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16. Abstract

This report details the conception, design and implementation of the Texas Skid Accident Reduction Program. The primary objective was to develop a system which would help each District identify highway segments that are over-represented in wet weather accidents. Within each Highway District, the wet-surface-to-dry-surface ratio of accidents for the previous three year period was calculated for the entire population of on-system roads. The wet-to-dry accident ratios were then calculated for each five or ten mile segment by moving along the roadways in 1/10 mile increments. The top fifty segments which were over-represented in wet weather accidents, that is, had a ratio higher than the District as a whole, were listed. A new comprehensive listing was developed using input from the District personnel visited during the study. This listing will be disseminated to the Districts on an annual basis. The data is expected to be incorporated into ongoing District analyses of on-system roadways. The data should be one of many tools used by the Districts to help prioritize and schedule their short- and long-term maintenance and rehabilitation programs.

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Skid, Friction, "Window", Wet Weather, Texture, Drainage, Rutting, Ponding, Highway Segments, Accidents, Microtexture, Macrotexture

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# FINAL REPORT

Project 9100

# PROGRAM TO REDUCE SKID INITIATED ACCIDENTS IN TEXAS

Program Development Report 910-1F
Skid Accident Reduction Program
Safety Recommendations H-87-2

by

Don L. Ivey, Lindsay I. Griffin III,
James R. Lock and D. Lance Bullard

Prepared for

Texas Department of Transportation

August 1992

Texas Transportation Institute
Texas A&M University System
College Station, Texas 77843

# METRIC (SI*) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 2.54 | centimeters | cm |
| ft | feet | 0.3048 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| in$^2$ | square inches | 6.452 | centimeters squared | cm$^2$ |
| ft$^2$ | square feet | 0.0929 | meters squared | m$^2$ |
| yd$^2$ | square yards | 0.836 | meters squared | m$^2$ |
| mi$^2$ | square miles | 2.59 | kilometers squared | km$^2$ |
| ac | acres | 0.395 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | millimeters | mL |
| gal | gallons | 3.785 | liters | L |
| ft$^3$ | cubic feet | 0.0328 | meters cubed | m$^3$ |
| yd$^3$ | cubic yards | 0.765 | meters cubed | m$^3$ |

Note: Volumes greater than 1000 L shall be shown in m$^3$.

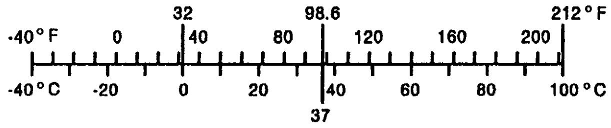
| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| yd | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| mm$^2$ | millimeters squared | 0.0016 | square inches | in$^2$ |
| m$^2$ | meters squared | 10.764 | square feet | ft$^2$ |
| yd$^2$ | kilometers squared | 0.39 | square miles | mi$^2$ |
| ha | hectares (10,000 m$^2$) | 2.53 | acres | ac |
| | | **MASS (weight)** | | |
| g | grams | 0.0353 | ounces | oz |
| kg | kilograms | 2.205 | pounds | lb |
| Mg | megagrams (1000 kg) | 1.103 | short tons | T |
| | | **VOLUME** | | |
| mL | millimeters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| m$^3$ | meters cubed | 35.315 | cubic feet | ft$^3$ |
| m$^3$ | meters cubed | 1.308 | cubic yards | yd$^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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# Implementation and Findings of the Skid Accident Reduction Program

The Texas Department of Transportation contracted with the Texas Transportation Institute (TTI) to develop a state wide program to reduce skid initiated accidents in Texas. This, a seemingly straightforward task on the surface, challenged the researchers to produce a practical, cost-effective method of identifying non-interstate segments of highway that were over represented in wet weather accidents. From the beginning it was clear what approach or methodology should not be taken, but somewhat more difficult to determine what approach should be taken.

Traditionally, TxDOT engineers are accustomed to using "Window Program" methodologies to identify suspicious roadway segments based on accident frequency. The problem with this methodology is the lack of concession made for traffic volume. Due to high traffic volumes, year after year, it is possible for the same roadway segments to appear as a problem, regardless of the relative degree of safety normalized by volume. TxDOT was required to investigate methodologies that would flag suspicious roadway segments without being specifically volume vulnerable.

Deciding that a new twist on an old idea might prove most useful, TTI used a combination of the "Control Chart" and "Window Program" methodologies based on complete Department of Public Safety accident data to determine and prioritize roadway sites over represented in wet weather accidents. The skid accident reduction program that has been developed during the course of the project is based upon a simple enabling assumption: if the ratio of wet-surface to dry-surface accidents for a given highway segment exceeds the ratio of wet-surface to dry-surface accidents for other highway segments in the immediate area, that segment is suspicious - that segment should be further evaluated to see if it would benefit from resurfacing, or from some other type of remedial treatment. Equations for identifying those highway segments that are "significantly" over represented in wet-surface accidents (and to what extent) were derived[1]. The result was a three year accident data set for non-interstate highway segments that expresses wet-weather accident experience for a highway segment in terms of the amount of "benefit" derived and statistically how the particular highway segment in question varies in terms of wet-weather accidents from the population (the average condition of district highway segments as a whole).

During the program development stages, field visits were made to TxDOT Districts that had volunteered to participate. One purpose of the visit was to develop the accident data reporting format in a form that could readily and easily be used by the District personnel. The available universe of information includes all data collected by the Texas Department of Public Safety on the ST-3 accident data recording form and the automated roadway information logs that are merged with the accident data to provide specific data for the given location. The Skid Accident Reduction Program data analysis phase provides location based information on wet and dry weather accidents. Quantitative information is given for each location and each is ranked according to the benefit that would be provided if the location had the same wet to dry ratio as the District taken as a whole.

Some constructive changes in the data presentation format were recommended by District personnel. These changes have been incorporated into the new format. Subsequent listings will reflect those changes.

TTI is prepared to supply accident data to each District on an annual basis. The data will include the previous three years' records. In most cases at least three years of data are needed to have a representatively large sample size for each segment. For the same reason, all Districts east of Interstate 35 will receive their reports with five mile windows. Each over represented location will be five miles in length. Each District west of the Interstate 35 line will receive their reports with ten mile windows. Interstate 35 provides a reasonable boundary as the annual rainfall is considerably less west of the line versus east of the line. Ten mile windows still may not have a large sample of wet weather accidents in some western Districts. These Districts do

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[1] For discussion on the development of the equations used to identify highway segments that may be over represented in wet-surface accidents, see "Proposed Program to Reduce Skid Initiated Accidents in Texas," TTI Program Development Report 9100-1, Skid Accident Reduction Program Safety Recommendations H-87-2, August 1990.

not have many wet weather days.

It was concluded that the Districts can best use the accident data late in the year to help schedule the following year's seal coat program. It is anticipated that the data may be supplied to the District offices during October of each year. The data will therefore not represent calendar years, but rather will be based on the fiscal year or third quarter reporting period.

It is anticipated that the District's Maintenance Engineer and the Traffic Engineer or their representatives could best make use of the Skid Accident Reduction Program listing. The Traffic Engineer is familiar with working with accident data and has the ability to request additional reports for each roadway segment in order to more fully investigate the type of collisions occurring. The Maintenance Engineer is familiar with the history of the pavement surface and any proposed modifications that have been scheduled.

There are four basic steps that might be taken by the District in their evaluation of the data and their wet pavement accidents.

1. The selected locations will be compared to the previous three year's maintenance program to track changes to the pavement over the reporting period. If the pavement surface or drainage has been modified in an attempt to reduce the wet pavement collisions, those changes will be documented. The District may then request post-modification accident data in an attempt to estimate the effect. The District will then determine if locations which have not been modified over the three year reporting period are scheduled for modification. These locations may warrant signing or other modifications until such work is performed. In most cases the location will fit into one of these two categories. If so, and the District is confident that the modification appropriately addressed the wet weather accident problem, then no further action is required for that particular location, with the exception of careful monitoring to verify the improvement.
2. If it is determined that the segment has not received any type of modification over the three year reporting period, and the location is not scheduled for the following year's program, the maintenance and skid records for the site may be examined. The RI-1 should be consulted to determine the geometric layout of the area. It is at this point that the Traffic Engineer might consult a more detailed listing of the location's accidents to determine the most probable causes.

3. A site visit may be made to the location to visually assess the condition of the pavement surface, the roadway drainage and the traffic characteristics that might contribute to a high demand for friction. If necessary the site may be subject to skid testing. Methods of estimating microtexture, macrotexture and degree of flushing may also be used in lieu of skid testing. These methods are described in this report.
4. Using the detailed accident data, the historical records of pavement modification, skid data and the site visit information, the Traffic and/or Maintenance engineers may determine if the site warrants modification.

If the accident data suggest a significant wet weather problem and no pavement deficiencies are found, the District may request a follow-up site visit. Prior to this visit, the accident data should be thoroughly examined to determine any factors common in the reported accidents. The Traffic Engineer may use "Case Study" to list each accident report for comparison purposes.

The data supplied under the Skid Accident Reduction Program will allow all Districts to examine the on-system roadways in a logical, consistent manner. The data, by their very nature, will control for traffic, rainfall and other factors not controlled when only accident frequencies are used.

The Skid Accident Reduction Program listings will be supplied to each District on an annual basis if TxDOT decides to fully implement the program. The accompanying User's Guide details the format, layout and information provided on the listings.

# SUMMARY

This report details the conception, design and implementation of the Texas Skid Accident Reduction Program. In an attempt to consolidate the knowledge base found in each of Texas' 24 Highway Districts, and to develop a common protocol to be used to assist the Districts in assessing the wet weather performance of the highway system, the Texas Department of Transportation contracted with the Texas Transportation Institute (TTI) at Texas A&M University to accomplish the project objectives.

The primary objective was to develop a system that would help each District identify highway segments that are over represented in wet weather accidents. This was accomplished by using the mainframe computer program "Window" to access and analyze the State's automated traffic records files. Within each Highway District wet-surface-to-dry-surface ratios of accidents for the previous three year reporting period were calculated for the entire population of on-system roads. The wet-to-dry accident ratios were then calculated for each five or ten mile segment by moving along each roadway in 1/10 mile increments. The top fifty segments that were over represented in wet weather accidents, that had ratios higher than the average of the District as a whole, were listed.

These listings were disseminated to five Districts during the second project year and in the third year to all Districts. In selected Districts TxDOT personnel and TTI field crews examined the maintenance history and maintenance schedule for each segment. Almost without exception the Districts had knowledge of the specific roadway section and had performed or had scheduled remedial measures. In several cases site visits were made to the segments to access the available friction and drainage and the demand for friction.

A new comprehensive listing was developed using input from the District personnel. TTI is prepared to disseminate this listing to all Districts on an annual basis. The Districts may incorporate the data into their ongoing analysis of on-system roadways. The data can provide another tool in the hands of District personnel to help prioritize and schedule their short and long term maintenance and rehabilitation programs.

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# I. INTRODUCTION

The determination of tractive resistance on road surfaces is older than public use of the automobile. Using horse drawn wagons, the U.S. Department of Agriculture (1) determined the rolling resistance on various road surfaces to define the economics of freight transportation before the turn of the century. The first work on stopping friction on roads in the U.S. was performed by Professor Agg at Iowa State in the middle twenties (2). Professor Agg's work was extended at Iowa State during the thirties by Ralph Moyer (3). Professors Agg and Moyer developed and used the true forerunner of the modern ASTM E-274 Friction Trailer. Based on their extensive testing of road surfaces, these pioneers reached conclusions that remain valid today. Their work was studied during the development of a comprehensive TRB State of the Art Report (4) in 1984. In the intervening years, with corroboration of the Iowa results provided by Oregon in the late thirties, much additional knowledge has been gained, but the basics have remained the same.

The First International Skid Prevention Conference was held in Charlottesville, Virginia in 1958. This conference emphasized the concern of the most progressive states working on the low pavement friction problem. Shortly thereafter, and in response to a nationally perceived need for standardization, the ASTM Committee E-17 on the measurement of tire - pavement friction was formed.

In 1962 the critical need for standardization was illustrated by the Tappahannock correlation study. It was found that the concern about unit-to-unit differences was valid and that by proper force calibration of the various trailers, much, but certainly not all, of the problems of variability, could be solved. The correlation study did give each participating state a good estimate of how each trailer compared with others. Improvements in many trailers and in the ASTM Standard resulted from that study. The Texas Highway Department (now Texas Department of Transportation) built it's first skid trailer in 1963 and soon assumed a role of leadership in the use of this device to determine the need for surface friction improvements.

During the period from the mid '60s to the present time, research and development on various aspects of pavement skid resistance have been largely concentrated in Texas. In that period, over thirty studies were conducted by the State Department of Highways and Public

Transportation and the Texas Transportation Institute. Subjects spanned the gamut of factors influencing skid initiated accidents. They included:

- construction of high friction and/or porous pavements.
- aggregate and surface polishing.
- surface micro-texture influences.
- influence of transverse and longitudinal tining of PCC surface texture and friction.
- prediction of water depth as a function of surface texture, cross slope, drainage path length and rainfall intensity.
- prediction of rainfall amounts and intensities.
- influence of rainfall on visibility.
- estimating skid numbers from texture.
- wet weather speed zoning.
- prediction and definition of hydroplaning conditions for automobile and truck tires.
- influence of water depth.
- development of a wet weather safety index.
- development of the first national skid trailer correlation and calibration center.

These efforts in Texas did not go unnoticed. The 1974 work on hydroplaning sponsored by FHWA is still considered the definitive work in pavement and geometric design criteria to minimize hydroplaning (5). Subsequent work on truck tire hydroplaning (6) and truck accident rates (7) in wet weather defined for the first time the susceptibility of unloaded tractor trailers to hydroplaning. A Texas engineer served as the Chairman of the Transportation Research Board's Committee on Surface Properties Vehicle Interaction from 1976 to 1982. Beginning with that tenure "The Influence of Roadway Surface Discontinuities (including friction variability) on Safety" was developed by the Committee and published as the Transportation Research Board's first "State of the Art" report (4). The ASTM's Kummer Lecture Award of Committee E-17 was presented in 1979 to the Texas Transportation Institute for work developing a wet weather safety index (8), and a contract was negotiated between FHWA and TTI to provide the first skid trailer correlation and calibration center in the fall of 1972 (9). This

Central Field Test Center is still providing a recognized service to states now operating friction trailers.

Texas is normally operating up to five skid trailers throughout the state, as requested by the various Districts, and has often employed both accident and friction data to reduce the number of skid initiated accidents in the state. Texas DOT is making an investment each year in surface improvement programs that is second to none. Therefore, it was with a sense of disbelief that Texas engineers read the conclusion that NTSB reached in its 1987 report NTSB/HAR-88/01, that Texas had no "statewide comprehensive program for reducing skid accidents on low coefficient of friction roads." It appears this misguided conclusion dates from a 1980 publication "Safety Effectiveness Evaluation, Selected State Highway Skid Resistance Programs" (NTSB-SEE-80-6). When the NTSB prepared that report, they referenced no fewer than seventeen Texas reports. Only five other states were referenced with California second to Texas with eight references, Missouri third with four references and Virginia, Florida and Pennsylvania with one reference each.

The problem NTSB's investigators seem to have in understanding the Texas program is in appreciating the environmental and available resource diversity in a state like Texas. It is true the skid accident reduction program varies significantly across Texas' twenty-four Districts. It is this District autonomy that has proved to be a major advantage in the State's highway organization. Construction techniques, maintenance methods and even manpower management are different in Amarillo and Harlingen, on the high plains and in the Rio Grande Valley respectively, separated north to south by over 800 miles. There is an annual rainfall of no more than 8 inches in parts of the El Paso District and in excess of 50 inches in the Beaumont District, these being separated east to west by over 800 miles of highly variable environmental and geologic conditions. In El Paso good high skid resistance aggregates are plentiful. In Beaumont almost all aggregates must be transported by barge or train from either Louisiana or central Texas. Is it so mysterious then that different Texas Districts have varying approaches to the reduction of skidding accidents?

In spite of the contributions Texas has made to definition of the problem and the high priority that skid accident reduction has traditionally been given in Texas, the Texas Department of Transportation has determined that further improvements can be made in the use of available resources. Thus, two significant studies have recently been completed. The first is devoted primarily to methods of improving friction using available aggregates and construction/maintenance techniques. The second, this study, is devoted to developing a flexible statewide program that will allow it to be adapted appropriately to Districts with the widely varying conditions encountered across Texas.

The Skid Accident Reduction Program that has been developed during the course of this project is based upon a simple enabling hypothesis: if the ratio of wet-surface-to-dry-surface accidents for a given highway segment exceeds the ratio of wet-surface-to-dry-surface accidents for other highway segments in the immediate area, that segment is suspicious - that segment should be further evaluated to see if it would benefit from resurfacing, or from some other remedial treatment.

Appropriate statistical equations for identifying those highway segments that are "significantly" over-represented in wet-surface accidents (and by what degree) have been derived. Procedures have been defined for presenting Texas traffic accident data in a format that will facilitate the identification of those highway segments which are potentially over-represented in wet-surface accidents. Engineering procedures for evaluating suspicious highway segments, i.e., highway segments that appear to be over-represented in wet-surface accidents, have been developed.

## II. IDENTIFYING ROADWAY SEGMENTS THAT ARE OVER-REPRESENTED IN WET WEATHER ACCIDENTS

Skidding accidents are a function of many variables acting singly and in concert, but, basically, all of these variables can be subsumed under two headings or factors: (1) available friction and (2) demand for friction. Available friction might be defined in terms of rainfall, pavement surface friction, and drainage; demand for friction might be viewed as a function of traffic volume, roadway geometry (e.g., vertical and horizontal curvature), among other considerations.

If available friction is high, but demand for friction is low, skidding accidents should be relatively rare events. Conversely, if available friction is low, but demand for friction is high, skidding accidents should be relatively common. For the two intermediate conditions (low available friction, low demand for friction; high available friction, high demand for friction), skidding accident frequency is undefined or less well defined (see Figure 1).

If a given segment of highway is characterized by low available friction (e.g., an $FN_{40}$ of, say, 22), and high demand for friction, there should be little debate that this segment is in need of resurfacing, at least from a friction standpoint. Similarly, if another highway segment is characterized by high available friction (e.g., an $FN_{40}$ of, say, 53), and low demand for

| Demand for Friction | Available Friction: Low | Available Friction: High |
|---|---|---|
| High | Frequent Skidding Accidents | Undefined Skidding Accidents |
| Low | Undefined Skidding Accidents | Rare Skidding Accidents |

Figure 1: A Simple, Two-Factor Description of Skidding Accidents

friction, there should be little or no debate that this segment is not in need of resurfacing. But what about the intermediate conditions?

Imagine that a two-lane rural highway with an $FN_{40}$ of 22 is located in an arid region of the state. The terrain is flat; the roadsides are clear. Crossing highways and driveways are few. Average daily traffic (ADT) is approximately 250. Demand for friction on this highway is obviously low. Nevertheless, the friction number cited, 22, is below 37, the minimum "acceptable" friction number most often quoted in the literature (e.g., Kummer and Meyer, 1967)(10). Should this segment of highway be resurfaced to reduce future wet-surface accidents? Probably not. In all likelihood, wet-surface accidents in this segment are very rare events. Resurfacing this highway would be a poor investment of funds, i.e., the same funds could be better spent at other locations to reduce more skidding accidents — and the deaths and injuries attendant to those accidents.

Consider a second example: an urban, two-lane highway with an $FN_{40}$ of 53 is characterized by a high demand for friction. Traffic is heavy throughout this segment, cross streets and driveways are common, and skidding accidents are numerous. Should this highway be resurfaced? No, not if the intent of resurfacing is to increase surface friction. An $FN_{40}$ of 53 suggests that whatever the cause or causes of wet-surface accidents at this location may be, inadequate friction is not one of them. Other explanations for the skidding accidents at this location should be sought.

