accomplish this merging and division are documented in the HSIS Programmer's Guidebook, available at FHWA.)

Finally, where appropriate and possible, a format which defines categories within a given variable has been developed for HSIS SAS variables. These categories are shown in the pages below. These formats have been saved in a format library which can be provided to the user. As a naming convention, the "format name" is the same as the variable name, with the only exception being for certain character variables (in contrast with numeric variables). More specifically, a SAS format name has to be preceded by a "$" if the variable is character in nature. There is an 8-character length limit on both variable name and format name. In cases where the variable name is already eight characters in length, the addition of the preceding "$" would make the format name one character too long. In these cases, the format name is the same as the variable name except the final character of the variable name is dropped.

California Contacts

State Liaison [2]-- Lynn Seamons (916-654-4318) -- Mr. Seamons is our main contact in the California DOT when questions arise concerning the California data files in general. He is the Manager of the Accident Surveillance and Coding Branch of the CALDOT Division of Traffic Operations, and is the primary custodian of the TASAS system. He should be the first contact on all questions related to all accident and roadway inventory files. He is assisted by Robert (Bob) Brown (916-654-2215), who can answer questions on all files in Mr. Seamons absence.

Traffic Counts -- Joe Avis (916-654-3072) -- Mr. Avis is the traffic count specialist within the Division of Traffic Operations. He is responsible for headquarters coordination and storage of the traffic counts collected by the district offices, and forwards the ADT to Mr. Seamons for inclusion in TASAS.

California Highway Patrol Accident Data -- Bev Christ (916-657-7432) -- Ms. Christ is the Governmental Program Analyst with the California State Highway Patrol. She works with the

---

[2] Liaison was Janice Benton 916 654 7271 (Sept. 2001) (Author’s note)

SWITRS data which is the basis for the HSIS driver information in the Vehicle Subfile and the Occupant Subfile. She can answer questions related to these data and to the overall nature of data collection by the State Highway Patrol and city agencies. (However, accident-related questions should be posed to Mr. Seamons first, as our main point of contact.)

APPENDIX H

DATA COLLECTION AND USE SUMMARY

INTRODUCTION

Twelve State Departments of Transportation were contacted in the course of the present effort. The purpose of these contacts was to inquire about the availability of crash, pavement texture, Friction Number, travel, roadway classification and other data relevant to the present effort. This effort sought to identify reliable multi-year state-wide databases that could readily be integrated and analyzed. Any identified databases would also have to be compatible across states, in order to allow direct comparisons with Wisconsin data.

This was a time-consuming process requiring repeated contacts by phone or e-mail; it produced results piecemeal. It was unknown at the outset whether the pieces would fit together when they were all finally gathered. Most information ended up not being used because data integration and testing would exceed the resources available for the present effort. An inventory of gathered information is presented in this Appendix for the purpose of facilitating future investigators who may be after similar types of information. **Appendix I** presents a list of the persons within each organization that provided the information described herein.

CALIFORNIA

HSIS: 1991-1998 crashes, roadway inventory, 1997 intersection information.
Caltrans: Contacts relating to freeway operation under winter weather conditions with District 3.
Disposition: Used crash and roadway inventory.
Reasoning: State-wide, multi-year information on longitudinal texture, some information on transversely tined pavements. Intersection information not used to avoid influence of extraneous variables on safety performance.

COLORADO

No data gathered.
Disposition: Not used.
Reasoning: Inadequate sample for safety performance evaluation—longitudinal texture was applied only recently.

ILLINOIS

HSIS: 1991-1998 crashes, roadway inventory. No information on pavement surface texture.
ILDOT: No additional pavement data gathered.
Disposition: Not used.
Reasoning: Only transversely tined pavements used. No information on rehabilitated sections or use of grinding.

IOWA

No data gathered.
Disposition: Not used.
Reasoning: Limited use of longitudinal texture.

MAINE

HSIS: 1991-1998 crashes, roadway inventory. No information on pavement surface texture.
MDOT: No additional data.
Disposition: Not used.
Reasoning: State mainly uses 8”-9” Asphaltic Concrete (AC) on Interstate highways; PCC has not been used since 1975-6. About 72 lane-miles of remaining PCC were to be overlaid with AC. Transversely tined PCC used on bridge decks.

MICHIGAN

HSIS: 1991-1998 crashes, roadway inventory
MDOT: Construction year, year of pavement improvement, low Friction Number, high Friction Number, average Friction Number, lane in which FN was collected, FN test date.
Disposition: Not used
Reasoning: Not clear which pavement surface texture was in place each year.

MINNESOTA

HSIS: 1991-1998 crashes, roadway inventory. No information on pavement surface texture.
MNDOT: No information on which PCC pavements were longitudinally ground.
Disposition: Not used.
Reasoning: No information on pavement surface texture.

NORTH CAROLINA

HSIS: 1991-1998 crashes, roadway inventory. No information on pavement surface texture.
NCDOT: No additional data.
Disposition: Not used.
Reasoning: Only about 200 miles of exposed PCC pavement available. Transversely tined surface treatment. Information on its location would have to be gathered by contacting each of NCDOT divisions 4, 5, 7, 9 and 10. Difficulty in identifying PCC sections.

UTAH

HSIS: 1991-1998 crashes, roadway inventory.
UDOT: No accurate surface texture database available. PCC pavements (a total of approximately 1,200 miles) transversely tined. Some diamond grinding performed on less than 10% of this mileage as rehab. Some grinding project limits identified by Region Materials Engineers. Skidabraider was also used in a couple of projects.
Disposition: Not used.
Reasoning: Extent of grinding not clear—some projects were in one direction only. Grinding project dates varied through the evaluation period complicating the evaluation. No established database to track pavement texture.

VIRGINIA

VDOT: 1992-2000 crashes (1996 data not complete); Traffic volumes 1996-2001; skid data; concrete pavement inventory (235 miles of longitudinally tined pavements, few transversely tined pavements, several hundred miles of milled pavements)—pavement section lengths varying from a few miles to over 30 miles in length; friction information (VDOT uses the ASTM E274 friction device and correct the Skid Number to 40 mph); pavement age.
Disposition: Preliminary analysis for 1997-2000 data. Not used in this report.
Reasoning: Many compatibility issues with HSIS data; difficult identification of highway class; some very short segments; scattered locations.

WASHINGTON STATE

HSIS: 1991-1998 crashes, roadway inventory
WADOT: Inventory of rehabbed freeway segments (1993-2001)--grinding applied mostly to right lane.
Disposition: Not used.
Reasoning: Limited database consisting of transversely tined texture. Rehabilitation occurred at different times during the analysis period, complicating the analysis.

WISCONSIN

WisDOT 1991-1998 freeway crashes on I-90, I-94, I-794 and I-894.
1975-1994 Friction Number database.
Metamanager mid-1999 roadway inventory (pavement type, travel information, urban/rural freeway classification).
Disposition: Used crash, Metamanager and Friction Number data.
Reasoning: State-wide multi-year information available. Reliable integration of crash and roadway data.

APPENDIX I

AGENCY CONTACTS

INTRODUCTION

The present Appendix contains the names and contact information of persons that provided the data listed in **Appendix H.**

CONCRETE PAVING ASSOCIATION OF MINNESOTA

Mark Snyder
Concrete Paving Association of Minnesota
7996 Beard Avenue North
Minneapolis, MN 55443
Tel: 763-561-0402
Cell: 612 309 6472
MBSnyder@cpamn.com

HIGHWAY SAFETY INFORMATION SYSTEM (HSIS)

Michael S. Griffith
Federal Highway Administration
Office of Safety and Traffic Operations R&D
6300 Georgetown Pike, T-303
McLean, VA 22101-2296
Tel: 202 493 3316

Yusuf Mohamedshah
HSIS Lab, Room T-211
6300 Georgetown Pike
McLean, VA 22101
Tel: 202 493 3464
Yusuf.Mohamedshah@igate.fhwa.dot.gov

MIDWEST RESEARCH INSTITUTE

Doug Harwood
Principal Traffic Engineer
425 Volker Boulevard
Kansas City, MO 64110
Tel: 816 753 7600 x1571

Author of WETTIME program

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Web site: www.ncdc.noaa.gov

National Climatic Data Center
Federal Building
151 Patton Ave.
Asheville NC 28801-5001
Tel: 828 271 4800
Fax: 828 271 4876

Sam McCown
Climate Services Branch
Tel: 828 271 4800x3174
Sam.McCown@noaa.gov

Alva L.Wallis
Tel: 828 271 4800x3175
Alva.L.Wallis@noaa.org

William Brown
Customer Services Branch
Research Meteorologist
Tel: 828 271 4800x3161
william.brown@noaa.gov

STATE CLIMATOLOGISTS

California

Mr. William A. Mork
CA Dept of Water Resources
Division of Flood Management
P.O. BOX 219000
Sacramento CA 95821-9000
Tel: 916-574-2614
Fax: 916-574-2767
Internet Email: morkb@water.ca.gov

Colorado

Dr. Roger A. Pielke, Sr.
Colorado Climate Center
Dept of Atmospheric Science
Colorado State University
Fort Collins CO 80523
Tel: 970-491-8545
Fax: 970-491-8449
Internet Email: pielke@atmos.colostate.edu
WWW: http://ccc.atmos.colostate.edu

Illinois

Dr. Jim Angel
Illinois State Water Survey
2204 Griffith Drive
Champaign IL 61820-7495
Tel: 217-333-0729
Fax: 217-244-0220
Internet Email: j-angel@uiuc.edu
WWW: http://www.sws.uiuc.edu/atmos/statecli/index.htm

STATE CLIMATOLOGISTS (Cont.)