### Developing Regression Equations to Identify Highway Segments That May be Over-represented in Wet-Surface Accidents

The previous discussion suggests that highway segments that are over-represented in wet-surface accidents cannot be identified solely on the basis of available friction (as measured, say, by friction number $FN_{40}$), but must consider both available friction and demand for friction.[1]

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[1] It has been suggested that the ribbed tire used in ASTM Standard E-274 is at least a partial explanation for the poor correlation between skid (friction) numbers and wet-surface accident frequency or rate. This hypothesis was considered and rejected. See "Assessing Wet Pavement Friction on Standard Reference Surfaces with Ribbed, Radial and Blank Tires," Report No. 5, Volume 2, April 1990.

An alternative method of measuring pavement friction (i.e., an alternative to ASTM E-274) was also evaluated during the course of this study.

This philosophy has been adopted in a number of studies (e.g., Ivey, Griffin, Newton, Lytton, and Hankins, 1981) (12) that have sought to predict where future wet-surface accidents will occur by regressing past "wet-surface accidents" or "wet-surface accident rate" on a variety of variables that are assumed to represent available friction (e.g., friction number ($FN_{40}$), annual rainfall, drainage, etc.) and demand for friction (e.g., roadway geometry, ADT, etc.). The objective of this philosophy is to develop equations that can accurately predict where future wet-surface accidents will occur as a function of $FN_{40}$, annual rainfall, ADT, etc.. If such equations could be developed, potentially hazardous locations could be identified and remedial measures taken before skidding accidents accumulate.

Unfortunately, the etiological complexity of wet-surface accidents guarantees that the regression approach to predicting future wet-surface accidents will always be found wanting. That is to say, regression equations are unlikely to ever be developed with sufficient predictive validity to accurately foretell where future wet-surface accidents will occur, or how many accidents will be sustained at a particular location.[2]

### An Alternative Approach to Identifying Highway Segments That May be Over-represented in Wet-Surface Accidents[3]

Instead of trying to develop traditional regression equations to predict where future wet-surface accidents will occur, the present study starts out with the basic hypothesis that all highway segments in the same geographic area should have approximately the same ratio of wet-

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This device was found to be unreliable. See "Evaluation of the Yandell-Mee Friction/Texture Device," Report No. 4, Volume 2, April 1990.

[2] For more discussion on the complexity of wet-surface accidents, and the factors associated with wet-surface accidents, see "A Preliminary Analysis of Wet Surface Accidents on Rural, Two-Lane Highways in the State of Texas," Report No. 1, Volume 2, May 1989 and "A Description of Wet-Surface Accidents on Rural, Two-Lane Highways in the State of Texas," Report No. 3, Volume 2, August 1989. For a demonstration of the difficulty and imprecision inherent in predicting wet surface accident frequency or rate on the basis of selected roadway, friction and traffic variables, see "A Reanalysis of Wet Weather Accident Data Contained in a Report by Rizenbergs, Burchett and Warren (1976)," Report No. 2, Volume 2, July 1989.

[3] The balance of this section is adapted from, and in places taken verbatim from, "Identifying Highway Control Sections that May be Over Represented in Wet-Surface Accidents," Report No. 6, Volume 2, August 1990.

surface-to-dry-surface accidents. Those segments that have a ratio exceeding other segments in the area are defined as "suspicious" and selected out for further consideration.

In the discussion that follows, highway segments will, as a matter of convenience, be defined in terms of control sections. And, the geographic areas surrounding individual control sections will be defined by the highway District in which the control section is located.

Consider the following example: a particular highway segment, control section 47.12, is selected from District 1. This control section sustained 153 wet-surface (W) and 263 dry-surface (D) accidents between 1986 and 1988 (Table 1). The ratio of wet-to-dry surface accidents in control section 47.12 is, therefore, 0.58 (153/263). During this same time period, however, the overall ratio (R) of wet-to-dry surface accidents in District 1 is 0.22 (2,527/11,651). Because the wet-to-dry ratio for control section 47.12 is substantially larger than the District-wide average, we might reasonably ask: if control section 47.12 is no more prone to wet-surface accidents than other control sections throughout the District, might a ratio this large (or larger) have occurred five or more times in a hundred by chance?

To answer this question we will make use of the following equation based upon the standard normal (Z) distribution:[4]

$$Z = \frac{(W - RD)}{\sqrt{(W + D)R}} \qquad (1)$$

A Z score of +1.65 (or higher) would not be expected by chance more than five times in a hundred if the control section in question were typical of other control sections in the District. In this particular example, the derived Z score is 10.10, a score that is highly unlikely if the "true" wet-to-dry accident ratio for control section 47.12 were really 0.22.

Figure 2 may help to explain the wet-to-dry surface accident ratio (R) for a highway District — and how the various control sections in the District compare to R. Figure 2 is based upon accident data taken from District 1 for calendar years 1986 through 1988.

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[4] Eq 1 is derived in Appendix A of Report No. 6, Volume 2.

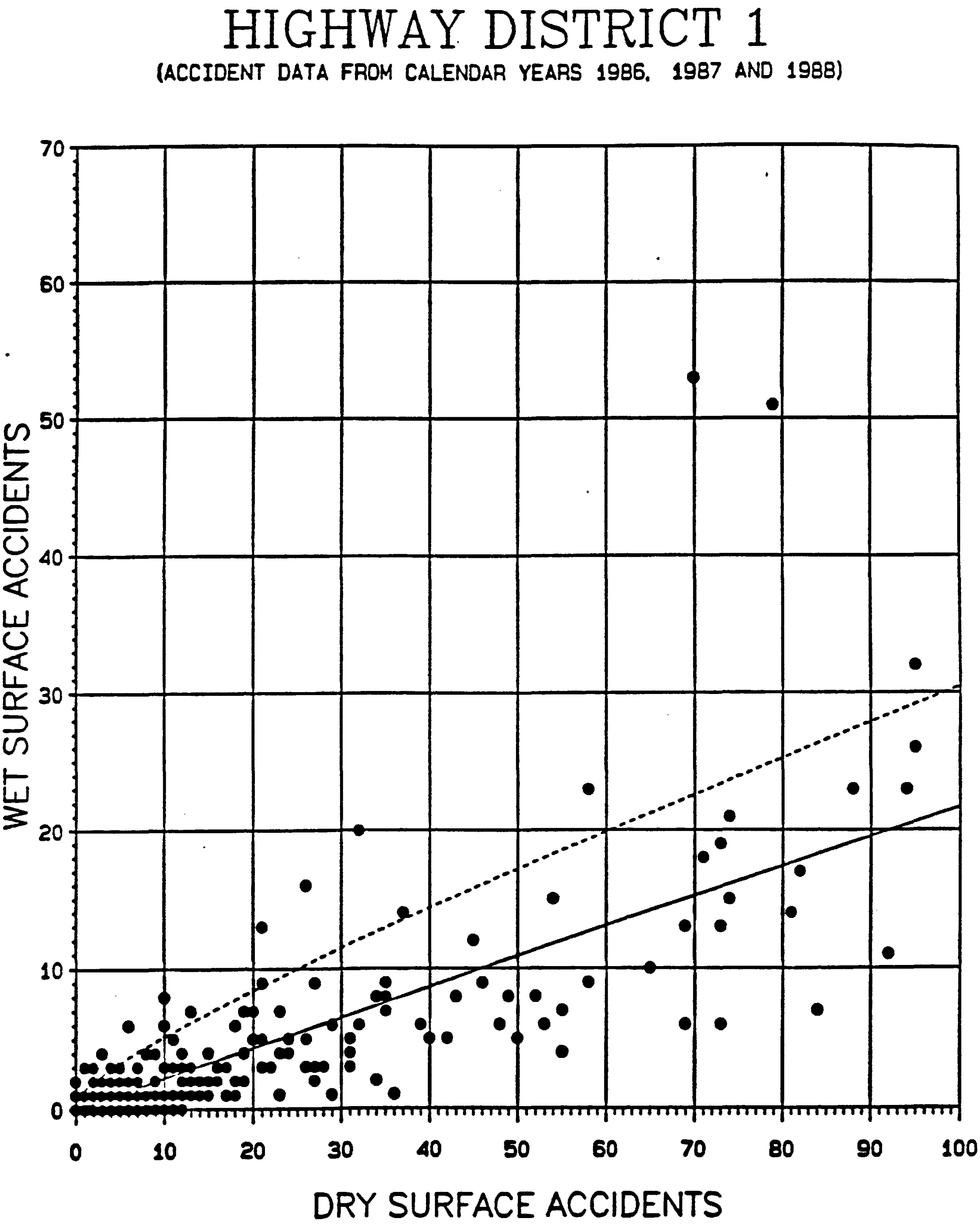

Figure 2: Wet and Dry Surface Accidents Recorded in Each Highway Control Section in District 1

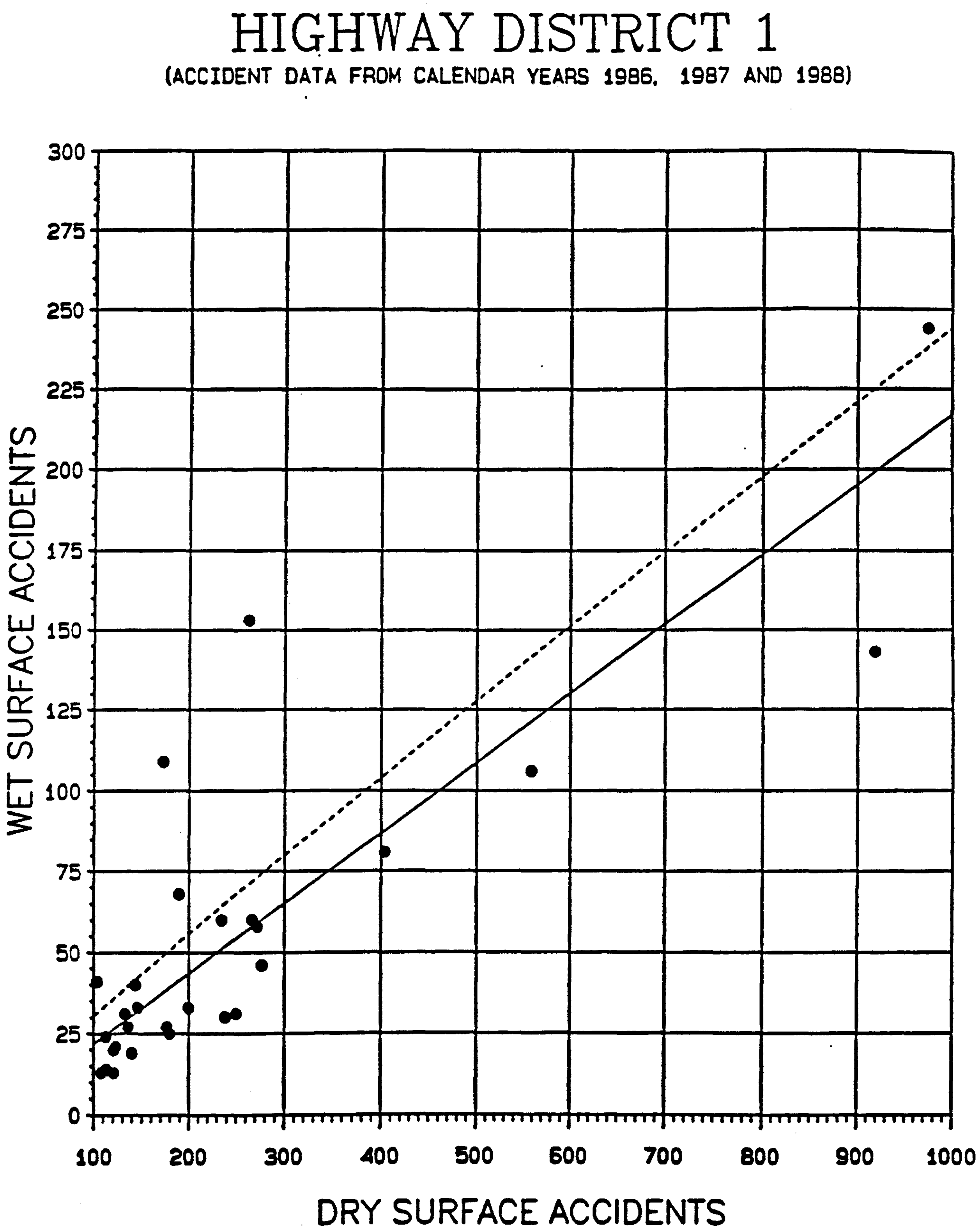

Figure 2: Wet and Dry Surface Accidents Recorded in Each Highway Control Section in District 1 (Continued)

The solid line in Figure 2 represents R. The slope on this line is 0.22. The dots scattered around this line represent highway control sections. Those dots that fall above the line depict control sections with "above average" wet-to-dry surface accident ratios. These control sections are potentially over-represented in wet surface accidents.

Those points that fall above the dashed line in Figure 2 represent control sections with wet-to-dry surface accident ratios that are "significantly" above the District average. Points above the dashed line would not occur more than five times in a hundred by chance if those control sections really had wet-to-dry surface accident ratios of 0.22.[5]

Table 1 rank orders the control sections in District 1 by the degree to which individual control sections appear to be over-represented in wet-surface accidents. The column labeled "BENEFIT" provides an estimate of the reductions in wet-surface accidents required to bring the wet-to-dry surface accident ratios for individual control sections into line with the District average. BENEFIT is calculated with the following equation:

$$\text{BENEFIT} = W - DR \tag{2}$$

By way of example, consider the first control section listed in Table 2. This control section (47.12) sustained 153 wet-surface accidents (W) — 95.96 more wet-surface accidents than expected, based upon (1) the District-wide, wet-to-dry surface accident ratio (R) of 0.21689 and (2) the fact that this control section sustained 263 dry-surface accidents (D). If this control

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[5] The equation for the dashed line in Figure 2 is derived from Eq 1 by rearranging terms and expressing W (wet surface accidents) as a function of D (dry surface accidents).

$$W = \frac{Z^2R + 2DR + \sqrt{(Z^2R + 2DR)^2 - 4\,(D^2R^2 - Z^2DR)}}{2}$$

In Figure 2, Z is set to +1.65 (the critical value of Z for a one-tailed test with $\alpha$ equal to 0.05). R is set to 0.22 (the ratio of wet-to-dry surface accidents in District 1).

Table 1: A Rank Ordering of the Control Sections in District 1 that May be Over Represented in Wet Surface Accidents

HIGHWAY DISTRICT 1
(ACCIDENT DATA FROM CALENDAR YEARS 1986, 1987 AND 1988)

| OBS | CNTL-SEC | WET | DRY | BENEFIT | Z | R |
|---|---|---|---|---|---|---|
| 1 | 47.12 | 153 | 263 | 95.9576 | 10.1021 | 0.21689 |
| 2 | 45.03 | 109 | 173 | 71.4778 | 9.1396 | 0.21689 |
| 3 | 730.02 | 53 | 70 | 37.8176 | 7.3218 | 0.21689 |
| 4 | 47.01 | 51 | 79 | 33.8656 | 6.3777 | 0.21689 |
| 5 | 47.02 | 244 | 975 | 32.5310 | 2.0007 | 0.21689 |
| 6 | 202.08 | 68 | 190 | 26.7907 | 3.5814 | 0.21689 |
| 7 | 83.02 | 41 | 104 | 18.4433 | 3.2888 | 0.21689 |
| 8 | 83.11 | 20 | 32 | 13.0595 | 3.8887 | 0.21689 |
| 9 | 45.06 | 32 | 95 | 11.3953 | 2.1712 | 0.21689 |
| 10 | 728.02 | 23 | 58 | 10.4203 | 2.4861 | 0.21689 |
| 11 | 610.01 | 16 | 26 | 10.3608 | 3.4328 | 0.21689 |
| 12 | 10.02 | 60 | 235 | 9.0306 | 1.1290 | 0.21689 |
| 13 | 2455.01 | 40 | 144 | 8.7677 | 1.3879 | 0.21689 |
| 14 | 2453.02 | 13 | 21 | 8.4453 | 3.1100 | 0.21689 |
| 15 | 749.01 | 14 | 37 | 5.9750 | 1.7965 | 0.21689 |
| 16 | 546.05 | 8 | 10 | 5.8311 | 2.9512 | 0.21689 |
| 17 | 45.05 | 26 | 95 | 5.3953 | 1.0532 | 0.21689 |
| 18 | 45.18 | 21 | 74 | 4.9500 | 1.0905 | 0.21689 |
| 19 | 728.03 | 6 | 6 | 4.6987 | 2.9125 | 0.21689 |
| 20 | 400.03 | 9 | 21 | 4.4453 | 1.7427 | 0.21689 |
| 21 | 546.06 | 7 | 13 | 4.1804 | 2.0072 | 0.21689 |
| 22 | 410.01 | 23 | 88 | 3.9136 | 0.7976 | 0.21689 |
| 23 | 767.01 | 6 | 10 | 3.8311 | 2.0566 | 0.21689 |
| 24 | 579.02 | 4 | 3 | 3.3493 | 2.7182 | 0.21689 |
| 25 | 136.07 | 15 | 54 | 3.2879 | 0.8499 | 0.21689 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 42 | 174.02 | 4 | 9 | 2.0480 | 1.2196 | 0.21689 |
| 43 | 91.01 | 7 | 23 | 2.0115 | 0.7886 | 0.21689 |
| 44 | 1292.03 | 2 | 0 | 2.0000 | 3.0366 | 0.21689 |
| 45 | 2606.01 | 2 | 0 | 2.0000 | 3.0366 | 0.21689 |
| 46 | 769.02 | 3 | 5 | 1.9155 | 1.4542 | 0.21689 |
| 47 | 1475.01 | 2 | 2 | 1.5662 | 1.6815 | 0.21689 |
| 48 | 510.05 | 3 | 7 | 1.4818 | 1.0061 | 0.21689 |
| 49 | 730.03 | 3 | 7 | 1.4818 | 1.0061 | 0.21689 |
| 50 | 401.01 | 9 | 35 | 1.4088 | 0.4560 | 0.21689 |

section were resurfaced, and if, thereby, wet-surface accidents were reduced to such a degree that the wet-to-dry ratio for control section 47.12 were now equal to the District-wide average, the estimated benefits of resurfacing, measured in reduced wet-surface accidents, would equal 95.96, over a three year period.[6]

Before we take the data in Table 1 too seriously (and assume that control sections with large potential benefits and significant Z's should be resurfaced), it behooves us to carry out other analyses to see if we can explain why certain control sections appear to be over-represented in wet-surface accidents. Consider the data in Table 2.

Table 2: Highway District 1 Wet-to-Dry Accident Ratios
by Population, Traffic (ADT) and Number of Lanes
(Accident Data from Calendar Years 1986, 1987 and 1988)

| POP | ADT | LANES | WET SURFACE ACCIDENTS | DRY SURFACE ACCIDENTS | WET/DRY |
|---|---|---|---|---|---|
| RURAL | < 1000 | 2 LANES | 175 | 874 | 0.20023 |
| RURAL | 1000-4999 | 2 LANES | 425 | 2294 | 0.18527 |
| RURAL | 1000-4999 | > 2 LANES | 4 | 56 | 0.07143 |
| RURAL | 5000-9999 | 2 LANES | 172 | 663 | 0.25943 |
| RURAL | 5000-9999 | > 2 LANES | 47 | 232 | 0.20259 |
| RURAL | 10000+ | 2 LANES | 11 | 94 | 0.11702 |
| RURAL | 10000+ | > 2 LANES | 122 | 546 | 0.22344 |
| URBAN | < 1000 | 2 LANES | 4 | 28 | 0.14286 |
| URBAN | < 1000 | > 2 LANES | 2 | 3 | 0.66667 |
| URBAN | 1000-4999 | 2 LANES | 122 | 510 | 0.23922 |
| URBAN | 1000-4999 | > 2 LANES | 41 | 212 | 0.19340 |
| URBAN | 5000-9999 | 2 LANES | 289 | 1083 | 0.26685 |
| URBAN | 5000-9999 | > 2 LANES | 262 | 886 | 0.29571 |
| URBAN | 10000+ | 2 LANES | 82 | 609 | 0.13465 |
| URBAN | 10000+ | > 2 LANES | 769 | 3561 | 0.21595 |
| | | | 2527 | 11651 | |

In Table 2, wet-to-dry surface accident ratios for District 1 are broken down by population (urban/rural), traffic (< 1000, 1000-4999, 5000-9999, 10000+), and number of lanes (2, >2). As we see from this table, certain population-traffic-lane combinations may be

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[6] Resurfacing is assumed to have no effect on dry-surface accidents.

associated with wet-to-dry accident ratios that are higher than the District-wide average. Thus, if a given control section appears to be over-represented in wet-surface accidents, that over-representation might result from the section's population-traffic-lane affiliation, rather than from some inherent deficiency in surface properties. In District 1, for example, urban highways with more than two lanes that carry 5000 to 9999 vehicles per day are associated with a wet-to-dry ratio of 0.30, rather than the District-wide average of 0.22. Accordingly, if a given urban, four-lane control section in District 1 carrying, say, 7500 vehicle per day is found to have a wet-to-dry surface accident ratio of 0.30, we should not be at all surprised, even though such a ratio might be "significantly" above the District-wide average. On the other hand, if this particular control section has a wet-to-dry ratio of 0.40, we might want to reapply Eq 1, and set R equal to 0.30 rather than 0.22. If we still obtain a significant Z when Eq 1 is reapplied, and a large potential reduction in wet-surface accidents (Eq 2), we will want to look more closely at this control section.