Maine

Dr. Gregory A. Zielinski
Maine State Climatologist
Institute for Quaternary and Climate Studies
University of Maine
Orono ME 04469-5790
Tel: (207) 581-3441
Fax: (207) 581-1203
Internet Email: gzielinski@maine.edu
WWW: http://www.umaine.edu/maineclimate/

Michigan

Dr. Fred V. Nurnberger
MSU/State Climatology
417 Natural Sciences Bldg.
Michigan State University
East Lansing MI 48824-1115
Tel: 517-355-0231
Fax: 517-432-1076
Internet Email: scmifred@pilot.msu.edu
WWW: http://climate.geo.msu.edu

Minnesota

Mr. Jim Zandlo
State Climatology Office
University of Minnesota
S-325 Borlaug Hall
St. Paul MN 55108
Tel: 651-296-4214
Fax: 651-625-2208
Internet Email: mcwg@soils.umn.edu
WWW: http://www.soils.agri.umn.edu/re search/climatology/

STATE CLIMATOLOGISTS (Cont.)

North Carolina

Dr. Sethu Raman
State Climate Office of North Carolina
Campus Box 7236
NC State University
Raleigh NC 27695-7236
Tel: 919-515-1440
Fax: 919-515-1446
Internet Email: sethu_raman@ncsu.edu
Internet Email: sco@cumulus.meas.ncsu.edu
WWW: http://www.nc-climate.ncsu.edu

Utah

Dr. Don T. Jensen
Utah State Climatologist
Utah Climate Center
Utah State University
4825 Old Main Hill
Logan UT 84322-4825
Tel: 435-797-2190
Fax: 435-797-2117
Internet Email: djensen@cc.usu.edu
WWW: http://climate.usu.edu/

Virginia

Dr. Patrick J. Michaels
Virginia State Climate Office
Clark Hall
University of Virginia
Charlottesville VA 22903
Tel: 804-924-0549 OR 7761
WWW: http://wsrv.clas.virginia.edu/~climate/

STATE CLIMATOLOGISTS (Cont.)

Wisconsin

Professor John A. Young, Acting State Climatologist
Lyle Anderson, Manager
State Climatologist Office
University of Wisconsin
1225 West Dayton Street
Madison WI 53706-1612
Tel: 608-263-2374
Fax: 608-262-5964
Internet Email: stclim@macc.wisc.edu
WWW: http://www.aos.wisc.edu/~sco

STATE DEPARTMENTS OF TRANSPORTATION

CALIFORNIA

Tom Pyle
Chief
Rigid Pavements
METS Office of Rigid Pavement Materials & Structural Concrete
Tom_Pyle@dot.ca.gov
Tel: (916) 227-5845

Bill Neal
Retired CalTrans
Author of PCC texture studies.

Bang D. Nguyen
Transportation Eng. Technician
Contact w/Bill Neal
Tel: 916 227 5717
Bang_D_Nguyen@dot.ca.gov

Jack Tonkin
District 3
Tel: 916 653 2143
Jack_Tonkin@dot.ca.gov

John Cottier
Chief
District 3
Office of Maintenance Equipment and Emergency Operations
John_Cottier@dot.ca.gov

Dale Ten Broeck
Deputy Director
District 3
Maintenance and Operations

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

COLORADO

Ahmad Ardani
Research Engineer
Colorado Department of Transportation, Research Branch
4201 E. Arkansas Ave.
Denver, CO 80222
Tel: 303 757 9978
Fax: 303 757 9974
Ahmad.Ardani@dot.state.co.us

Skip Outcalt
Colorado Department of Transportation, Research Branch
4201 E. Arkansas Ave.
Denver, CO 80222
Tel: 303 757 9984
Fax: 303 757 9974
Skip.Outcalt@dot.state.co.us

ILLINOIS

Richard (Rick) Meyers
HSIS Liaison
Manager
Traffic Safety
Accident Information Section
Annex 1st F Springfield
3215 Executive Park Drive
Springfield, IL 62766
Tel: 217 782 2575
meyersra@nt.dot.state.il.us

Eric E. Harm, P.E.
Bureau Chief
Engineer of Materials and Physical Research
Bureau of Materials and Physical Research
MPR Building
Springfield
Tel: 217 782 7202