As an alternative to reapplying Eq 1, a nomograph has been prepared to facilitate re-evaluating control sections that may be over-represented in wet-surface accidents (Figure 2). The equation underlying the functions in Figure 3 is defined in Footnote 5. To use this nomograph, select R: a wet-to-dry ratio (0.10 to 0.30) against which a given control section is to be evaluated. Move to the right of the origin by an amount equal to the number of dry-surface accidents sustained in the control section. Move vertically by an amount equal to the number of wet-weather accidents sustained. If the resulting point lies above the function representing R, the section is "significantly" over-represented in wet-surface accidents.

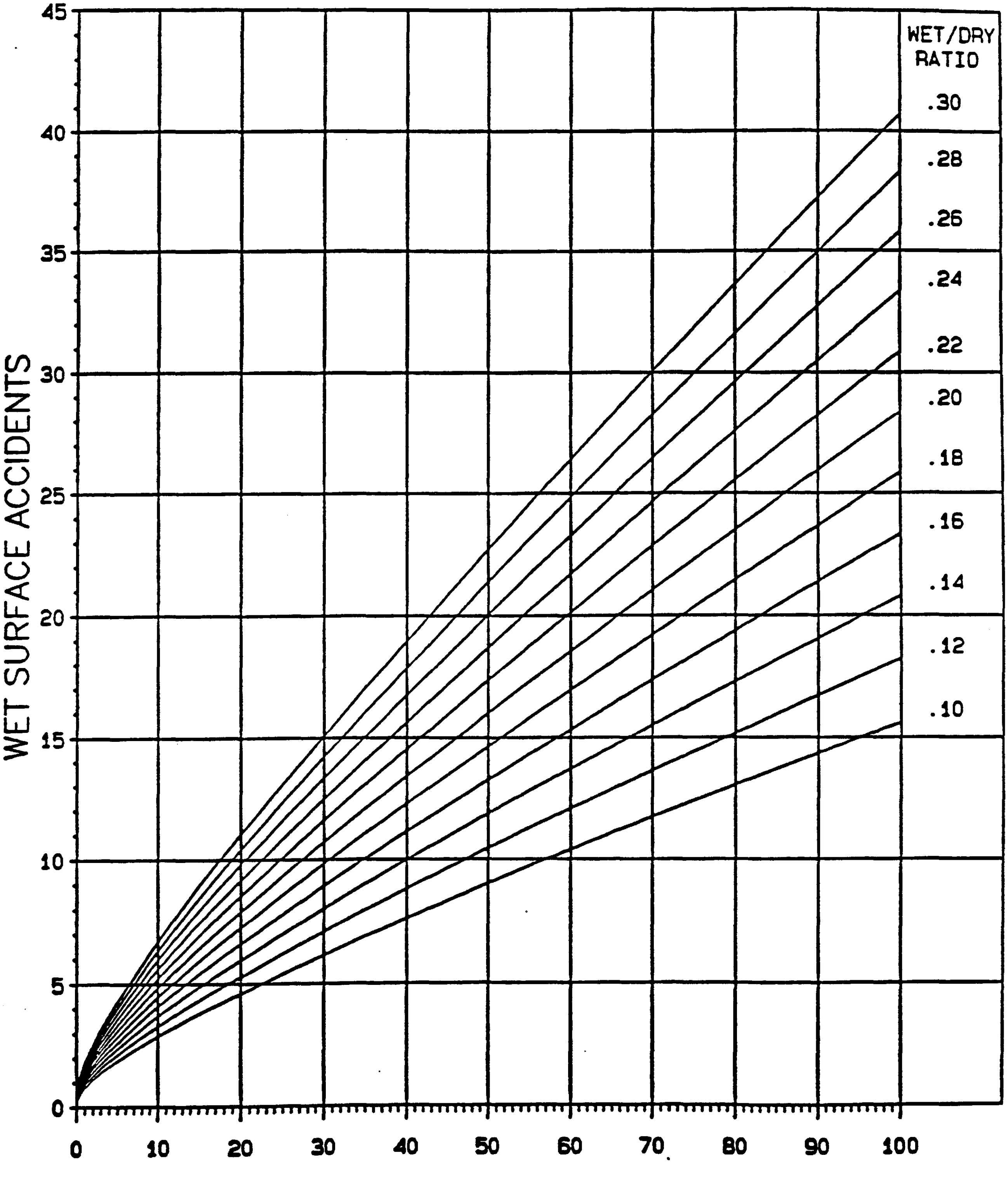

Figure 3: Nomograph for Identifying Highway Segments That May be Over Represented in Wet Surface Accidents

## III. TEXAS SKID ACCIDENT REDUCTION PROGRAM

From inception, the objective of the skid accident program was to produce the most effective method of reducing accidents at a cost that would be considered reasonable by the people of Texas. The "golden sledge hammer" approach was considered grossly inappropriate, as it has been since the First International Skid Prevention Conference in 1958. This approach is simple, costly in the extreme, and guarantees an ineffective use of funds for accident reduction. It would involve the periodic testing of 72,000 miles of Texas highways using a skid trailer, followed by the immediate resurfacing of all lane miles where the skid resistance falls below some arbitrary level, such as the 35 value so popular with NTSB. The "golden sledge hammer" approach is analogous to putting on an entire roof every time three shingles need replacing.

It is often clear what should not be done, while more difficult to determine clearly what should be done. Criteria which were used in efforts to determine the latter follow:

1. The program must be effective in reducing accidents.
2. The program should use to the best advantage the major resources available, e.g.:
    - accident data and analytical expertise,
    - expertise in causal relationships,
    - friction test devices,
    - local knowledge of roadway friction conditions.
3. The program must be practical for District participation.
4. The program must be implementable at a reasonable cost.

In developing the program proposed here, the key resources of the two participating organizations were arranged to enhance economic effectiveness.

Texas Department of Transportation

- Division 8Pav - Management of skid trailer operations and site analysis.
- Districts - Current knowledge of conditions, construction and maintenance procedures and site analysis.

Texas Transportation Institute

- Division III - Accident records, data analysis, interpretation of available friction, causal relationships and site analysis.

The proposed program is illustrated by the flow diagram of Figure 4. The three groups involved are Texas DOT Districts, Texas DOT Division 8Pav and TTI. The individual functions are shown in blocks labeled (a) through (f). In this section the functions are described.

After the first study year and before significant time had been spent in the Districts, TTI proposed the somewhat complex program illustrated by Figure 5. As visits to District offices and roadway sites began during trial implementation of the program, it was quickly evident that the proposed program was unrealistically complex. In District after District it was found an in house, sometimes relatively informal, program was in place to identify low friction areas and correct them within reasonable time periods, periods defined by the perceived severity of the problem.

During this period the writers became aware that the complex interaction of Division, District and TTI was unnecessary. What would be of practical help was supplying, on a yearly basis, the wet weather accident statistics for each District. This would then be consulted as the yearly District seal coat program was developed. This redundancy in the program would further assure that no critical sites would be overlooked. Based on this information and in response to this opinion, a simplified program was developed which is illustrated by Figure 4.

*TTI*

a. Based on complete Department of Public Safety accident data available in TTI's Safety Division for the preceding three years, roadway sections in each participating District will be defined in terms of wet weather accident experience. Those sites that are over-represented in wet weather accidents will be determined and prioritized using a combination of the "Control Chart" and "Texas Reference Marker System" methodologies. These techniques, developed to suite the needs of this program, are described in section II of this report.

b. The prioritized sites discovered in (a) will be supplied by TTI directly to the participating Districts.

## FIGURE 4
## PROPOSED TxDOT SKID ACCIDENT REDUCTION PROGRAM

| TTI | TxDOT District | TxDOT Division |
|---|---|---|
| Accident Data Analysis Determination of over-represented sites within Districts using modified "Window Program" and "Control Chart" technology. (a) | Monthly survey of all District Highways to determine any Condition C sites. (c) | Determine ASTM E-274 FN's on sites requested by Districts. (f) |
| Supply prioritized list of suspect sites to Districts. (b) | Quick response signing and/or maintenance on Condition C sites. (d) | |
| | Prioritize sites for maintenance and seal coat program considering the prioritized "Benefit" values supplied by TTI. (e) | |

# FIGURE 5
# PROPOSED TxDOT SKID ACCIDENT REDUCTION PROGRAM ORGANIZATIONAL RESPONSIBILITIES

## TTI

Accident Data Analysis Determination of over-represented sites within districts using modified "Window Program" and "Control Chart" technology. (a)

Supply prioritized list of suspect sites to District. (b)

Secure and analyze "case study" records and/or hard copy accident reports for selected Cond. A & B sites. (c)

Provide Level 2 Team Members. (d)

Document changes District makes in roadway section and post modification accident history (for Benefit/Cost records). (e)

## TxDOT District

Weekly survey of all Dist. Highway's location of condition "C" sites. (f)

Quick response signing and/or maintenance of Condition "C" sites. (g)

Level 1 Team investigation of prioritized sites to determine site condition. (h)

Verify condition from maintenance records. (Has site been modified?) (i)

If site is Condition C notify maintenance for quick response. (j)

If site is condition A or B notify Division of FN requirement. (k)

Provide Level 2 Team members. (l)

Level 2 Team survey and analysis of Condition B District sites. (m)

Recommendations for possible modification of Condition B District sites. (n)

Document post modification drainage evaluation when drainage is modified. (o)

## TxDOT Division

Determine ASTM E-274 FN's on Condition "B" sites. (p)

Provide Level 2 Team Member. (q)

Document post modification FN documentation when surface is modified. (r)

*Texas DOT Districts*

c. One or more individuals in the Maintenance office will be trained to recognize Condition C sites from both the friction and drainage viewpoints. This/these individual(s) will periodically inspect all District highways. Any conditions appearing to be in the C category will be reported to the Maintenance Engineer. (Condition C, defined in more detail in the next section, is "a zone of available friction that is inadequate even for design maneuvers.")

d. The Maintenance engineer will determine the appropriate immediate response if the site identified in (c) is indeed a Condition C. Signing or low cost surface treatments are short term options. Geometric traffic and conflict aspects of the site will also be documented.

e. The Maintenance engineer will use the "Benefit" provided as one input to prioritize maintenance efforts and the seal coat program.

*Texas DOT Division*

Division 8Pav will use the ASTM E-274 trailers to provide FNs for specific sites requested by the Districts and will also act as a District resource in determining reasons for high levels of wet accident/dry accident ratios.

### Discussion

The responsibilities of TTI in the Texas Skid Accident Reduction Program are basically twofold. First, TTI will identify those highway segments that may be over-represented in wet-surface accidents and develop a list of candidate segments (by District) that are deserving of further consideration and investigation. To identify highway segments that may be over-represented in wet-surface accidents, the same methodological and statistical procedures discussed previously will be employed. Rather than identifying individual control sections that may be over-represented in wet-surface accidents, all possible highway segments of a fixed length within a highway District will be considered. The ability to search through "all possible" fixed length highway segments within a District was accomplished by modifying an existing computer program developed by TTI for Texas DOT, the WINDOW program (11).

The WINDOW program, as modified to meet the requirements of the Texas Skid Accident Reduction Program, can be thought of as an algorithm or procedure that carries out the following four steps during execution:

(1) Control sections within each highway District are strung together in "going-down-the-road" order to create "tracks," i.e., extended lengths of highway that typically range from one end of a District to another.

(2) A "window" of fixed length, say, 2, 5 or 10 miles (defined by the user), is then passed down each track in 0.1 mile increments. The first window on a track might extend from 0.0 to 4.9. The second window would extend from 0.1 to 5.0. The third from 0.2 to 5.1, and so on.

(3) For each window created by the program, wet-surface and dry-surface accidents within that window are tallied. The resultant Z score and BENEFIT associated with each window will be calculated as part of the yearly report to each District.

(4) Individual windows are then rank ordered on BENEFIT, and information from the first 50 windows is printed out in a format very similar to that shown in Table 2.[7]

Second, TTI will take these rank orderings of windows (one rank ordering for each District) and try to ascertain if particular windows are over-represented in wet-surface accidents due to some extraneous factor or factors that may be unrelated to available friction (e.g., intersection, traffic volume, number of lanes, urban/rural, etc.). Those windows that cannot be explained and those windows that still appear to be over-represented in wet-surface accidents will be sent to the Districts. The District may also request that the CASESTUDY program be used to provide more insight to particular site problems. When the CASESTUDY program is executed, summary copies of all accident reports for all wet-surface accidents that occurred in the segment during the study period (typically a two or three year period) are output — one page per accident. By reading through these summary reports, it is often possible to determine why accidents are occurring at a given location. If more detailed information is still needed after the

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[7] The control sections shown in Table 1 will be replaced by beginning and ending reference markers for each of the 50 windows output by the program.

CASESTUDY reports have been read, that information may be sought from the Department of Public Safety in the form of hard copy reproductions or individual accident reports.

## IV. ESTIMATING THE NEED FOR FRICTION

It has long been understood that the required level of available tire/pavement friction is a function of the vehicle maneuvers that are attempted on that surface. If all controlled accelerations are imparted to a vehicle through the tires, the tire control forces are limited by the tire/pavement available friction. It is traditional to represent control forces in terms of g's, or decimal parts of the acceleration of gravity. For example, AASHTO (13) assumes the development of about 0.3 g's in calculating stopping sight distance and about 0.1 g's for the allowable lateral acceleration on a curve for curve design purposes. Other values have been estimated for passing maneuvers, and emergency path correction maneuvers (14). Kummer and Meyer (10) prepared a definitive evaluation of most of these maneuvers in arriving at the skid resistance values contained in the classic NCHRP 37.

Unfortunately, achieving or not achieving the various levels estimated by these studies seems to have little to do with wet weather accident rates in general. Although generally higher levels of friction seem to reduce accident rates somewhat, it is not yet possible to accurately predict how changing the level of skid resistance will achieve accident reductions at a specific site. This is usually found to be true unless the skid resistance at a site is extremely low, and the site also has a significant number of skid initiated accidents. In that case, the seemingly obvious is often true, i.e. raising the level of available friction will reduce skid initiated accidents.

The program suggested here is an effort to bring limited resources to bear on those parts of the highway system where changes in available friction, roadway geometry or signing will result in significantly decreasing wet weather accidents. In this effort Figure 6 has been developed. Friction numbers from zero to fifty (friction values from 0 to 0.5) are compared to a Friction Demand Index (FDI) given values from one to five. An FDI of 1 is an area where the demand for friction is extremely low (e.g. a low volume rural road which is comparatively level with only long radius curves). An FDI of 5 might be associated with a highway intersection resulting in serious traffic conflicts. If one were intelligent and/or intuitive enough, every roadway situation could be assigned a reasonable FDI. Figure 6 has been roughly divided into three zones: Condition A, a zone of available friction that is adequate for all but the most

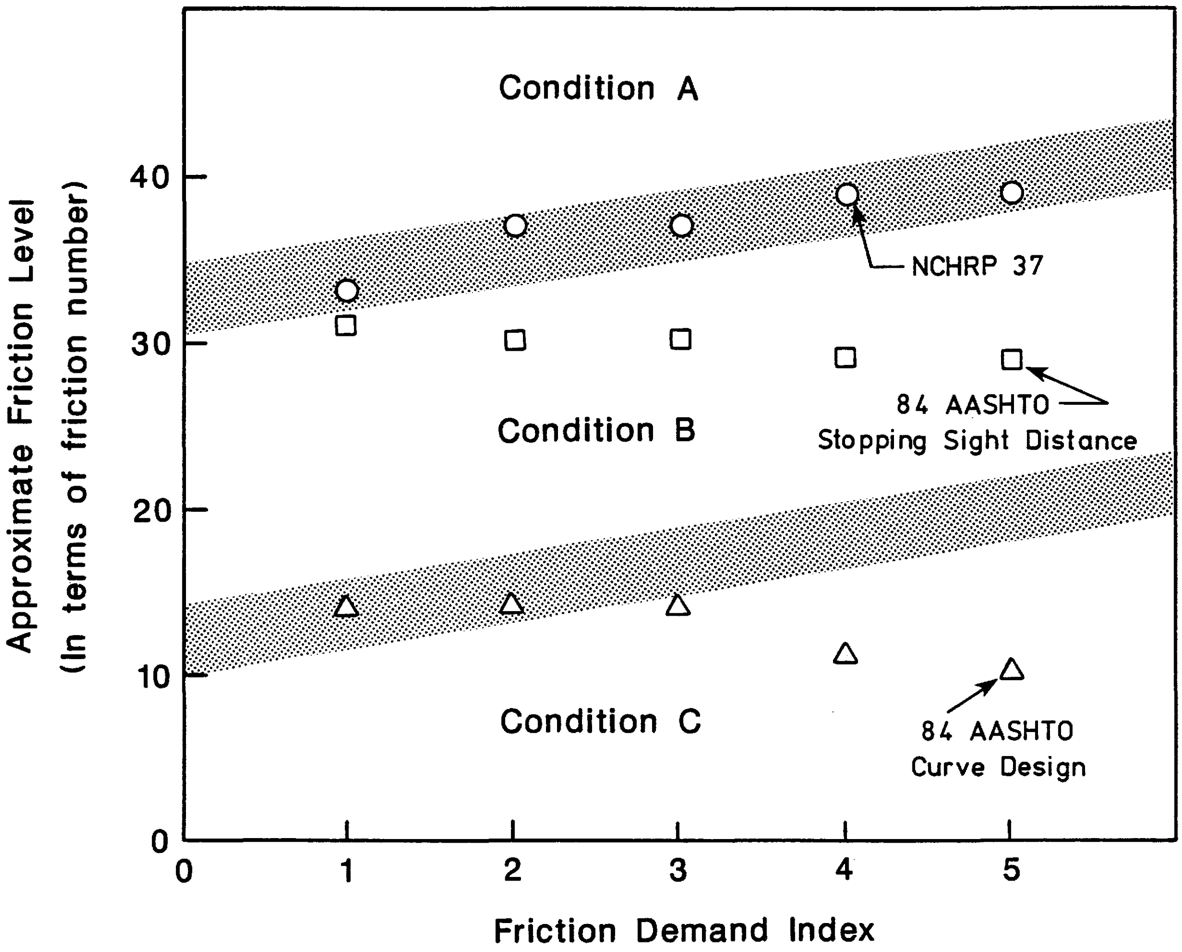


Figure 6. Tentative Condition Boundaries

precipitous emergency maneuvers; Condition B, a zone of available friction that is representative of the friction needed for design maneuvers but may not be adequate for many emergency maneuvers; and Condition C, a zone of available friction that is inadequate even for design maneuvers.

There is a hazy division between these zones. This is because the division is not precise and may be even more ill defined than the width of the shadowed zone presented. It is reasoned that the level of the division between Conditions A-B and B-C should be higher as the FDI increases. Simply put, the higher the potential demand for friction, the higher the level of friction needed to accommodate the demand. The division between A and B follows the trend of NCHRP 37 if one allows a mean traffic speed of 30 mph to be equivalent to an FDR value of 1 and a mean traffic speed of 55 mph to be equivalent to an FDR value of 5. Above this boundary available friction will have no significant influence on accidents. Below this line an influence on certain types of accidents is possible.