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

LaDonna R. Rowden. P.E.
Pavement Technology Engineer
Illinois Department of Transportation
Bureau of Materials and Physical Research
126 East Ash Street
Springfield, IL 62704-4766
Tel: 217 782-8582
Fax: 217 557-6941
RowdenLR@nt.dot.state.il.us

IOWA

Jim Grove
Concrete Pavement Engineer
Iowa DOT, 800 Lincoln Way
Ames, IA 50010-1226

MAINE

Ron Emery
Tel: 207 287 3247

Guy Berthiaume
Product Evaluation Engineer
Tel: 207 287 2257
guy.berthiaume@state.me.us

Dale Peabody
Division Head
Transportation Research Division
16 State House Station
Augusta ME, 04333-0016
Tel: 207 287 2152
Fax: 207 287 3292
dale.peabody@state.me.us

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

MICHIGAN

Donald J. Mercer
HSIS liaison
Michigan Department of Transportation
Tel: 517 335-2629
mercerd@mdot.state.mi.us

David L. Smiley
Michigan DOT
Construction & Technology Division
P O Box 30049
Lansing, Michigan 48909
Tel: 517-322-1766
SMILEYD2@mdot.state.mi.us

Steven Bower
Tel: 517 322-5198
Tel: 810 225-2622
BowerS@state.mi.us
BowerS.mt.mdot@mdot.state.mi.us

James Culp
Engineer of Construction & Technology
Bureau of Highway Technical Services
Tel: (517) 322-1085
culpj.mt.mdot@mdot.state.mi.us

Tom Hynes
Tel: 517 322-5711
HYNEST.mt.mdot@mdot.state.mi.us

John Thomas Lavoy
Tel: 517 322-5698
LavoyJ.mt.mdot@mdot.state.mi.us

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

Ronald L. Vibbert
Manager, Strategic Systems Operations & Maintenance
Bureau of Transportation Planning
Michigan DOT
PO Box 30050
Lansing, MI 48909
Tel: (517) 373-9561
Fax: (517) 373-9255
Sufficiency file that includes pavement “Improvement Year”
VibbertR@state.mi.us

Thomas J. Hattis
Friction Numbers and Sufficiency File
Tel: 517 322-1231
HATTIST@state.mi.us

Dan Sokolnicki
Pavement Management Section
Pavement Surface Age information
Tel: 517 322-5721
SokolnickiD@mdot.state.mi.us

MINNESOTA

David W. Janisch
Pavement Management Unit
Pavement Management Engineer
Tel: 651 779 5567
dave.janisch@dot.state.mn.us

Dave Rettner
Minnesota Department of Transportation
Office of Materials and Road Research
Mail Stop 645
1400 Gervais Avenue
Maplewood, Minnesota 55108

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

Benjamin Worel
Mn/ROAD Operations Engineer
Minnesota Department of Transportation
Office of Materials and Road Research
Mail Stop 645
1400 Gervais Avenue
Maplewood, Minnesota 55109-2044
Tel: 651 779 5522
Fax: 651 779 5616
Pager: 651 629 8719
Ben.Worel@dot.state.mn.us

Joseph Mead
Joseph.Meade@dot.state.mn.us

Rosario Guerrero Adiarte
Transp Info Res Divisional Sup
395 John Ireland Blvd
Mail Stop 450
St. Paul, MN 55155-1899
Tel: 651 297-2888
Fax: 651 296-3311
Rosario.Adiarte@DOT.STATE.MN.US

Douglas John Schwartz
Concrete Engineer
Office of Materials & Road Research
1400 Gervais Avenue
Maplewood, Minnesota 55109
Tel: 651 779 5576
Fax: 651 779 5580

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

NORTH CAROLINA

Tony D. Wyatt, P.E.
HSIS Liaison
Traffic Safety Systems Management Unit
Tel: 919 733 1593
awyatt@pmu.dot.state.nc.us
awyatt@dot.state.nc.us

Roberto Canales, P.E.
Branch Manager
State Construction and Materials Engineer
State Construction and Materials Branch
1539 Mail Service Center
Raleigh, NC 27699-1539

1 S. Wilmington Street (Delivery)
Raleigh, NC 27601
Tel: 919 715 5662
rcanales@dot.state.nc.us
RCanales@pmu.dot.state.nc.us

George Gibson
Unit Head
Pavement Management Unit
Tel: 919 250 4094
ggibson@dot.state.nc.us
ggibson@mail.dot.state.nc.us

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

UTAH

Rick Julio
HSIS Liaison
Roadway Geometric Engineer
Utah DOT
Tel: 801 965 4264
rjulio@dot.state.ut.us