The shaded zone between Condition B and Condition C is less well defined by vehicle control requirements and better defined by accident analysis experience. While a number of studies have shown the ill-defined but significant trend to higher skid accident rates as friction number values descend into the twenties, there does not seem to be some level below which the rates increase dramatically. The reason for this may be that so few sites are allowed to exist with friction values between 10 and 20. McCullough and Hawkins (15) show no values below 20, Rizenbergs et al. (16) and Schultz (17) show no values below 17, Schlosser (18) shows no values below 28. An exception seems to be in the work of Giles (19), who shows a precipitous rise in the "Liability to be a Skid Accident Site" as the "Side Force Coefficient" goes from 0.4 to 0.3. Ivey et al. (12) previously estimated that this side force coefficient range was probably consistent with a Skid Number (now Friction Number) variation from as low as 15 to as low as 10, reinforcing the selection of the 10 to 20 shaded zone as an appropriate boundary for dividing Condition B and Condition C. This boundary would encompass the 84 AASHTO curve design friction requirements but clearly would not satisfy the friction requirements for stopping sight distances (13).

Finally, it must be acknowledged that these divisions into conditions A, B and C are somewhat arbitrary, and may be considered at best a reasonable beginning estimate. As implementation of this program gains momentum, and the investigation of a number of over-represented sites is completed, there may be good cause to shift these boundaries.

## V. FRICTION DEMAND INDICES

In order to effectively use Figure 6 to classify a section of roadway, it is sometimes necessary to determine a Friction Demand Index (FDI). The words "sometimes necessary" are used because of the relative insensitivity of the boundaries to FDI. In the simplest site surveys, it is only possible to classify the surface as A, B or C, so the FDI will be of importance only from the viewpoint that Condition B situations should be given a higher priority if they occur where FDI is high. Condition C situations would be given a high priority no matter what the FDI.

FDI values will be of greater importance when skid trailers are used to develop accurate FN values at over-represented sites. With known values of FN, the sites can be accurately classified as falling into Conditions A, B or C. In order to develop guidance in estimating FDI's, Tables 3, 4 and 5 are provided. Table 3 gives a guide for estimating FDI values based primarily on traffic speed and roadway geometry. The influence of speed on demand for friction is shown along with factors such as vertical and horizontal curve characteristics.

Table 4 gives the influences on FDI of specific horizontal curve characteristics. Seemingly, there is a duplication of the consideration of horizontal curves. Table 3, however, is appropriate to the roadway in general, including curves, while Table 4 is specific to the curves. The higher value of FDI should always be used if more than one value is implied by the tables.

Table 5 gives FDI values for various characteristics of grade intersections. Note there is again a seeming duplication of the consideration of intersections, but as in the case of horizontal curves, Table 3 is appropriate to the overall roadway, while Table 5 is specific to intersections. It is expected that Tables 3, 4 and 5 will require modification and possibly expansion as field experience is gained.

# TABLE 3

## FRICTION DEMAND INDEX (SELECTION 1)

| FRICTION DEMAND INDEX | ROADWAY GEOMETRY CONDITIONS |
|---|---|
| 1 | Mean traffic speeds less than 45 or rural road with straight tangents and/or long radius curves with few visibility problems (e.g. those visibility problems caused by vertical curves or intersections). |
| 2 | Mean traffic speeds less than 55 or highways with low access on straight tangents and long radius curves with few visibility problems. |
| 3 | Mean traffic speeds less than 55 or highways with medium access and long radius curves. No extreme visibility problems. |
| 4 | Mean traffic speeds less than 65 and highways with low access and long radius curves. No extreme visibility restrictions. |
| 5 | Mean traffic speeds less than 65 or highways with medium or high access levels, medium or sharp curves or significant visibility restrictions. |

Definitions

| | |
|---|---|
| gradual curves | $D \leq 2°$ |
| medium curves | $2° < D \leq 5°$ |
| sharp curves | $D > 5°$ |

# TABLE 4
# FRICTION DEMAND INDEX (SELECTION 2)

| FRICTION DEMAND INDEX | HORIZONTAL CURVES |
|---|---|
| 1 | Mean approach traffic speeds less than curve design speed or advisory speed signing not required. ($D \leq 2°$) |
| 2 | Mean approach traffic speeds less than curve design speed or advisory speed signing not required. ($2° < D \leq 5°$) |
| 3 | Mean approach traffic speeds less than curve design speed or advisory speed signing not required. ($D > 5°$) |
| 4 | Mean approach traffic speeds more than curve design speed. (Advisory speeds > 10 mph below posted speed.) |
| 5 | Mean approach traffic speeds more than curve design speed. (Advisory speeds > 20 mph below posted speed.) |

## TABLE 5

## FRICTION DEMAND INDEX (SELECTION 3)

| FRICTION DEMAND INDEX | GRADE INTERSECTIONS |
|---|---|
| 3 | Mean approach speeds less than 45, unlimited visibility and MUTCD advance signing. |
| 4 | Mean approach speeds less than 55, good visibility and MUTCD advance signing. |
| 4 | Mean approach speeds less than 55, limited visibility and MUTCD+ signing and marking. |
| 5 | Mean approach speeds less than 65, good visibility and MUTCD advance signing. |
| 5 | Mean approach speeds less than 65, limited visibility and MUTCD+ signing and marking. |

Definitions:

MUTCD - minimum requirements stated.

MUTCD+ - minimum requirements stated plus addition optional signing or marking allowed by MUTCD.

Unlimited visibility - vision of intersection and advance signing is unlimited by roadway geometry or roadside obstructions.

Good visibility - the intersection can be seen at the same time the MUTCD advance signing can be seen.

Limited visibility - some of the MUTCD advance signing must be placed before the intersection is visible.

## VI. PAVEMENT FRICTION EVALUATION

### Overview

In order to determine the relative tire-pavement friction available from a particular interface, the surface characteristics or friction resistance of the asphaltic concrete pavement must be identified and quantified. Friction resistance is a quantification of the pavement's ability to prevent vehicle skidding under normal and emergency conditions. While this quantification may be obtained by using a locked-wheel skid trailer (ASTM E-274), it is not necessary to skid all of the highways in each District on a continuous basis. In many cases it would be a significant waste of safety funds.

There are four basic levels of data collection techniques currently employed in assessing and documenting the skid resistance of a particular pavement.

### Research Method

The first level of data collection and analysis would be considered a research method and as such uses the most accurate, consistent, expensive and cumbersome equipment. This approach is used by many research agencies and highway departments. The ASTM E-274 locked wheel skid trailer is by far the most accepted and popular skid resistance measurement tool used in the United States. With this system a surface is wetted to a calculated average depth of 0.020", and a 40 mile per hour locked wheel friction number is obtained. These measurements are typically taken in the left wheel path. The skid trailer is used by some Districts for pavement inventory purposes, and by others for spot checks.

The research method also employs other tools that measure the side forces generated by a rolling tire at a particular slip angle and normal load. The Mu-Meter (ASTM E-670) is used by several highway departments and airport facility managers. In Europe the SCRIM and Skidometer along with several derivatives are commonly used.

The research level tools, using various techniques to arrive at a tire-pavement friction estimate, have one thing in common. Because of the expense and time required to collect data, they are not practical for day-to-day use by District personnel.

## Full Scale Testing

The next level of testing could be considered full scale testing. Many law enforcement agencies and accident reconstructionists operate on this level. This level employs the use of a passenger car or truck in one of three operational methods. The four wheel lock up is the most common. With this technique the vehicle is brought up to test speed and the brakes are rapidly applied to lock all four wheels creating 100 percent slip. The vehicle is skidded to a stop and the tire-pavement friction is estimated using an on-board accelerometer, a pavement marking gun, or by measuring the skid mark length.

A preferable way to employ the full scale test vehicle is to use a pulse stop versus the slide-to-stop. With the pulse stop, the vehicle is brought up to test speed and the brakes are activated. The vehicle is allowed to decelerate to some pre-determined speed and the brakes are released. An on-board accelerometer is needed to accurately measure the pulse stop deceleration.

The third basic technique under the full scale testing level uses a diagonal braking vehicle (dbv). This is a standard vehicle with two diagonally opposed brakes activated while the other two wheels are free to roll and generate cornering force. There is a distinct advantage to the dbv over the above two as testing can be conducted in a curve while still maintaining vehicle control.

The full scale testing methods are not without significant problems. The first and most obvious is the safety of the operator and the general public when tests are being conducted on public roads. Significant problems occur in the area of tire-pavement lubrication. Pavement contamination, be it water or something else, has a significant influence on the tire-pavement friction. With the full scale testing it is difficult if not impossible to maintain a constant water depth for all of the tires. Additionally, the measurement considers two lateral positions on the road surface which may not be the center of the wheel paths. The results are often not repeatable nor comparable to the skid trailer.

## Low Speed Testing

Various low speed test devices have been developed for use in the laboratory and the field. The most common of these include the British Pendulum tester, the various portable friction measurement devices such as the Pennsylvania State and New York Thruway devices, and the assorted varieties of the basic drag sled. Other than the obvious problems of controlled lubrication and interference with traffic flow, the low speed devices simply do not replicate the mechanical interference and dynamics of a rolling or sliding vehicle tire.

### Observational Techniques

The fourth level of tire-pavement skid resistance quantification can best be classified as observational techniques.

The most popular and longest living early observational method was developed by J. Stannard Baker in 1940. Mr. Baker developed a table to classify pavements based on pavement surface type and wear condition. He later added provisions for dealing with wet and dry surfaces and speed gradients. Many other examples of tabular text skid resistance quantification techniques have been developed since 1940. Most have been used briefly and discarded.

Stereo photography is considered an observational technique, but it should also be considered a research tool as the time and equipment needed to document and quantify a particular surface is formidable.

Pavement texture boards have been developed which contain samples of pavement surface types. The boards typically have three rows and four columns of samples. The pavement macroscopic texture increases down the rows and the microscopic texture increases along the columns. The board has, in the upper left corner, a sample with the least micro/macro combination, and in the lower right corner, a sample with the highest micro/macro combination. The friction numbers, speed gradients, and surface texture are known for each sample on the board. It is put in use by comparing the pavement surface in question with each sample on the board. The skid resistance of the pavement surface may then be estimated using touch and sight by finding the best match.

Attempts to synthetically reproduce the micro/macro texture combinations found in the field have failed. It is necessary to core the existing pavements to construct the boards. This approach has not been found practical.

A final observational method, which is the recommended approach, combines a three point examination of the surface, a photographic comparison procedure and a common sense approach. This technique is being proposed for use by District inspectors. The three point examination and photographic comparison methods classification scheme are the subject of the next section of this report.

The Observational Approach

A $200,000 ASTM E-274 friction measurement trailer is required and twenty separate measurements with that trailer are needed to define the average friction number (FN) on a pavement surface to within ± one friction number. Of course, if the same pavement is measured four months later it may have changed by as many as ten friction numbers, or if it is measured with an automobile tire it may be ten friction numbers different. In many cases it is impossible to tell the influence of a ten friction number difference on safety. Is it reasonable then to rely on such a sophisticated system and testing procedure that is subject to such wide variation and exhibits such a subjective relationship to safety, to dictate the need for surface treatment or maintenance?

Consider an alternative approach. Suppose it is possible for a person with reasonably good judgement and experience to simply look at a pavement and feel it, and thereby reach certain judgments. These judgments would not be, for example, "This pavement has a friction level of 65, 35 or 17". These judgments would typically be characterized by the following categories:

- The pavement friction is high.
- The pavement friction is medium.
- The pavement friction is low.

This is the level of distinction that the writers consider to be adequate for a field survey to identify those pavements which are obviously inadequate (Condition C), those which may require more detailed definition, perhaps by friction trailer (Condition B), and those which clearly have more than adequate surface friction (Condition A).

Is there real concern that an individual can be this discerning based simply on sight and feel, or that one can be trained to be that discerning? Maintenance personnel have been looking at pavements and making such judgments since Joseph Barnett (20) prepared curve design tables in 1940, tables which are still viable today. When surveys of friction numbers are provided to these same personnel, there are generally few surprises. These individuals know the condition of their roadway surfaces unless the surfaces change precipitously. They do not know whether a surface friction level is 17 as compared to 12 or 20, but they certainly recognize if a wet pavement is relatively slick.

They can also recognize when the friction is good. It is not necessary, or even of significance to discriminate between a friction level of 40 and one of 60. They are both more than adequate. They are simply good, high friction surfaces. By defining these two friction conditions the high and the low, the medium friction surfaces have also been defined. They are simply everything else.

From the viewpoint, then, of developing procedures for a state-wide skid accident reduction program it is possible, and in many cases demonstrated, that many Department personnel are already capable of making these distinctions. What remains is to define procedures that can be followed by less experienced personnel to achieve a degree of consistency in this admittedly gross definition of relative levels of available pavement friction. In the following paragraphs, that will be attempted. There is also a Field Guide developed for the Texas Skid Accident Reduction Program that provides a detailed analysis of pavement evaluation (21).

In evaluating an asphaltic concrete pavement surface using simple procedures, there are three basic steps proposed. These steps are:

- Evaluation of flushing.
- Evaluation of Large Scale Roughness, LSR (macrotexture).
- Evaluation of Small Scale Roughness, SSR (microtexture).

The combination of these three basic evaluations should result in the definition needed to categorize a surface into the required Condition A, B or C.

### Flushing

Flushing is the most obvious condition, and perhaps the most dangerous. Complete flushing, that is, complete covering of the aggregate by asphalt, results in the lowest level of friction, sometimes approaching a friction number of 6 when wet. If complete flushing is observed, the pavement should automatically be classified a Condition C. What often occurs, however, is that flushing is only partial. If, for example, the aggregate is still exposed on 75% of the surface, this degree of flushing is not severe and the surface friction may be excellent. The degree of flushing must be estimated to determine if it is a significant problem.

The test proposed for flushing consists of visually comparing the pavement surface with standard photographs. Figure 7 gives an example of a surface with 80% flushing (20% rock on the surface). Figure 8 illustrates a surface with 50% flushing. Using these photographs the evaluator should categorize the surface as follows:

- Less than 50% flushing.
- Between 50 and 80% flushing.
- More than 80% flushing.

If there is less than 50% flushing, other tests are necessary to determine the surface condition. This surface will be either a Condition A or B. If there is from 50 to 80% flushing, other tests are necessary to determine surface condition. This surface will be either Condition B or C. If there is 80% or more flushing, the surface is categorized as Condition C, and no further tests are necessary.

Figure 7 Example of 80% flushing

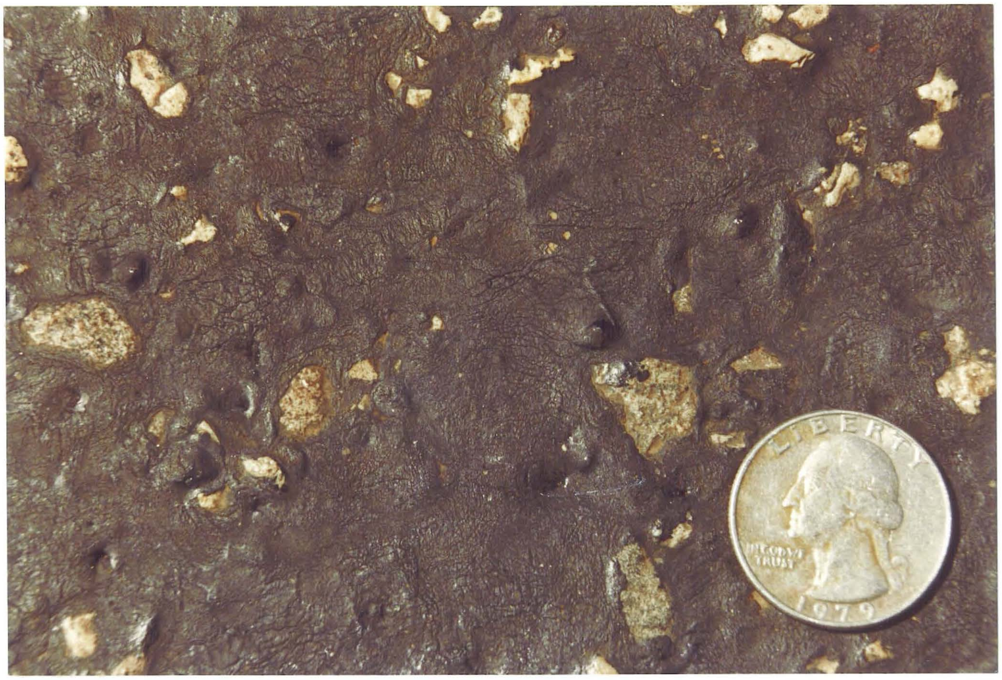
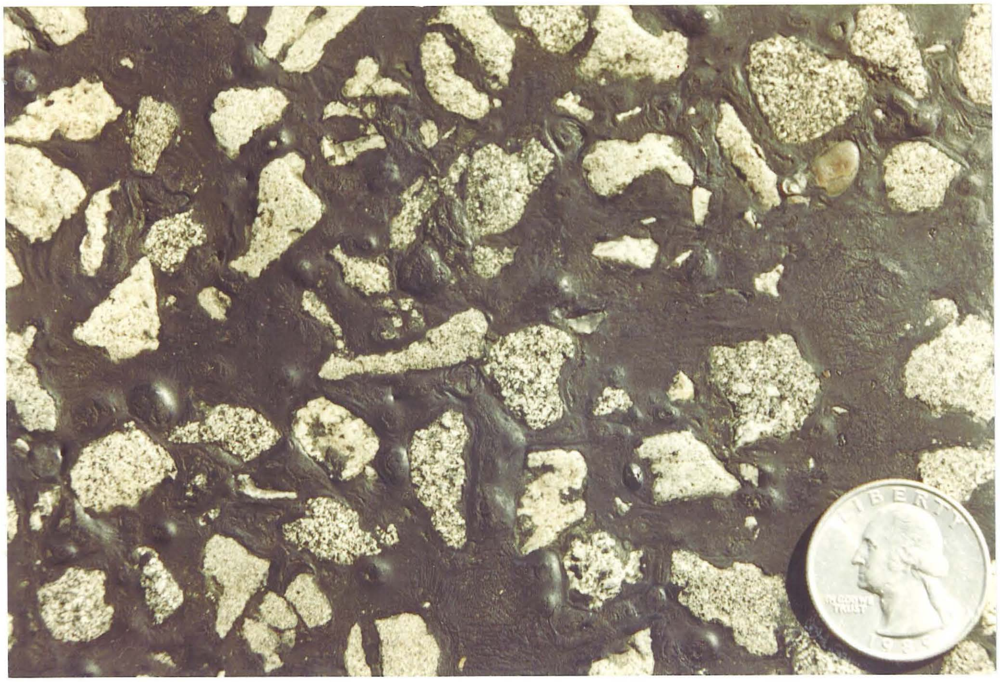


Figure 8 Example of 50% flushing



## Large Scale Roughness, LSR (Macrotexture)

Large Scale Roughness, LSR, is essentially the roughness that can be easily seen from a standing position. It is in general the roughness caused by the large aggregate in the mix. It is traditionally represented as the average depth of the recesses between the top level of the large rocks. This texture is greater than 0.5 mm (2/1000 inch) in height and provides the drainage path for water on the pavement surface. The LSR prevents water build-up between the tire and pavement surface, thus increasing the speed required to hydroplane. Macrotexture or LSR is defined by ASTM E-867 as: the deviations of a pavement surface from a true planer surface with the characteristic dimensions of wavelength and amplitude from 0.5 mm up to those that no longer affect tire-pavement interaction.

The simplest and fastest way to evaluate this roughness is by use of the Siliputty (silicon putty) device, although the Standard Texas Sand Patch test (ASTM E-965) can also be used. A Siliputty test can be run after practice in 30 seconds, compared to the sand patch, which requires over a minute. On a highly traveled road, this difference may be important. The evaluation of this test result is shown by Table 6.

Table 6 Evaluation of Large Scale Roughness (Macrotexture)

| Large Scale Roughness, LSR (Inches in thousandths) | Evaluation |
|---|---|
| $LSR \leq 10$ | 1 Poor |
| $10 < LSR \leq 20$ | 2 Marginal |
| $20 < LSR \leq 30$ | 3 Fair |
| $30 < LSR \leq 40$ | 4 Good |
| $LSR > 40$ | 5 Excellent |

## Small Scale Roughness, SSR (Microtexture)

Small Scale Roughness, SSR, is essentially the roughness that cannot be seen from a standing position. SSR is the surface features less than 0.5 mm (2/1000 inch) in height. Microtexture, or SSR, is needed to penetrate the thin water film present between the tire and pavement after the bulk water is removed by the pavement LSR and the tire's tread. It may be considered as the roughness of the surface of the large aggregate in the mix. Because of the small size of this roughness it is most difficult to evaluate with precision. As an example, if a rock is sandstone with sand grains obvious on the surface, the small scale roughness is excellent. If a rock is a well rounded, river and traffic polished, e.g. a smooth round river rock, the small scale roughness is poor. If a rock is a crush limestone, the SSR will probably be an intermediate or medium level, but some limestones can become well polished under the influence of traffic. Some limestone rock asphalt cold mixes are also quite susceptible to surface polishing. Using these end conditions for comparison, Table 7 may be used to assess SSR.

Table 7 Estimating Small Scale Roughness (Microtexture)

| SSR Number | Surface Texture Equivalent to: |
|---|---|
| 5 | A grainy surfaced sandstone. |
| 4 | |
| 3 | The fracture surface on a newly crushed limestone. |
| 2 | |
| 1 | A smooth surfaced siliceous river rock. |

During the course of this study a continued attempt was made to determine the SSR number in a more objective way than Table 7. Of course it is possible for one to carry a pocketful of rocks of varying SSR to use for comparison but it was hoped something slightly more sophisticated might be found. Several microtexture boards were constructed using squares of sand paper and/or emery cloth. One of these is shown in Figure 9. While such "boards" are easily duplicated for supply to all Districts, they may be of more value in demonstrating microtexture than in actually evaluating it.

Another attempt was made by constructing a series of texture discs. Three of these are shown in Figure 10. They are made using half-inch diameter marbles arranged in a 6-inch diameter concrete cylinder mold top. The marbles are secured in place when coated with epoxy. Various types of clay or sand are sprinkled on different areas of the disc as shown in Figure 11. The disc the writers feel has the most potential for field use is number three. It represents SSR

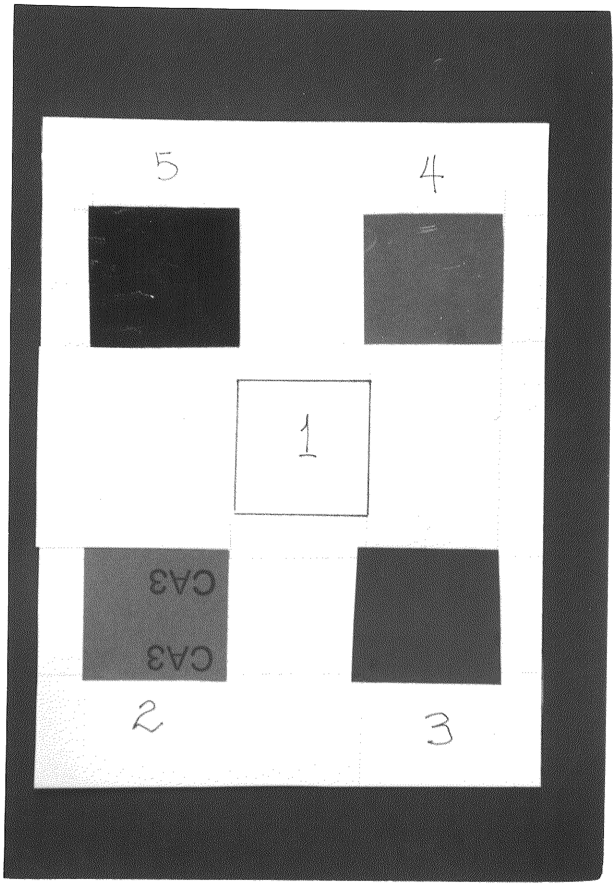


Figure 9. Example of Microtexture Board

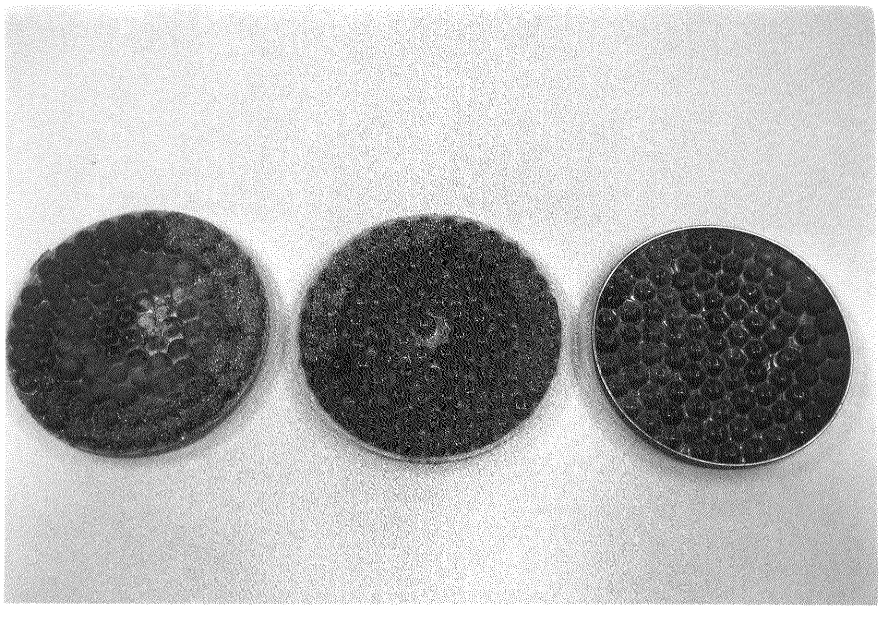


Figure 10. Examples of Texture Discs

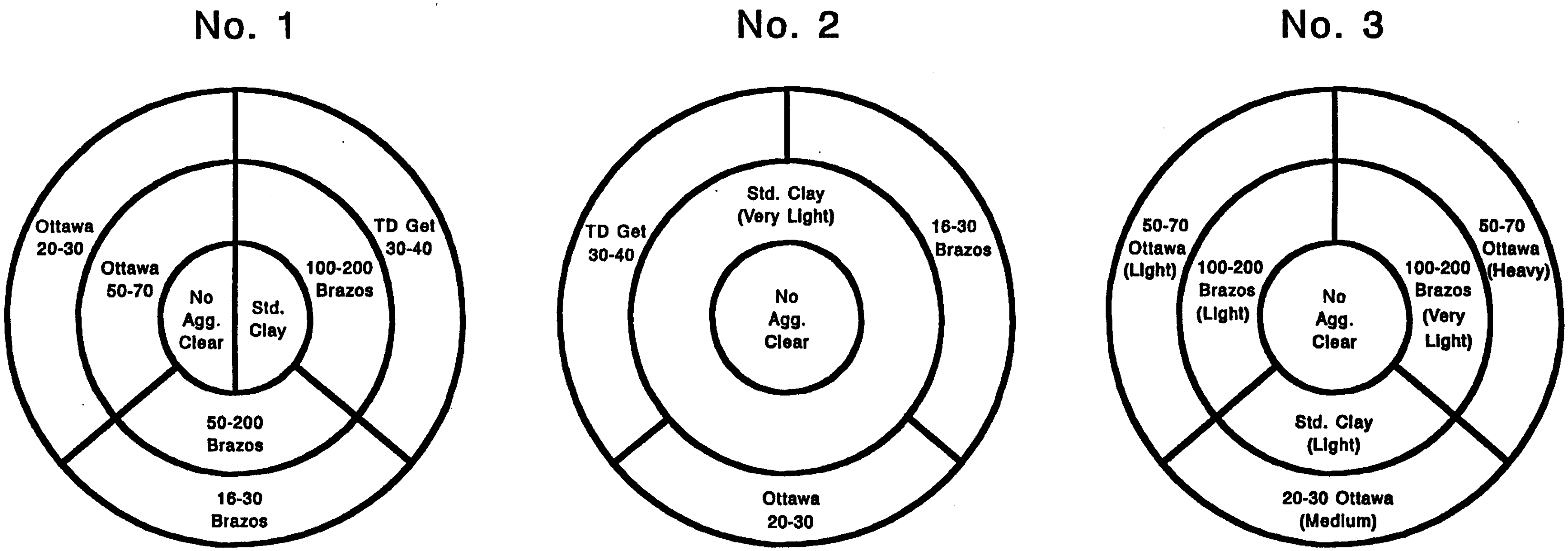


Figure 11. Illustration of fine aggregate used on Texture Discs.

numbers one, three and five, as one moves from the center to the outside of the disc. As in the case of the texture board, these values of microtexture are subjective, but comparison with aggregates in the field may have some value. Districts wishing to try this approach can be supplied with microtexture discs.

Using the results of these three tests, the surface friction condition may be estimated using Table 8.

Table 8 Assessment of Surface Friction Condition

| LSR | SSR | Flushing 80% or more Condition | Flushing between 50 & 80% Condition | Flushing less than 50% Condition |
|---|---|---|---|---|
| 5 | 5 | C | B | A |
| 3 | 5 | C | B | A |
| 1 | 5 | C | C | B |
| 5 | 3 | C | B | A |
| 3 | 3 | C | C | B |
| 1 | 3 | C | C | C |
| 5 | 1 | C | C | B |
| 3 | 1 | C | C | C |
| 1 | 1 | C | C | C |

## Field Observations Using the Rating Scale

The previous section describes the way to inspect the three main surface components which combine to develop frictional characteristics for a roadway surface. This classification and rating scheme may be put to use in the field to document the pavement condition. In the field everything is not quite so clinical or neat. The observer must use experience and judgement in the classification. A few observations and examples are presented in this section.

Category A is considered a pavement surface with high skid resistance. This surface requires no maintenance or modification due to tire/pavement available friction. See Figure 12.

Category B describes a pavement surface that is moderately worn, either because of polishing, loss of aggregate or flushing, or a combination of all three. See Figure 13. A Category B pavement may have adequate skid resistance in many cases, assuming that the surface has good surface drainage characteristics or is located on a segment of roadway where

Figure 12. Category A Surface

Figure 12. Category A Surface (Cont.)

Figure 13. Category B Surface

Figure 13. Category B Surface (Cont.)

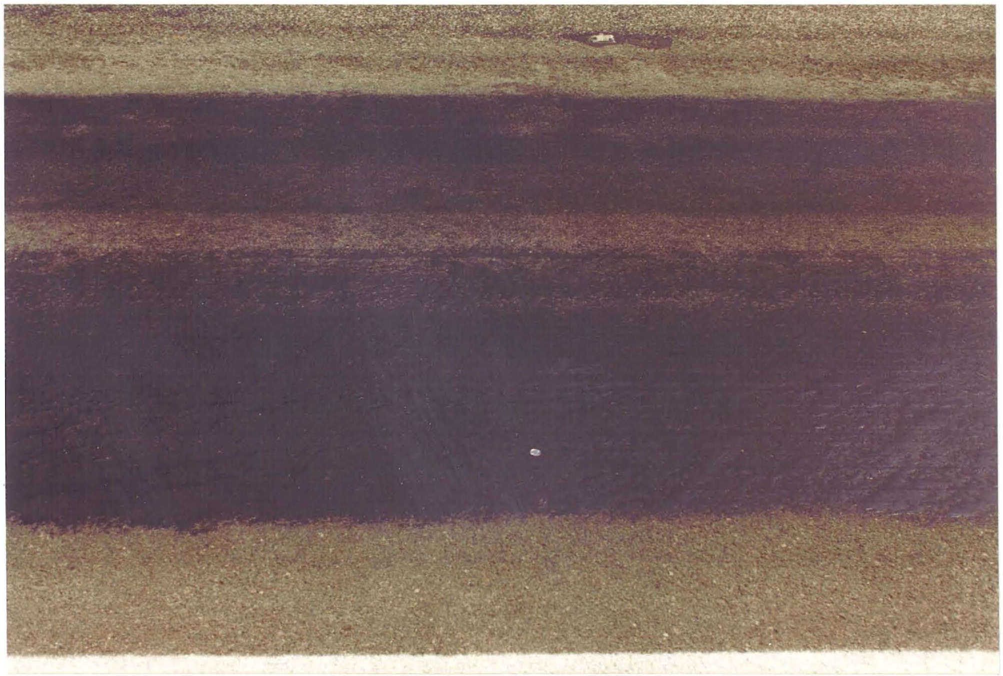
the demand for friction is not too high. More skid resistance may be needed on horizontal or vertical curves or in intersection areas where a design change in traffic velocity occurs. A Category B pavement may require some immediate modification to the roadway surface or it may need to be signed until the surface is modified with a seal coat or overlay. It may also require no treatment whatsoever.

A Category C surface is one that probably requires some kind of immediate attention. This surface may be degraded due to polishing, loss of aggregate, bleeding, or a combination of all three. See Figure 14. The wheel paths will exhibit extreme polishing or flushing, and the lateral variations in pavement texture are significant. This surface may exhibit a friction number $FN_{40}$ below 20. This condition can also be caused by patching or crack sealing. Since the demand for friction is greatest where there is horizontal and/or vertical curvature and in intersection areas. These roadway segments should be of special concern if they receive a Category C rating.

When traveling on the highway, the most obvious differences seen and heard are the differences in surface texture. Those differences are apparent because the different surface textures reflect the light differently and different macrotexture (LSR) conditions make tire noise changes obvious. For example, a surface that is flushed tends to reflect the light in a very uniform manner, whereas a surface that has good macrotexture (high LSR) reflects the light off the aggregate faces in many different directions causing a more dull appearance. The appearance is not shiny like the flushed or polished areas. The key to spotting a road that has a problem is looking at how the difference in reflectivity and color of the road surface varies laterally across the road. Basically the highest difference will be between the wheel paths and the center line of the lane or the center line of the roadway, and should be so noted. LSR differences can also be noted by driving in and out of the wheel paths while listening to changes in tire noise.

A Category A road will not usually vary much in appearance laterally or across the road. The appearance of the road (the color and light reflectivity) will appear uniform. A Category C road, on the other hand, may have severe problems in the wheel paths. The aggregates may be polished and compacted and the wheel paths may be severely flushed. This usually gives a darker, shinier appearance in the area that is so damaged. Typically, the greater the difference

Figure 14. Category C Surface



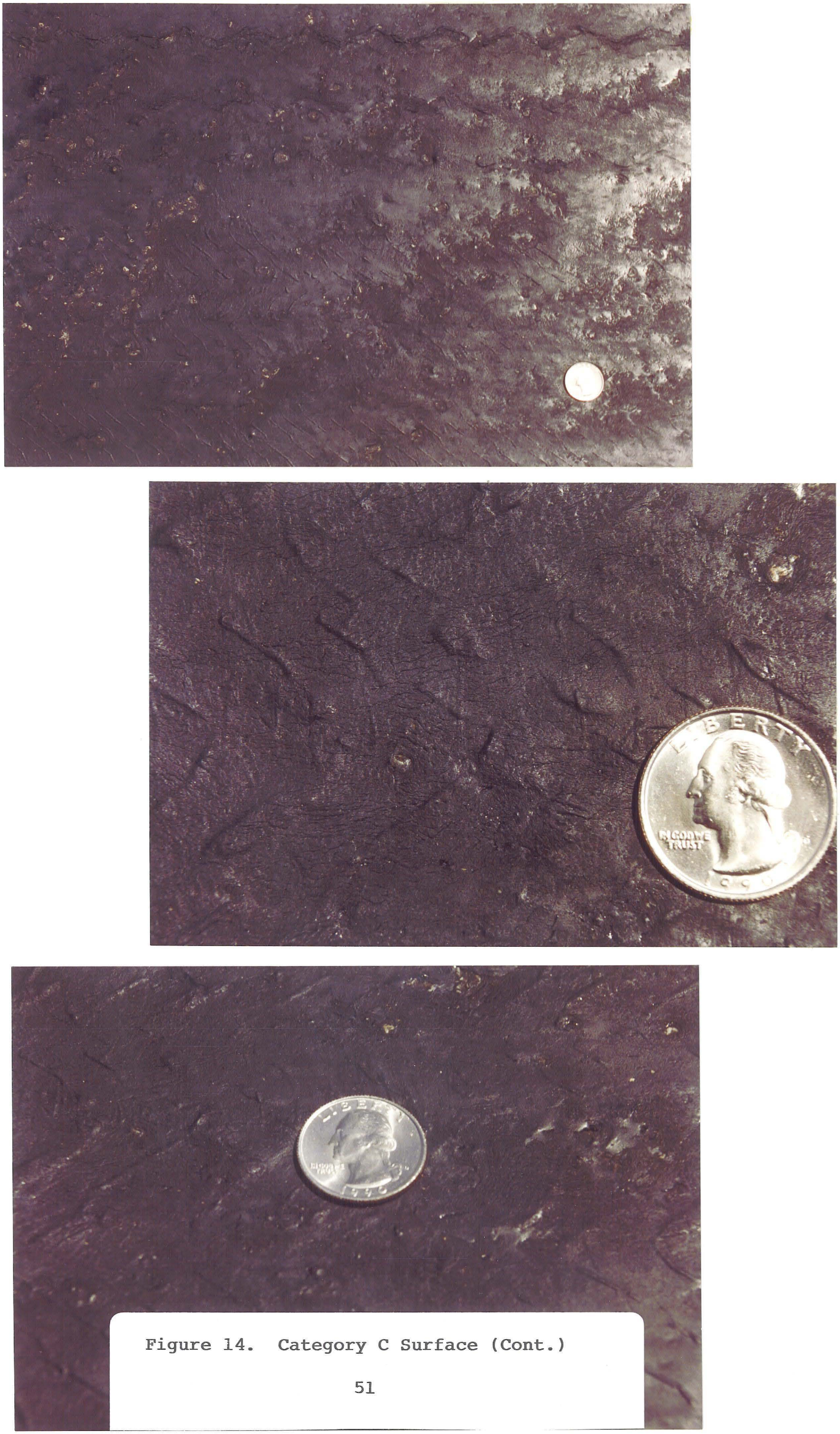


Figure 14. Category C Surface (Cont.)

in the appearance of the road in the wheel paths and lane and roadway centers, the more that roadway has degraded and the skid resistance is reduced. This is usually true for any type of asphalt or concrete surface regardless of the type of aggregate used, with the exception of some lightweight aggregates which give higher friction values as they wear. The relative texture of the wheel paths is judged using the center line of the roadway and the center of the lane as a guide to the original condition of the road.

As the road is being visually inspected for color, light reflectivity, apparent smoothness of the surface and, importantly, the relationship of those characteristics laterally across the road, several factors must be kept in mind. The first is the demand for friction. If this particular roadway segment is located on a straight level road, the demand for friction will be low. Therefore more lateral variation and a lower available friction may be allowable. The other factors that must be considered are the surface drainage characteristics. These are discussed in Section VII, and include evaluation of the horizontal and vertical slopes of the road, rutting, water drainage path length and pavement edge buildup.

### Rating Surface Conditions with the Photographic Scale

Pavements were inspected and photographed for the pavement photo scale (PS) from Texas DOT Districts 4, 11, 12, 14, 17, 20 and 21. These Districts cover a wide spectrum of pavement materials used in the state as well as atmospheric, weather and traffic conditions. Although different aggregates are often used in different Districts, using the photo scale to help rate a pavement segment is not dependent on the type of aggregate or the highway District. The reason for this is that as most pavements degrade then lose skid resistance. This degradation is a relative factor to that particular highway and that particular aggregate. It is not necessary to compare the wear, compaction, or flushing of one pavement surface to another. Simply, what we are doing is looking at how an individual pavement surface degrades relative to its original condition, not relative to another pavement with a different type of material. While it is true that some pavements will degrade much slower than others, once they achieve a certain degradation, the aggregate type may be irrelevant.