Mack Christensen
Traffic and Safety Studies Engineer
Tel: 801 965 4264

John Butterfield
Chief
Construction Materials
Tel: 801 965 4111
jbutterf@dot.state.ut.us

Neeley Lloyd
UDOT Program Development Group
Pavement Management Engineer
Tel: 801 965 4158
lneeley@dot.state.ut.us

Doug Anderson
Head
UDOT Research
Tel: 801 965 4377
danderso@dot.state.ut.us

Vandre Bruce
UDOT Planning
Tel: 801 965 4835
bvandre@dot.state.ut.us

Charles Mace
Materials Engineer
UDOT Region 1
Tel: 801 399 5921 x 306
Tel: 801 399 0351 Lab
Cell: 801 510 1220
Cmace@dot.state.ut.us

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

Tim Biel
Materials Engineer
UDOT Region 2
Tel: 801 975 4926
tbiel@dot.state.ut.us

Steve Park
UDOT Region 2
Pavement Management Engineer
spark@dot.state.ut.us

Scott Andrus
Materials Engineer
UDOT Region 3
Tel: 801 227 8035
sandrus@dot.state.ut.us

Larry Gay
Materials Engineer
UDOT Richfield District
Tel: 435 896 1306
lgay@dot.state.ut.us

VIRGINIA

Trenton M. Clark, P.E.
Assistant State Pavement Engineer
VDOT - Materials Division
1401 East Broad Street
Richmond, VA 23219
Tel: 804-328-3129
Cell: 804-840-7559
Fax: 804-328-3136
clark_tm@vdot.state.va.us

Larson, Charles (Chuck) D.
State Pavement Management Engineer
Tel: 804-786-7646
larson_cd@vdot.state.va.us>

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

Robert Borter
Sr. Systems Analyst\Systems Architect
Virginia Department of Transportation
ITD: 804 786 5949
Materials: 804 328 3174
Borter_rj@vdot.state.va.us
robert.borter@virginiadot.org

WASHINGTON STATE

Design
Tel: 360 705 7230

Construction
Tel: 360 705 7820

Materials Lab
Pavement Management System
Tel: 360 709 5400

Asphalt
Linda Pierce
Pavement Engineer
Tel: 360 709 5470
PIERCEL@WSDOT.WA.GOV

Concrete
Kurt Williams
General Materials Engineer
Tel: 360 709 5440

WISCONSIN

Laura Fenley
Pavement Structural Design Engineer.
Truax Center
3502 Kinsman Boulevard
Madison, WI 53704
Tel: 608 246-5455

STATE DEPARTMENTS OF TRANSPORTATION (Cont.)

Richard C. Lange
4802 Sheboygan Ave Rm. 501
Madison, WI 53702
Tel: (608) 266-1620
richard.lange@dot.state.wi.us
Crash data

Bradley G. Javenkoski
4802 Sheboygan Ave Rm 951
Madison, WI 53705
Tel: 608 264 8725
Fax: 608 267 7856
bradley.javenkoski@dot.state.wi.us
Metamanager data

Harold (Mike) Shcumacher
4802 Sheboygan Ave Rm 901
Madison, WI 53707
Tel: 608 267 5006
Fax: 608 267 7856
harold.schumacher@dot.state.wi.us
Metamanager data

Peter A. Amakobe
4802 Sheboygan Ave Rm. 651
Madison, WI 53707
Tel: (608) 266-2842
peter.amakobe@dot.state.wi.us
Friction Number data

APPENDIX J

STATISTICAL TESTS

INTRODUCTION

The present Appendix contains statistical tests performed on Liquid precipitation Safety Ratio (LSR) differences**.** The two-sample and k-sample non-parametric Smirnov tests[1] for samples of equal size were used, which are based on the following assumptions:

1. The samples are random samples.
2. The samples are mutually independent.
3. The measurement scale is at least ordinal.
4. The random variables are continuous.

These assumptions hold for the continuous LSR variable.

LSR calculations were carried to nine significant digits, using the following equation:

$$LSR = \frac{(wet - to - dry\ ratio)}{\left(\frac{\%\ time\ wet\ \ pavement}{\%\ time\ dry\ \ pavement}\right)}$$

(See equation *(5)* on page 12 of the report.) Both the wet-to-dry ratio (numerator) and the ratio of percent time wet pavement over percent time dry pavement (denominator) were calculated to nine significant digits. Thus some minor discrepancies due to rounding may be observed between tables presented elsewhere in the report and information presented in this Appendix.

---

[1] See W.J. Conover, Practical Non-Parametric Statistics. John Wiley & Sons, Inc. 2nd edition, New York,1980.

TEST 1:
LSR DIFFERENCES BETWEEN TT WISCONSIN AND LT CALIFORNIA RURAL FREEWAY PAVEMENTS WITH ADT <60K VPD

Liquid Safety Ratio (LSR) information for Wisconsin Transversely Tined and California Longitudinally Tined PCC pavement rural freeways with ADT less than 60,000 vehicles per day is provided in summary form on **Table 1**, page 14 of the report. Needed crash information (number of crashes on dry and wet pavement) is provided on **Table C2** (Appendix C). Weather information required to calculate the LSR is provided in **Tables E3 and E4** (Appendix E). All necessary information is summarized on page J4. Calculations are carried to nine significant digits.

Liquid precipitation Safety Ratio (LSR) distribution differences between the two pavement textures were investigated based on the two-sample, one-sided, non-parametric Smirnov test for samples of equal size.

The null hypothesis $\mathbf{H_o}$: The two LSR distributions are identical.
The alternative hypothesis $\mathbf{H_1}$: Longitudinal Tining is associated with higher LSR values than Transverse Tining.

This one-sided test was motivated by the higher overall LSR values for LT compared to TT pavements listed on Table 1 page 14 of the report.

The test statistic was $T_1^+ = 0.375$, which is smaller than the critical value $w_{0.90} = 0.500$ ($n = 8$). Thus the null hypothesis cannot be rejected at the 0.90 level of confidence. The hypothesis that the two LSR distributions are identical cannot be rejected based on the available eight years of data.

Table J1 Liquid Safety Ratio calculations for WI TT and CA LT pavement surface textures

California

Rural freeways

Rolling and Level Terrain

Longitudinally Tined PCC

ADT less than 60,000 vpd

Year	Dry pvt crashes	Wet pvt crashes	wet-to-dry ratio	$\left(\frac{\%\ time\ wet\ pavement}{\%\ time\ dry\ pavement}\right)$	**LSR**
1991	2429	188	0.077398106	0.047268908	1.637399936
1992	2315	249	0.107559395	0.045026178	2.388819127
1993	2390	215	0.089958159	0.052742616	1.705606695
1994	2370	223	0.094092827	0.036344756	2.588896926
1995	2339	330	0.141085934	0.061702128	2.286565140
1996	2492	356	0.142857143	0.049369748	2.893617021
1997	2460	214	0.086991870	0.033160622	2.623348577
1998	2172	411	0.189226519	0.061767838	3.063512098

Wisconsin

Rural freeways

Transversely Tined PCC

ADT less than 60,000 vpd

Year	Dry pvt crashes	Wet pvt crashes	wet-to-dry ratio	$\left(\frac{\%\ time\ wet\ pavement}{\%\ time\ dry\ pavement}\right)$	**LSR**
1991	95	18	0.189473684	0.085450346	2.217354196
1992	96	27	0.281250000	0.088578089	3.175164474
1993	162	32	0.197530864	0.091981132	2.147515036
1994	131	10	0.076335878	0.063420159	1.203653217
1995	180	21	0.116666667	0.076834862	1.518407960
1996	160	37	0.231250000	0.056919643	4.062745098
1997	149	20	0.134228188	0.055617353	2.413422819
1998	233	32	0.137339056	0.064230343	2.138227024

TEST 2:
LSR DIFFERENCES BETWEEN LT CALIFORNIA FREEWAY PAVEMENTS: RURAL WITH ADT < 60K VPD VS. URBAN WITH ADT <60K VPD VS. URBAN WITH ADT 60K+ VPD

Liquid Safety Ratio (LSR) information for California Longitudinally Tined PCC pavement freeways is provided in summary form on **Tables 1, 2 and 3**, pages 14 and 15 of the report. Needed annual crash statistics (number of crashes on dry and wet pavement) for rural and urban California LT freeways is provided on **Table C2** (Appendix C). Weather information required to calculate the LSR is provided in **Table E4** (Appendix E). All necessary information is summarized on page J6. Calculations are carried to nine significant digits.

Liquid precipitation Safety Ratio (LSR) distribution differences between the three LT California freeway classifications were investigated based on the three-sample, one-sided non-parametric Smirnov test for samples of equal size.

The null hypothesis $\mathbf{H_o}$: LSR distributions for the three LT freeway classifications are identical.
The alternative hypothesis $\mathbf{H_1}$: LSR are, from lower to higher:
Rural freeways with ADT < 60K vpd
Urban freeways with ADT 60K+ vpd
Urban freeways with ADT < 60K vpd

This one-sided test was motivated by the relative magnitudes of the overall LSR values shown for LT pavements in **Tables 1, 2 and 3** on pages 14 and 15 of the report.