The objective is to examine the difference in a road surface as it wears and to quantify the wear into one of three levels: one that is safe (Category A), one that is marginally safe (Category B) and one that appears to be unsafe (Category C). This classification can often be done independently of the time it took for the roadway to degrade or the material type used. Most different aggregate types come into play only when trying to compare the rate of degradation of several pavements. For example, consider one road segment constructed of a good-wearing Grade 4 lightweight that has been classified as a Category B surface, and a second road segment which has also been classified as a Category B surface, which is constructed of a very fast-polishing aggregate. Obviously, the Grade 4 lightweight road would normally take much greater time to reach a Category C rating with equivalent ADT and vehicle mix, and indeed might never reach that condition. Definitions of the terms "Safe," "Marginally Safe" and "Unsafe" are as follows:

Safe - No matter how impaired the driver or defective the vehicle, the wet pavement available friction will have nothing to do with a loss of control while traversing the pavement surface. This includes the influence of alcohol or other drugs and any other infirmity or lack of physical capability.

Marginally safe - A high percentage of drivers could traverse the wet pavement surface without significant difficulty. A small group of drivers may experience some difficulty in performing emergency maneuvers without temporary losses of traction.

Unsafe - A significant percentage of drivers would experience difficulty in traversing the wet pavement surface without temporary losses of traction.

"Traversing the pavement surface" - This implies the ability to perform all "design" vehicle maneuvers such as stopping, passing and cornering considered by AASHTO under "Elements of Design."

In order to appropriately classify the roadway surface condition, one should examine the surface with a minimum of five views. The first view is a general longitudinal view of the travel lane and the entire roadway. The rater is looking at the general appearance of the road surface both near the rater and further down the road towards the horizon. On a two lane road, he will see four individual wheel paths, two road edges, two travel lane center lines and one roadway center line. Each of these areas will have a particular appearance of color, roughness and reflectivity.

The second view will be a lateral view of the travel lane of interest. This provides a closer look at the lateral differences of pavement texture. Pavement flushing, compaction, aggregate loss and polishing become more evident as the wheel paths are compared to the center of the travel lane, the center line and the roadway edge. For reference purposes, an object of known size, shape and texture should be placed on the road. In the example photographs used in the Photo Scale, a quarter is used as that reference.

The next three views more closely examine the pavement surface in the wheel path itself rather than the lateral variations across the road. The third view is a normal view of the road surface from a standing position. The observer should make note of the type and size of aggregates and generally the area percentage of flushing.

View number four is a close-up view of the aggregate. This view is from a location normal to the surface with the reference (quarter) in place for comparison purposes. This close-up view allows the examination of the microtexture of individual aggregates for sharpness or polishing and also to note the percentage of flushing. The pavement macrotexture is also examined by determining if the aggregate is compacted into the base, fractured or polished.

The final view is an oblique view of the pavement surface with the reference (quarter) present. This allows one to determine the relative macrotexture present in the roadway surface. In order to determine the relative wear of the wheel path, this same inspection technique should be conducted in the center line of the travel lane where the road has received little wear. The difference in the wear condition will often be easily determinable.

In addition to examining the pavement and the photographs, the road surface should be lightly rubbed with the finger tips to sense the microtexture of the surface. A roadway that has a lot of microtexture feels like a very gritty sandpaper (#220 or lower), while a road surface with less microtexture will feel smoother, like a smooth sandpaper or in the extreme even as smooth as paper (See Figures 9 and 10). While the observer is kneeling on the road, one should also note weather the road feels smooth or rough. It has been noted that a road with high macrotexture may cause discomfort to the observer's knee, while a road surface with little macrotexture will provide a sensation similar to kneeling on a smooth finished concrete slab. It is a combination of microtexture and macrotexture that produces the skid resistance of a particular road surface.

Example photographs and descriptions of pavements that are appropriate for each of the three categories follow.

### Category A

A Category A classification is appropriate for a pavement surface that presents no safety problem to the traveling public. The pavement surface is rather homogeneous in appearance and texture laterally and longitudinally, with the exceptions of purposefully grooved or milled surfaces. Friction numbers, $FN_{40}$, for a Category A surface will be in the thirties or higher in each wheel path. The Category A surface has gritty microscopic texture (SSR), and the aggregates are protruding from the base material to give the surface good macroscopic texture (LSR).

A Category A should generally have less than 50 percent of the aggregate covered by flushing or bleeding of the asphalt mixture.

### Category B

The Category B surface is fitting for many of the roadways in the state that are in the middle to end of their life cycle. In some cases this is five or seven years, while under other circumstances pavement surfaces do not show significant wear or distress conditions after fifteen or twenty years. Accordingly, the age of the pavement surface often cannot be reliably used to predict safety. Under wet conditions drivers should exercise some caution on these segments.

The factors which should be evaluated are the SSR and LSR (microscopic and macroscopic pavement textures), the texture variations laterally across the surface, and the percentage of flushing in the wheel paths. Category B surface conditions are usually noticeable to even the casual observer. The wheel paths may be somewhat flushed. The aggregate is somewhat polished, compacted or missing, or some combination of those. These surfaces will typically have an $FN_{40}$ in the twenties or lower thirties. In many cases one wheel path will show significantly more wear than the other. These surfaces may require some type of short term maintenance or signing, or may be closely monitored for subsequent degradation as the segment is waiting for routine seal coat or overlay according to the District's maintenance schedule.

*Category C*

A Category C pavement surface offers little in the way of skid resistance. This is true for all travel speeds. Surface conditions in the wheel paths are significantly different from the centerline indicating major wear and distress. These pavements are typically flushed in the wheel path with little micro or macro texture available. Less than twenty percent of the aggregate is visible in the wheel paths and the aggregate is worn or polished and compacted. Friction numbers $FN_{40}$ for these wheel paths typically are typically below twenty. A Category C rating indicates that the roadway segment is in need of immediate attention. Friction numbers should be obtained to support non-scheduled or emergency repairs. Warning signs should be placed just prior to each segment, according to Department policy, until modifications can be made.

# VII. FULL INVENTORY FRICTION TESTING

Full inventory friction testing has been proposed at various times, usually by Federal agencies, and is done in some states. This certainly gives a rather complete data base of available friction and certainly identifies objectively areas where the friction levels are low. In some cases where there is a need to relate these levels to aggregate performance throughout a state, it might even be useful in the short term. If it is being done to reduce the frequency of skidding accidents, however, it is a futile effort. Simply increasing the friction in areas where friction levels have fallen below some arbitrarily defined level will not significantly decrease wet weather accident rates. Studies making an effort to relate these variables directly have generally failed for the past twenty years.

Because this is such a futile effort it is also most wasteful of badly needed resources. While it is of potentially great value to know what the friction levels are on roads that have an atypically high wet weather accident rate, generally on Category B or C pavements, it is of no value whatsoever to know the friction level on all the Category A pavements in the state. In truth, it is no value to know the friction level precisely on Category C pavements. A simple inspection by a knowledgeable individual tells all there is need to know, i.e. the friction level is <u>too</u> low.

It is estimated from the wet weather accident data that has been examined during the past three years in Texas that roughly 80% of full inventory friction testing would be of negligable use in reducing wet weather accidents. Full inventory testing is simply an unconscionable waste of public funds. The alternative is using friction trailers as a precise measurement tool on selected road surfaces where an effort is being made to understand the reason for atypically high wet-to-dry accident ratios. This is shown conclusively by the analyses in this report.

## VIII. EXPOSURE TO RAINFALL

It is not a new observation that the degree to which wet weather accidents pose a problem is directly related to the proportion of time the pavement is wet. Figure 15 shows that the ratio of wet accidents to all accidents is convincingly related to the average annual rainfall in the state. The same relationship is true for injury accidents and fatal accidents. Such variations within a state should also be true. As illustrated by the annual rainfall variability from west to east Texas (Figure 16), a variation from 8 to 55 inches, the wet surface accident problem should be much greater in east than in west Texas. Figure 17 shows the exposure time in west Texas to be less than 2% while the exposure time in east Texas is about 4%.

In the report by Gallaway et al. (5), Ivey reasoned that the design rainfall intensity from a reduction of hydroplaning viewpoint should be a variable, and an area of lower annual rainfall should have a different design intensity than one with higher annual rainfall.

Figure 18 shows the probability of encountering a specific intensity of rainfall. By combining the probabilities of rainfall, the probability of a specific intensity if rainfall does occur, the probability of problem levels of tire tread depth and low tire pressure levels, Ivey developed the following table (Table 9) showing recommended design rainfall intensities. These values purport to limit the probability of hydroplaning to one in one hundred thousand. While there is some concern for the accuracy of the predictions, it is clear that the probability of a prudent driver encountering a hydroplaning condition will be very low if pavement drainage is designed for these conditions. These values therefore, are recommended for use in this program.

If west Texas, central Texas and east Texas are divided according to the annual rainfalls of 8 to 19 inches, 20 to 39 inches and 40 to 60 inches, the selected design rainfall intensities are:

| | |
|---|---|
| ● West Texas | 0.25 in/hr |
| ● Central Texas | 0.50 in/hr |
| ● East Texas | 0.65 in/hr |

These values will be used in the section of this report on pavement surface drainage.

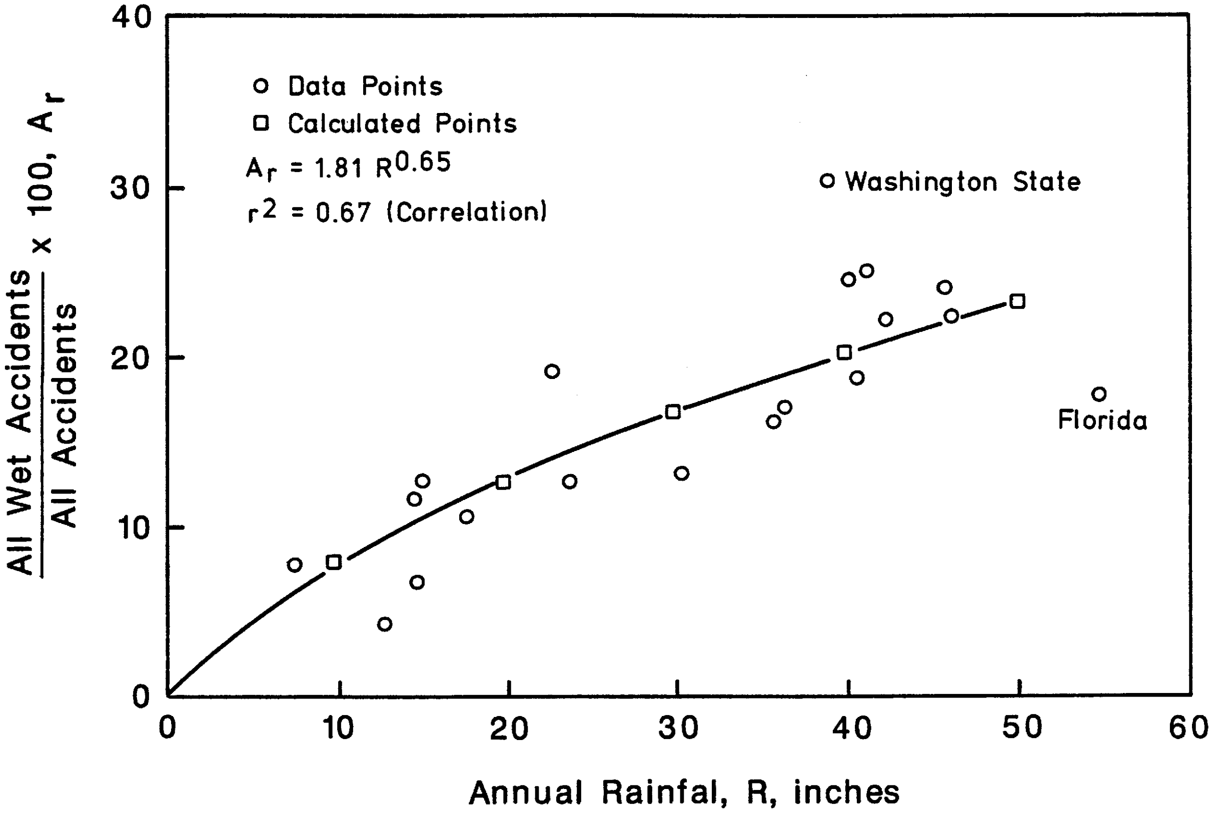


Figure 15 Ratio of Wet Accidents to All Accidents
(After Galloway, et al. (5))

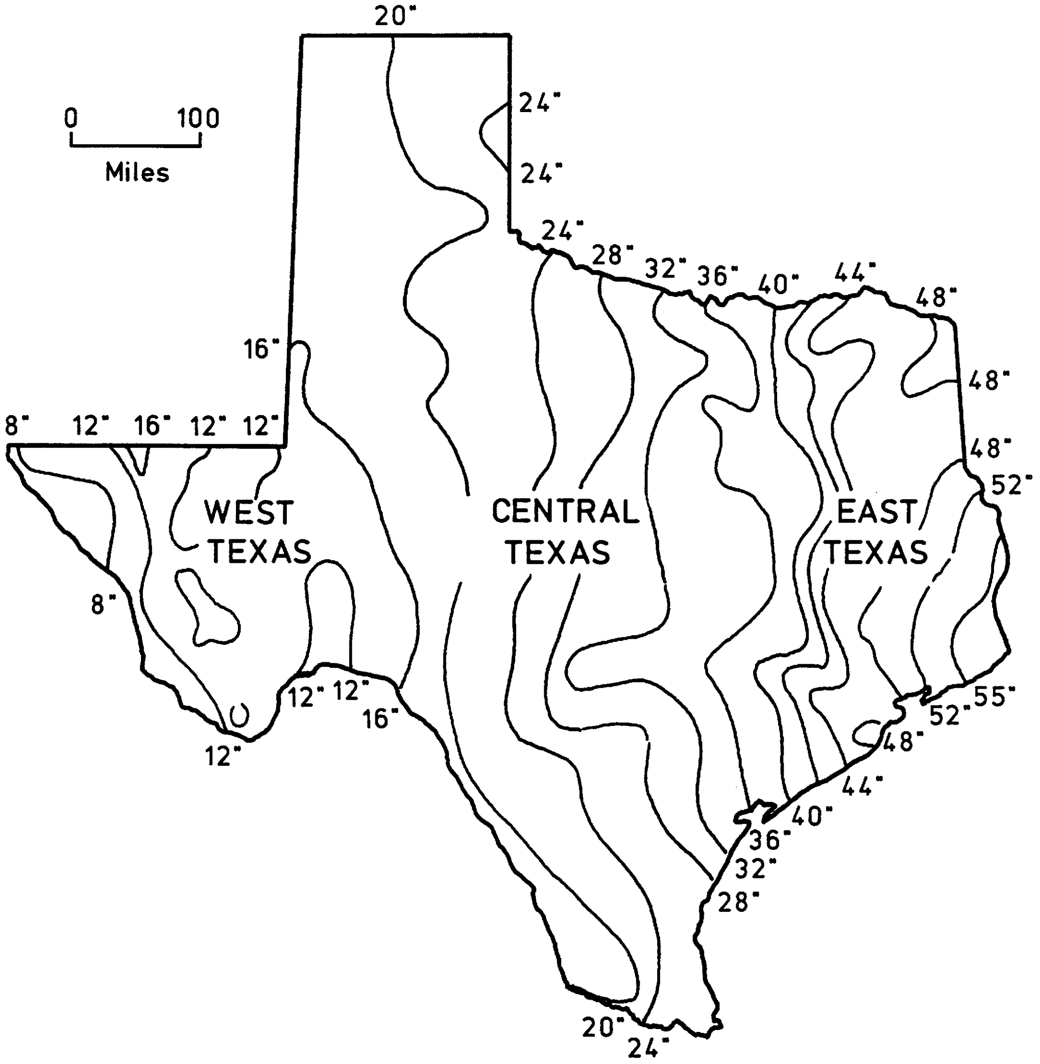


Figure 16 Average Annual Rainfall
(Reference 5)

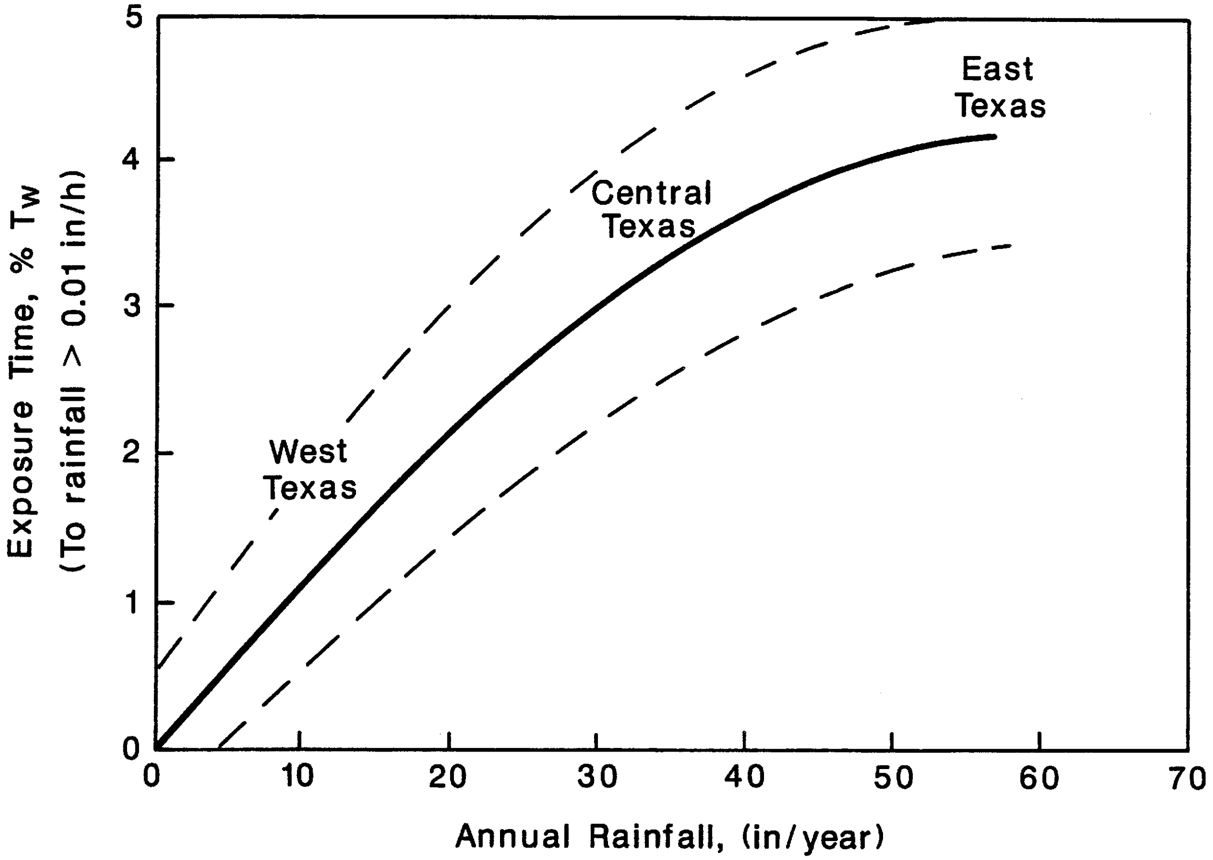


Figure 17 Exposure Time
(Reference 5)