Assuming that the empirical distribution of:
LSR for Rural freeways with ADT < 60K vpd is $S_1(x)$; that of
LSR for Urban freeways with ADT 60K+ vpd is $S_2(x)$; and that of
LSR for Urban freeways with ADT < 60K vpd is $S_3(x)$,

The test statistic for differences between $S_1(x)$ and $S_2(x)$ is T_2 = 0. 750 which is equal to the critical value $w_{0.995} = 0.750$ (n = 8, k = 3, p = .995). Thus the null hypothesis of no differences in LSR distributions between rural freeways with ADT < 60K vpd and urban freeways with ADT of 60K+ vpd is rejected at the 0.995 level of confidence. Urban freeways with ADT of 60K+ vpd have higher LSR values than rural freeways with ADT < 60K vpd.

The test statistic for differences between $S_2(x)$ and $S_3(x)$ is T_2 = 0. 500 which is equal to the critical value $w_{0.900} = 0.500$ (n = 8, k = 3, p = .900). Thus the null hypothesis of no differences in LSR distributions between urban freeways with ADT of 60K+ vpd and urban freeways with ADT < 60K vpd is rejected at the 0.900 level of confidence. Urban freeways with ADT < 60K vpd have higher LSR values than urban freeways with ADT of 60K+ vpd.

Thus, the alternative hypothesis holds true at the 0.900 level of confidence.

Table J2 Liquid Safety Ratio calculations for CA LT pavement surface textures: rural with ADT < 60K vpd; urban with ADT < 60K vpd; urban with ADT 60K+ vpd

California

Rural freeways
Rolling and Level Terrain
Longitudinally Tined PCC
ADT less than 60,000 vpd

Year	ADT	Dry pvt crashes	Wet pvt crashes	wet-to-dry ratio	$\left(\frac{\%\,time\ wet\ pavement}{\%\,time\ dry\ pavement}\right)$	**LSR**
1991	<60K	2429	188	0.077398106	0.047268908	1.637399936
1992	<60K	2315	249	0.107559395	0.045026178	2.388819127
1993	<60K	2390	215	0.089958159	0.052742616	1.705606695
1994	<60K	2370	223	0.094092827	0.036344756	2.588896926
1995	<60K	2339	330	0.141085934	0.061702128	2.286565140
1996	<60K	2492	356	0.142857143	0.049369748	2.893617021
1997	<60K	2460	214	0.086991870	0.033160622	2.623348577
1998	<60K	2172	411	0.189226519	0.061767838	3.063512098

California

Urban freeways
Rolling and Level Terrain
Longitudinally Tined PCC
ADT less than 60,000 vpd
ADT more than 60,000 vpd

Year	ADT	Dry pvt crashes	Wet pvt crashes	wet-to-dry ratio	$\left(\frac{\%\,time\ wet\ pavement}{\%\,time\ dry\ pavement}\right)$	**LSR**
1991	<60K	2571	309	0.120186698	0.047268908	2.542616362
	60K+	50761	6036	0.118910187	0.047268908	2.515611066
1992	<60K	2380	418	0.175630252	0.045026178	3.900625366
	60K+	47715	7852	0.164560411	0.045026178	3.654771914
1993	<60K	2556	425	0.166275430	0.052742616	3.152582160
	60K+	47464	7505	0.158119838	0.052742616	2.997952132
1994	<60K	2568	353	0.137461059	0.036344756	3.782142857
	60K+	52144	6534	0.125306843	0.036344756	3.447728269
1995	<60K	2392	424	0.177257525	0.061702128	2.872794372
	60K+	50062	9405	0.187867045	0.061702128	3.044741762
1996	<60K	2517	443	0.176003178	0.049369748	3.565000549
	60K+	55957	9044	0.161624104	0.049369748	3.273747813
1997	<60K	2385	311	0.130398323	0.033160622	3.932324423
	60K+	59488	6990	0.117502690	0.033160622	3.543440484
1998	<60K	2387	601	0.251780478	0.061767838	4.076239111
	60K+	57739	12014	0.208074265	0.061767838	3.368650604

Wisconsin Highway Research Program
Dr. Hussain Bahia, Technical Director
bahia@engr.wisc.edu
1415 Engineering Dr., Rm. 3350
Madison, WI 53706
608-265-4481

WisDOT Research & Library Unit
Ann Pahnke, Program Analyst
ann.pahnke@dot.state.wi.us
4802 Sheboygan Ave., Rm. 801
Madison, WI 53707
608-267-2294