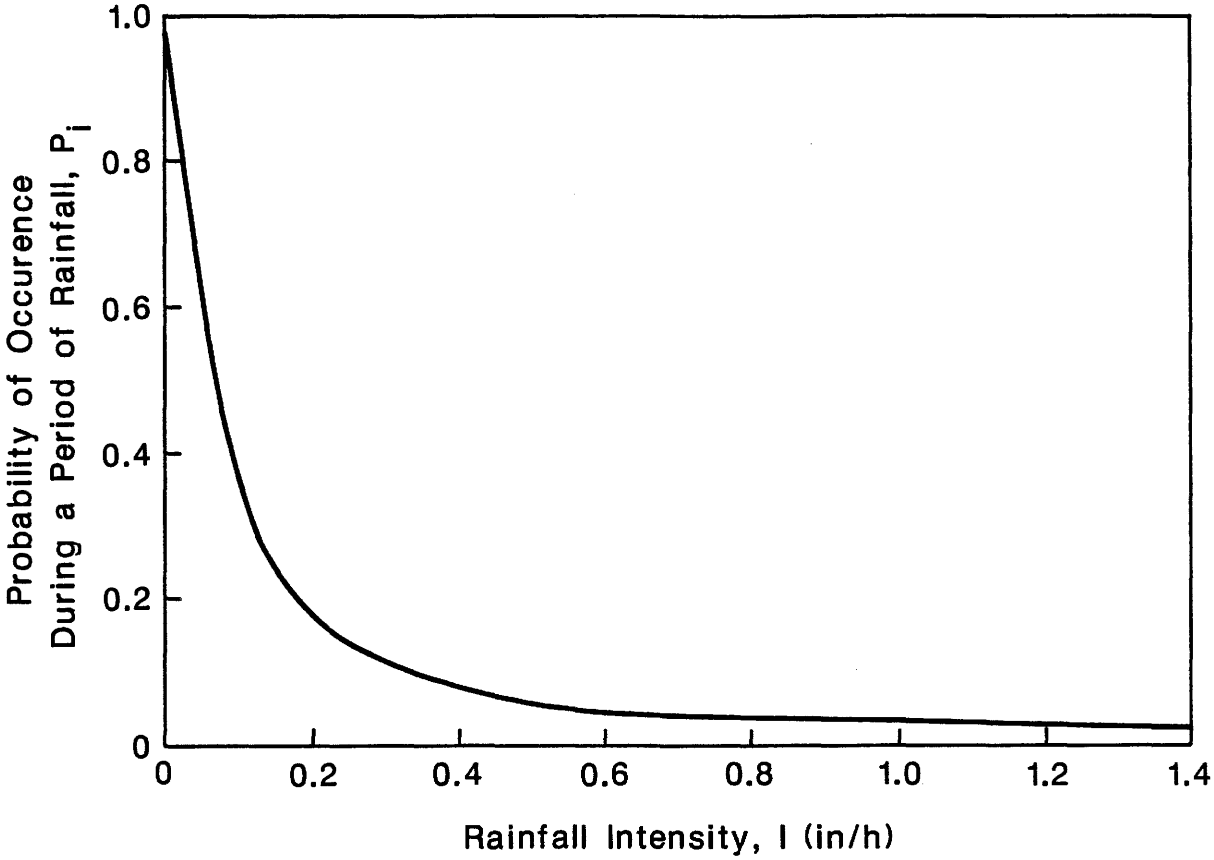


Figure 18 Rainfall Intensity
Probability of Occurence
(Reference 5)

Table 9 Design Rainfall Intensities (After Gallaway et al. (5))

| Annual Rainfall inches/year | Design Rainfall Intensity inches/hour |
|---|---|
| 5 | 0.10 |
| 10 | 0.19 |
| 20 | 0.37 |
| 30 | 0.50 |
| 40 | 0.60 |
| 50 | 0.65 |
| 60 | 0.66 |

# IX. PAVEMENT SURFACE DRAINAGE

The safety significance of small layers of water collecting on pavement surfaces for short periods of time was not appreciated until NASA's work in the '60s defined hydroplaning for aircraft tires. A number of studies on automobile tire hydroplaning followed, with a comprehensive study relative to highway surface design presented by Gallaway et al (5) in 1979. This report remains a definitive work on the subject of automobile tire hydroplaning and is used extensively here. Truck tire hydroplaning was not defined until the middle 1980s (6). That phenomenon has also been considered here.

The purpose in this section is to provide an objective and reasonably straightforward approach to determining the adequacy of pavement drainage. The approach will be to segregate surfaces into three conditions:

- Good Drainage - Condition D-A
- Average Drainage - Condition D-B
- Poor Drainage - Condition D-C

These categories are analogous to the three conditions of friction defined previously as A, B and C, with the possible exception that poor drainage does not always mean a roadway which will be over-represented by wet weather accidents.

In determining whether drainage is good, average or poor, it was necessary to develop criteria related to drainage problems. The problems identified are summarized by the following:

- Surface lacking in large scale (macro) texture.
- Surface lacking in cross slope. (The transition from superelevation to normal crown at each end of a horizontal curve for a crowned road surface unavoidably produces two segments of poorly draining pavement.)
- Excessive drainage path length.
  - o Combination of highway grade and cross slope often results in longer drainage path lengths at the bottom of sag vertical curves and on many grades.
  - o On very long radius curves (generally $D \leq 1°$), low values of superelevation make full pavement width the drainage path length. Where

a significant grade and/or multiple lanes are involved, the drainage path length is even greater.

- Ponding on the traveled surface.
    - o Due to rutting in the wheel paths.
    - o Due to pavement unevenness.
    - o Due to shoulder buildup.
    - o Due to curbs.
    - o Due to inadequate or clogged drains.

Table 10 gives the evaluation factors necessary to categorize the drainage. Techniques to access these factors without major survey expenditures are given in Section 6. Charts to estimate the combined influences of cross slope texture and drainage path length and the significance of puddling are presented here. If all criteria under cross slope, texture and drainage path length are either met or violated there is no need to consult Table 10. It is obviously a D-A or D-C rated surface. If the assessment is divided, the three factors can be considered cumulatively by use of Table 10.

Assessing the influence of pavement drainage on safety is not straightforward as is usually the case relative to low values of surface friction. European studies that show the degree of rutting of a roadway surface are inversely related to wet weather accidents, e.g. the greater the rut depth, the lower the wet accident rate. The writers are also aware of several anecdotal examples where the wet accident rate increased when a badly rutted or ponding surface was improved.

The answer to this inverse relationship seems to lie in the capability of prudent drivers to adapt to poor surface drainage conditions. When a roadway is badly rutted, poorly sloped or otherwise susceptible to accumulations of water, the main populace of drivers apparently accommodates the problem by reducing speed and increasing attention to the driving task. One can expect a reckless driver to lose control on poorly drained sections of roadway when driving too fast.

# TABLE 10

# DRAINAGE ADEQUACY RATING (DAR)

CONDITION
D-A Drainage Good

- Pavement cross slopes of 2%.
- Pavement texture $\geq$ 40 thousandths. See figs. 19 & 20
- Drainage path lengths less than 24 feet.
- No rutting or ponding problems.
- Extant drains adequate and clean.

CONDITION
D-B Drainage Average

- Pavement cross slopes between 1 and 2 percent.
  $(1\% \leq S \leq 2\%)$ See figs. 19 & 20
- Pavement texture between 10 and 40 thousandths.
  $(10 \leq S \leq 40)$
- Drainage path lengths between 24 and 48 feet.
  $(24 \leq L \leq 48)$
- Rutting and/or ponding of minor significance.
  (Ruts $<$ 0.25 inches, ponding depths less than 1/4 inch over distances in wheel paths less than 10 feet.)
  See Figure 20.
- Drainage marginal in capacity due either to design or maintenance problems.

CONDITION
D-C Drainage Poor

- Pavement cross slopes $< 1\%$. See figs. 19 & 20
- Pavement texture $\leq$ 10 thousandths.
- Drainage path lengths exceed 48 feet.
- Rutting or ponding problems.
  (Ruts exceed 0.25 inches, ponding depths exceed 1/4 inch over distances in wheel paths exceeding 10 feet.
- Storm drains inadequate and/or clogged.

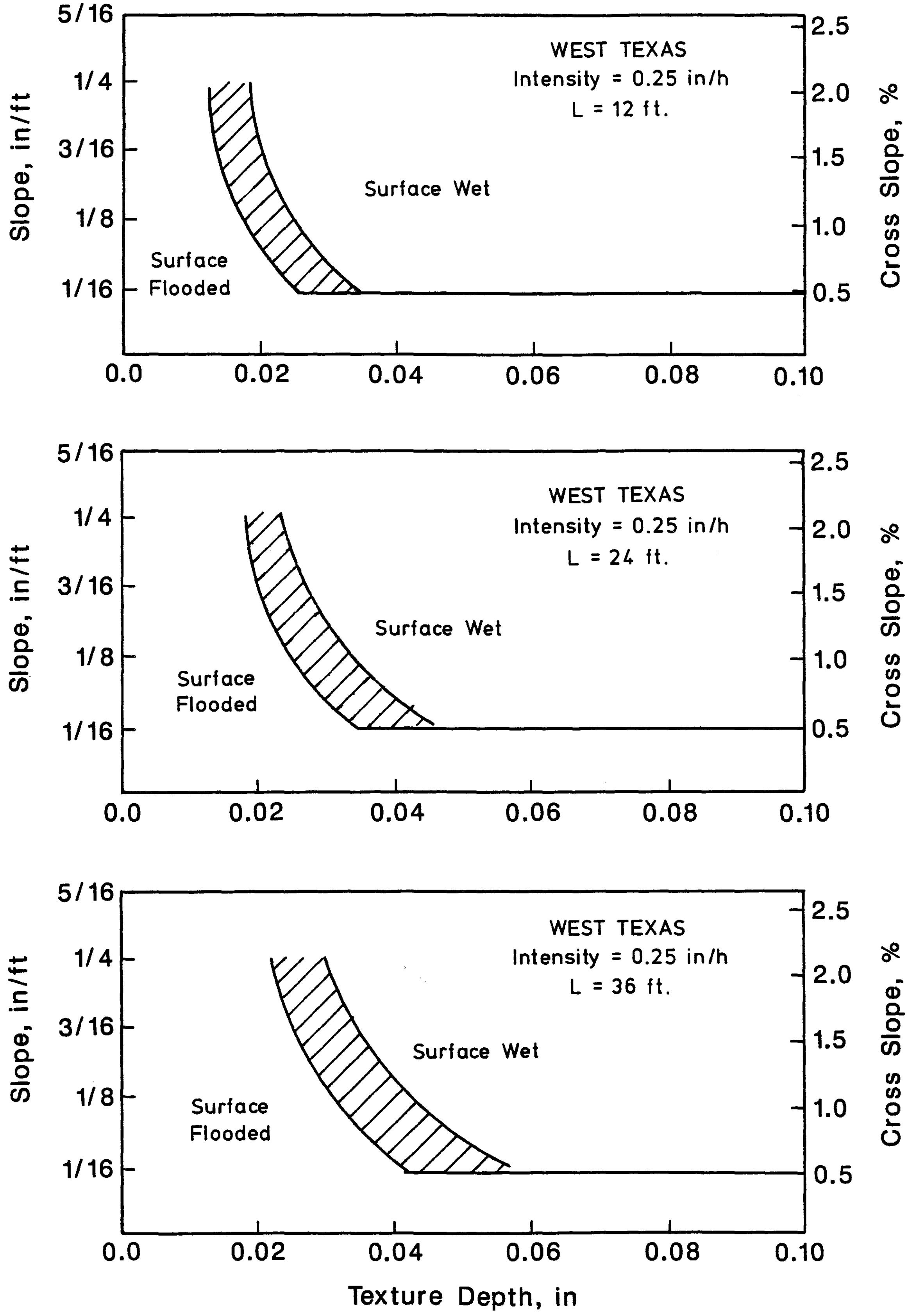

5/16
1/4
3/16
1/8
1/16
Slope, in/ft
2.5
2.0
1.5
1.0
0.5
Cross Slope, %
WEST TEXAS
Intensity = 0.25 in/h
L = 12 ft.
Surface Wet
Surface
Flooded
0.0
0.02
0.04
0.06
0.08
0.10
5/16
1/4
3/16
1/8
1/16
Slope, in/ft
2.5
2.0
1.5
1.0
0.5
Cross Slope, %
WEST TEXAS
Intensity = 0.25 in/h
L = 24 ft.
Surface Wet
Surface
Flooded
0.0
0.02
0.04
0.06
0.08
0.10
5/16
1/4
3/16
1/8
1/16
Slope, in/ft
2.5
2.0
1.5
1.0
0.5
Cross Slope, %
WEST TEXAS
Intensity = 0.25 in/h
L = 36 ft.
Surface Wet
Surface
Flooded
0.0
0.02
0.04
0.06
0.08
0.10
Texture Depth, in

Figure 19

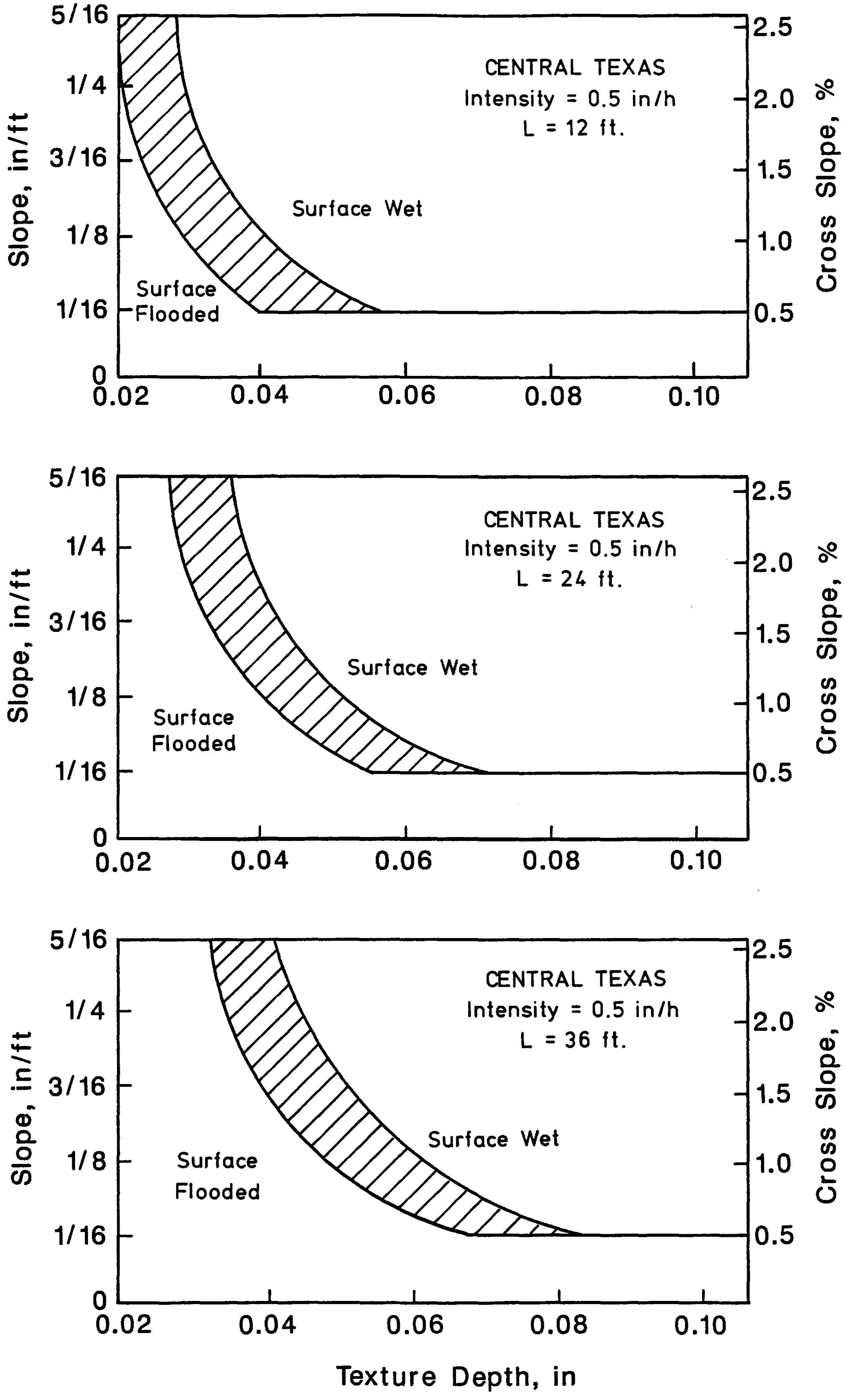


Figure 19 (Cont.)

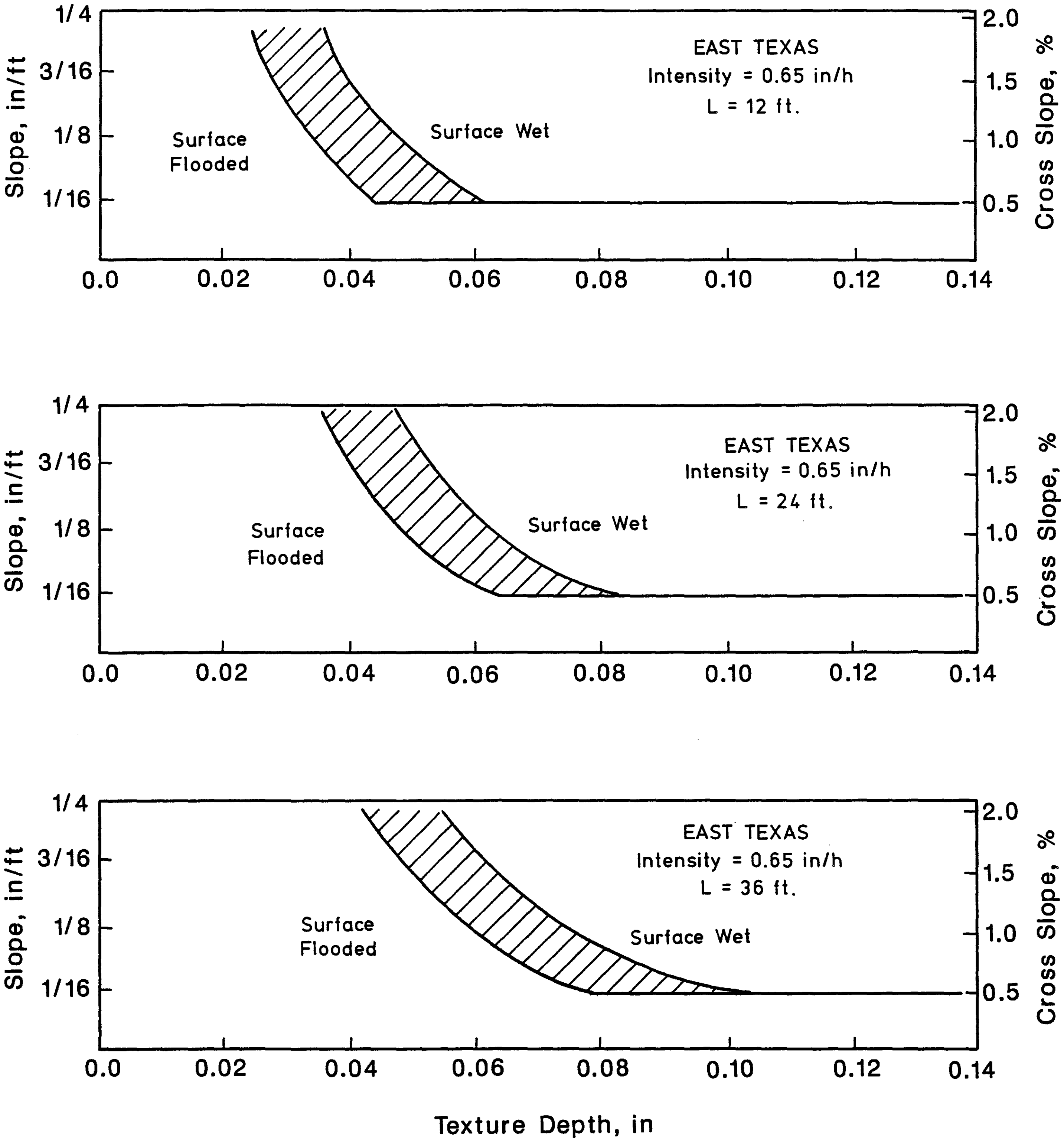
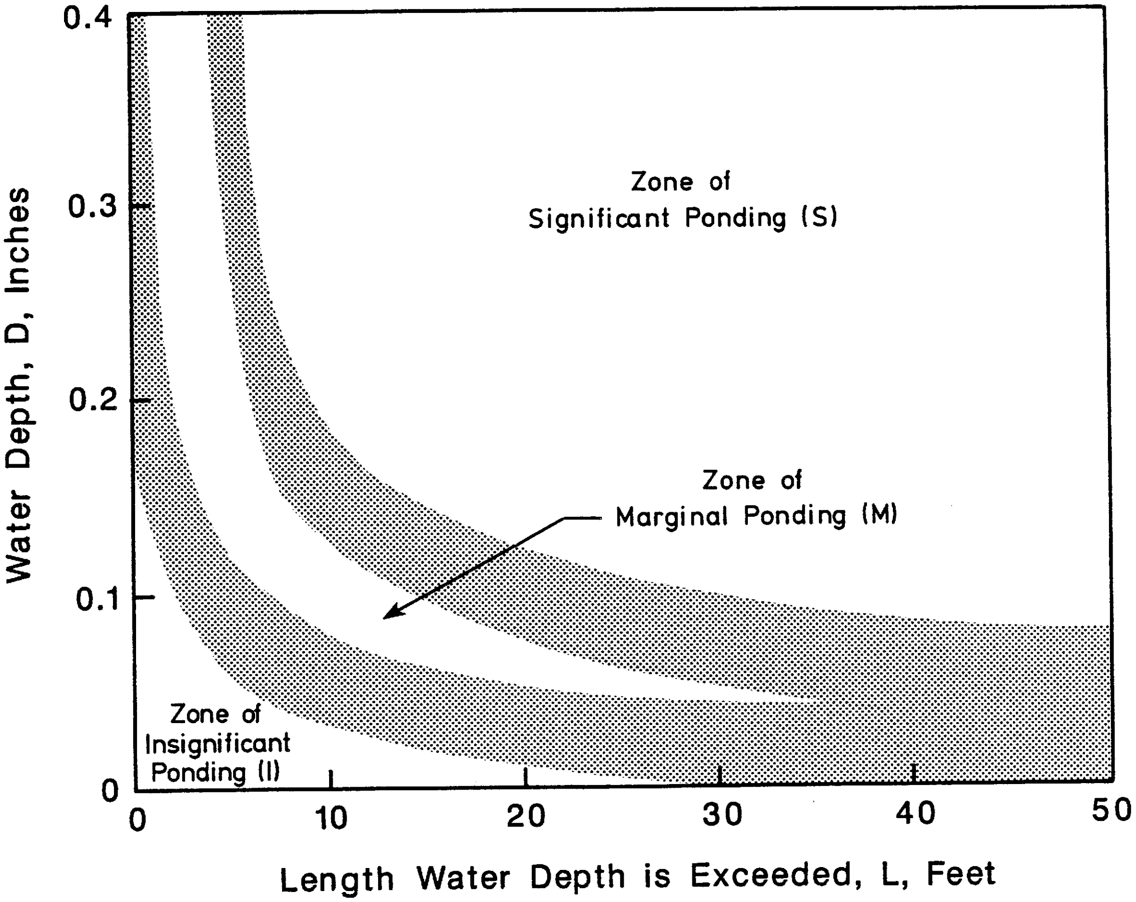