Research Implementation & Project Closure

Project Information	
(To be completed by WHRP staff when draft report is received) **Date completed:** May, 31, 2007	
Project Title: Wet Pavements Crash Study of Longitudinal and Transverse Tined PCC Pavements	**Project ID:** 0092-00-08
Technical Oversight Committee: Rigid Pavement	**TOC Chair:** Jim Parry
Project Start Date: February 21, 2000	**WisDOT Project Manager:** Jim Parry
Project End Date: December 14, 2001	**Approved Contract Amount:** $83,100
Final Report Dated: December 31, 2006	**Actual Project Expenditures:** $83,100
Principal Investigator: Alex Drakopoulos **Organization:** Marquette University	**Co-investigators (including research assistants) and Organizations:** David A. Kuemmel, Marquette University

Implementation / Further Research Recommendations

(Information provided by TOC and WisDOT project manager when final report is approved) **Date completed:**

1. What WisDOT policy or practice does this research project pertain to? Please identify the specific section(s) of the Facilities Development Manual (FDM), Construction and Materials Manual (CMM), Standard Specifications, other manual, or accepted practice to which this research pertains.
This practice pertains to the application of surface texture to concrete pavement, as specified in Chapter 415 of the Standard Specifications.

2. Based on the results of this research, the following steps are recommended. (Please select either A, B or C, and provide detail in Items 3 to 7, below.)

☐ **A. No further activity is necessary. (Please skip to Item 7.)**

☐ **B. Revisions to WisDOT policy or practice <u>are not appropriate at this time</u>. However, to gain further value from this research, we recommend follow-up research and/or validation activities as detailed in 3 through 6, below.**

☒ **C. The Technical Oversight Committee recommends implementing changes to the following WisDOT policies or practices. (Please identify specific section(s) of specific manuals, where applicable):**
Longitudinal tining is now recognized as the preferred surface texture for PCC Pavement in the Standard Specifications and the CMM.

3. Describe the scope and objectives of follow-up research or implementation of specific changes to WisDOT procedures.
The objective is to specify preference for the longitudinally tined surface texture because it can more easily and reliably be constructed with low-noise characteristics than the random transverse tining previoiusly used. Implementation has already been completed based upon the findings in the draft final report for this research study.

4. Details of Follow-up Research or Implementation Activities:

Task	**Person responsible**	**Target completion date**
1.		
2.		
3.		
4.		
5.		
6.		

5. Estimated cost, if any, for equipment, training, printing, etc.:
Small

6. Expected benefits and how they will be measured (dollar savings, time savings, etc.):
The expected benefits are quiet PCC pavements with safe performance in wet weather conditions.

7. Reasons for terminating activities related to this research project:
Project completed.

Project Closure

(Information provided by principal investigator and WisDOT project manager when final report is approved)
Date completed: April 24, 2007

Timeline and budget

1. Was the project completed on time (i.e., per the original contract between WisDOT and the performing organization)? ☐ Yes ☒ No	**1a. If not, what additional time was needed to complete the project?** **What were the reasons?** ☐ Data access ☐ Testing delay ☐ Construction delay ☐ Administrative delay ☐ Reporting/revision delay ☐ Research subcontractor delay ☒ Work plan modification
2. Was additional funding sought for this project? ☒ Yes ☐ No	**2a. If yes, how much?** $8,100 **Was the funding approved?** ☒ Yes ☐ No **For what purpose?** To provide WisDOT-suggested revisions

Partnerships and facilities

3. Did this research effort include partnerships with other universities, agencies, or other stakeholders? ☐ Yes ☒ No	**3a. If yes, please list. Include the locations of any out-of-state institutions.**
4. Indicate the location of facilities used: ☒ University ☒ Wisconsin DOT ☐ Other:	**4a. Please describe the type of laboratory and testing facilities used.** WisDOT and Marquette University libaries, WisDOT databases, WisDOT personnel, NOAA and FHWA databases, Marquette Universities computer facilities.

Student involvement

5. Were graduate students employed for this study? ☒ Yes ☐ No	**5a. If yes, how many?** 1 **Number male** **Number female** 1
6. Did any of the graduate students use this research project in a published thesis or article? ☐ Yes ☐ Not sure ☒ No ☐ N/A	**6a. Citations of published theses or articles:**
7. Were undergraduate students employed for this study? ☐ Yes ☒ No	**7a. If yes, how many?** **Number male** **Number female**
8. If known, please list the graduate students' current occupations or affiliations (e.g., continuing graduate education, employed at a public agency or private firm, etc.) and completed degrees and awarding institutions. Tribhuvan International Airport (TIA), Kathmandu, Nepal. MS in Civil Engineering, Transportation, Marquette University	**9. If known, please list the undergraduate students' current occupations or affiliations (e.g., continuing graduate education, employed at a public agency or private firm, etc.) and, where applicable, completed graduate degrees and awarding institutions.**