Figure 19 (Cont.)



0.4
0.3
0.2
0.1
0
Water Depth, D, Inches
Zone of
Significant Ponding (S)
Zone of
Marginal Ponding (M)
Zone of
Insignificant
Ponding (I)
0
10
20
30
40
50
Length Water Depth is Exceeded, L, Feet

Figure 20

The places where prudent drivers have control problems and where one would expect high ratios of wet-to-dry accidents are those places that violate driver expectancy, i.e. where a short segment of highway is poorly drained on a roadway which has generally good drainage conditions. It is these unexpected rainfall accumulations which tend to be a significant hazard to drivers.

Comparison of District Data

To determine how to prioritize available funds for the reduction of wet weather accidents, an effort was made to develop a relationship between population, annual rainfall and "Benefits." The "population" of the major town or city within a District was used as a gross indicator of traffic volume. The annual rainfall has been previously shown to be a good indicator of exposure to wet pavement, and the sum of the top ten benefit values within a District may be some indication of the cost effectiveness of efforts to reduce skidding accidents.

Figure 21 is an illustration of the possible relationship between Benefits and Exposure. The trend of increased benefits is not unexpected. The scatter of the data, especially the position of the point representing Houston, probably shows the gross nature of the factors chosen to indicate the dependent (Benefits) and independent (Exposure) indices.

One might be tempted to conclude that something is quite different in the Houston area than in other major cities such as Dallas, Ft. Worth and San Antonio. The writers suggest several candidate differences, e.g. the terrain in Houston is flat compared to the hilly nature of the other cities. This would indicate more difficulty in providing good drainage in Houston. If the "Gallaway" effect is present, then the Houston drivers, knowing the nature of flooded streets they will consistently encounter, drive more conservatively. This would reduce the frequency of accidents. Determining the real reason, if it is not simply an anomaly in the arbitrary way the sum of Benefits was calculated, would take a study of far more sophistication than this. The only justifiable conclusion that may be drawn is that it may be most cost effective in each District to spend safety dollars for pavement surfacing where the pavements are most slippery and/or on areas where pavement flooding violates driver expectancy, in combination with the highest determined "Benefits."

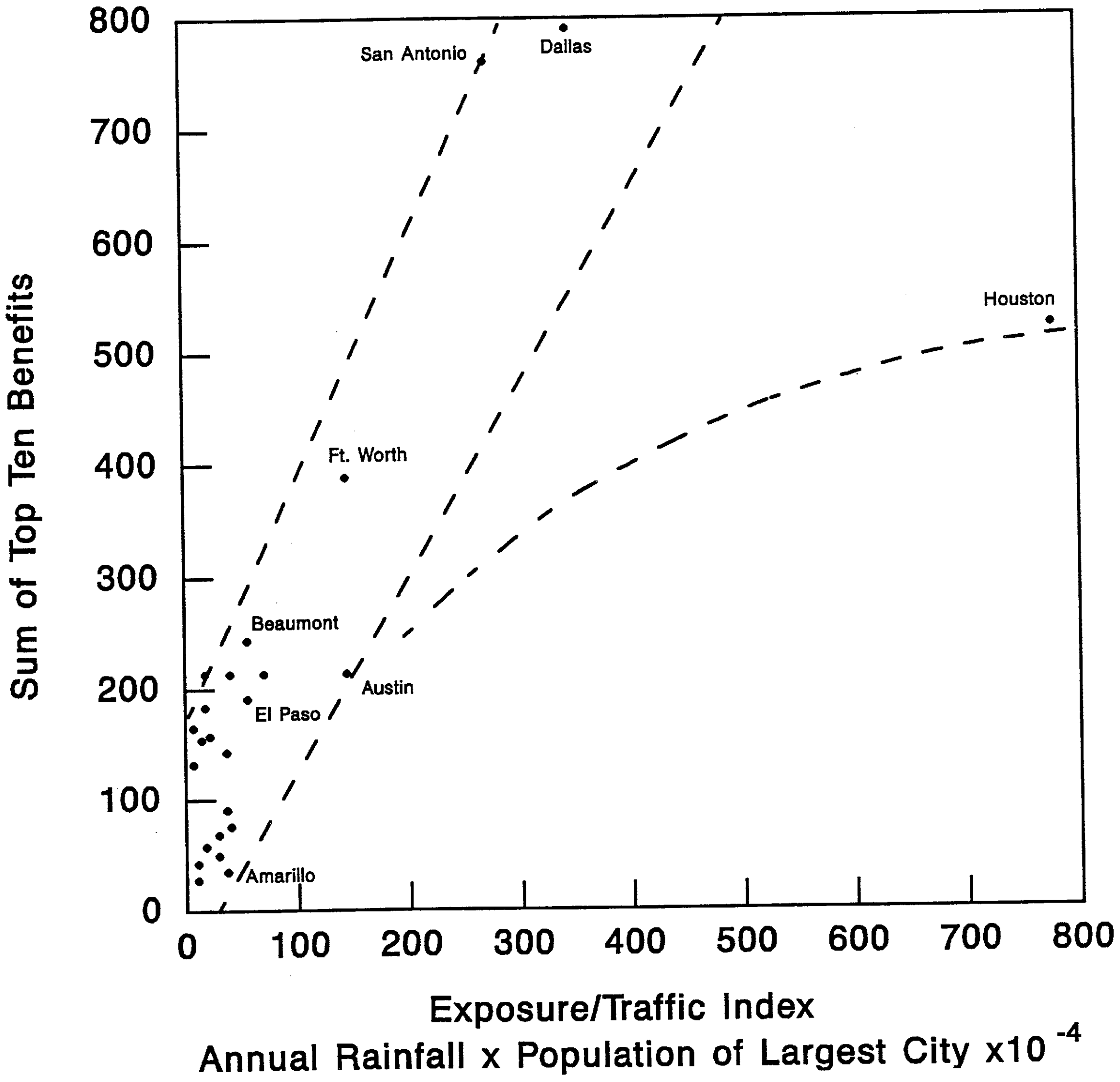


Figure 21. Potential Benefits vs. Exposure-Traffic Index.

# X. FIELD VISITS TO DISTRICT PARTICIPANTS

Field visits to volunteer Texas DOT District participants in the proposed Texas Skid Accident Reduction Program were made by TTI project personnel as part of this project. The following participating Districts and associated personnel were visited in 1991, and accident data were mailed to these Districts in 1992.

- District 11 (Lufkin) - Bill D. Basham
- District 23 (Brownwood) - Sam E. Swan
- District 15 (San Antonio) - John P. Cooper
- District 21 (Pharr) - Rogelio Sandoval
- District 20 (Beaumont) - Lonnie Traxler

The following participating Districts and associated personnel were visited in 1992 and were provided with accident data.

- District 1 (Paris) - James B. Hutchinson, Jr. and Paul R. Hutchins
- District 2 (Ft. Worth) - Glenn E. Elliott, Wallace Euler and David Bass
- District 9 (Waco) - Billy S. Pigg and Larry J. Colclasure
- District 13 (Yoakum) - Paul Frerich
- District 16 (Corpus Christi) - Dallas G. Commuzzie and Ray Mims
- District 18 (Dallas) - Thomas L. Kelley and Leroy Wallen
- District 8 (Abilene) - Otis Jones and Pat McCinley
- District 7 (San Angelo) - Walter McCullough, Dennis Wilde, Mark Tomlison and John Mill
- District 17 (Bryan) - George Boriski, Bob Richardson, Catherine Hejl and Bob Ostracil

The purpose of these visits was to present and discuss the proposed skid accident reduction program and to determine how the District is currently identifying pavements with inadequate frictional properties. Figure 22 shows a representation of the Districts visited under this program and the year in which the visit occurred. During many of these site visits, locations identified as over-represented in wet-pavement accidents were inspected by TTI and

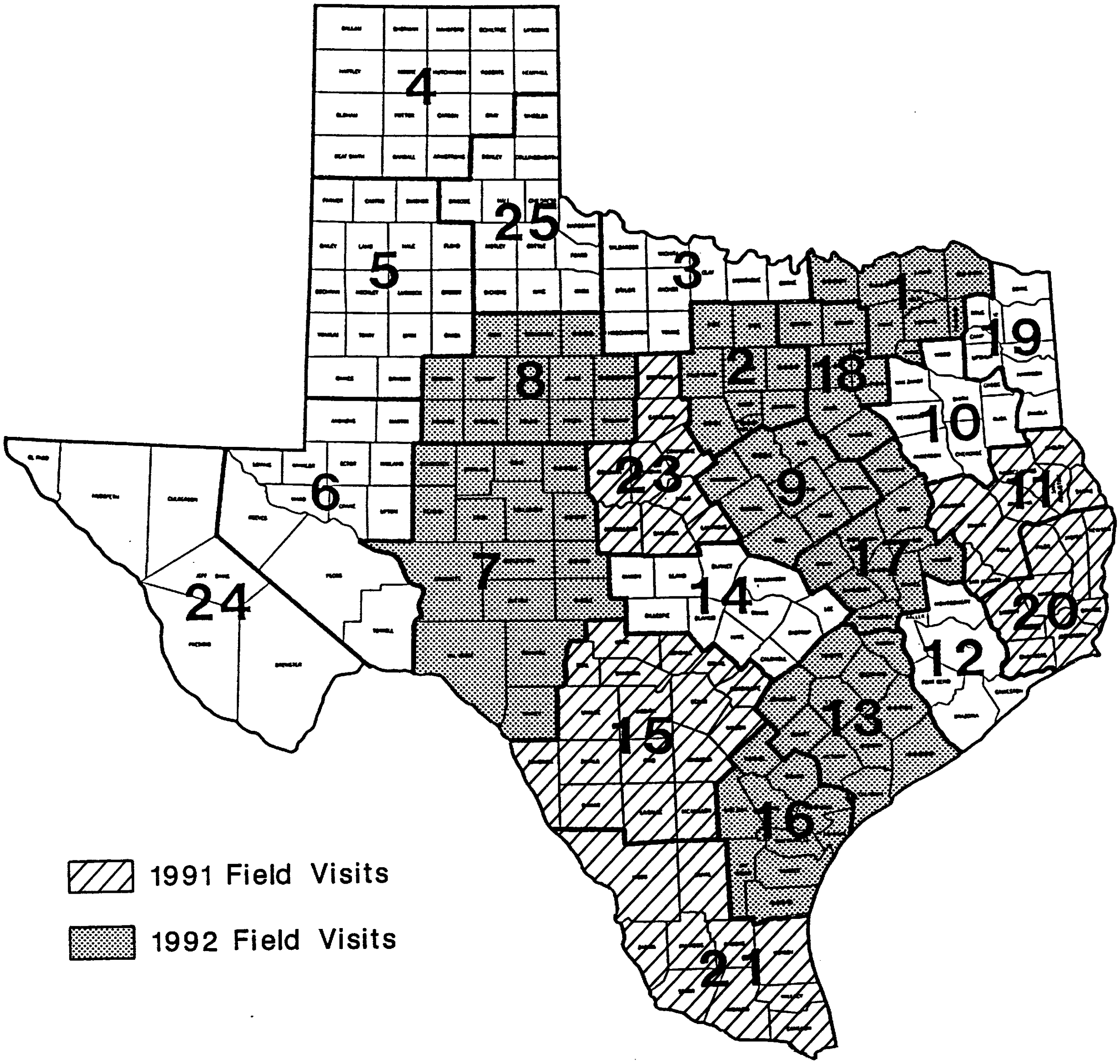


Figure 22. Field visits to TxDOT Districts.

Texas DOT personnel. Additionally, all participants were supplied with the basic tools needed to implement the skid accident reduction program, namely: (1) accident data for the three preceding years, (2) a Pavement Surface Evaluation Field Guide and (3) a Macrotexture Putty Kit.

During these visits it quickly became clear that each District already had in place a methodology and program for identifying and correcting pavement surface deficiencies. Typically, different programs were operating in each District providing similar results. In most cases the Districts were ahead of the accident data on scheduling pavements for seal coat or some other remedial measure. It can be concluded from these observations that although there was not one "single" comprehensive skid accident reduction program in existence, there are probably 24 programs obtaining essentially the same result. With the new wet-surface-to-dry-surface accident ratio program now available, the Districts will have yet another tool at their disposal to monitor the on-system roadways. This is one tool that can be consistent statewide and common to every District.

After gaining an understanding of how an individual District monitors its roadways, the Skid Accident Reduction Program was presented. The accident data were presented in detail. Considerable discussion of the "Benefit" and "Z" values occurred. It was clear during discussions at each District office that the personnel were well aware of most of the problem segments of roadway that we had selected for consideration. As the accident data was presented, usually the District personnel would follow through and check off at least the top five to twenty sites as having already received or in the process of receiving some remedial treatment. Seldom was a problem roadway segment found in the accident data that the District had not already identified.

The Pavement Surface Evaluation Field Guide and Macrotexture Putty Kit were presented following discussion of the accident data. The field guide was reviewed and discussed. Implementation of the guide as a tool for the engineers as well as for the field personnel was discussed. Following the discussion on evaluating pavement surfaces, the putty kit was introduced and its use described in detail. TTI project personnel demonstrated its use on selected roadway surfaces.

During the visits with District personnel, each District was asked about the methodologies presently in use to identify potential problem segments of roadway in terms of wet-surface accidents. Discussion occurred related to the benefit and complimentary nature of the new methodology with methodologies already in use. All the Districts were already using accident frequencies to some extent for identifying potential problem segments. Individual Districts varied widely on their annual use of ASTM Skid Trailers.

In several of the western Districts, it was clear that all the benefits (B values) which appeared to be worthy of some attention were on major highways, usually urban arterials. This may be the case for two reasons. First, these are the only places in a predominately rural District where there is enough traffic to produce pavement polishing and/or flushing. Second, the overall exposure of traffic to wet conditions is so low, due of course to annual rainfall of less than 18 inches, that drivers have very little experience in coping with wet weather driving, thus more frequently over-driving the always reduced wet weather available friction levels. This inexperience characteristic may show itself where there is more traffic with reduced headway and opportunities for recovery. Thus the urban highways or arterials show more of a problem than the less frequently traveled rural farm to market routes. Whether these observations are true is perhaps not as important as the clear identification from accident data that the place to put resurfacing money, from the safety viewpoint, is on the main highways and arterials.

One particular section of road that was of interest to project personnel was identified by the accident data and was well known to District personnel. It was a section through a small town where there was a curve with inadequate superelevation. Remedial treatment for this situation was already scheduled.

It may well be that the proposed skid accident reduction program will do little good in Districts where the annual rainfall is less than 20 inches. The accident data may still be useful to those Districts each year prior to developing the annual seal coat program, primarily as a check to make sure there are no surprise sites of over-represented wet weather accidents.

In conclusion, the program was in general well received by District personnel. The majority of the Districts visited expressed the need for the accident data within the first quarter of each year in order to be of use in planning the following year's seal coat programs.

# APPENDIX A

## Assessing Wet Pavement Friction On Standard Reference Surfaces With Ribbed, Radial and Blank Tires

# ASSESSING WET PAVEMENT FRICTION ON STANDARD REFERENCE SURFACES WITH RIBBED, RADIAL AND BLANK TIRES

by

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April 1990

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## INTRODUCTION

It has long been known that wet surface accident probability (or wet surface accident rate) is not a simple function of skid number. This point is succinctly demonstrated in some data provided by Rizenbergs, Burchett and Warren (1976) and reproduced in Figure 1.[1] The scatter in these data suggests that if the relationship between wet surface accident rate and skid number is ever to be modeled accurately, other variables (e.g., annual rainfall, traffic, roadway geometry, etc.) must be taken into account. Previous attempts to define these "other variables" and to take them into account, however, have met with only limited success (e.g., Ivey, Griffin, Newton and Lytton, 1981).

In a 1980 article, Henry implies that one factor that may explain some of the scatter in plots such as those shown in Figure 1 is the ASTM E-501 ribbed tire used in the ASTM E-274, full-scale, locked-wheel skid test.[2] The E-501 tire used in recording skid numbers has seven circumferential ribs (0.66 in wide) separated by six grooves (0.20 in wide). These six grooves, in effect, are paths for draining water from beneath the tire during skid testing. Passenger car tires – particularly worn or bald passenger car tires that, presumably, are more likely to be involved in wet-surface accidents – do not have such effective drainage paths. Therefore, on a low-texture surface, a worn or bald passenger car tires should generate a lower skid number than a ribbed tire, other factors being equal.

Having argued that the ASTM E-501 ribbed tire lacks "face validity" (i.e., it does not does not generate the same skid number that a bald passenger car tire generates), now consider this: if a bald tire (e.g., the ASTM E-524 blank tire) records lower skid numbers than the ASTM E-501 ribbed tire, but if the differences in recorded skid numbers between the blank and ribbed tires are constant regardless of the pavement tested, then none of the scatter in Figure

---

[1] The accident data in Figure 1 were collected at 230 sites along rural, two-lane highways in the state of Kentucky (1969-1971). The 230 sites ranged in length from 2.0 to 16.7 miles. Traffic volumes ranged from 650 to 8,400 vehicles per day.

[2] References to applicable ASTM standards of the American Society for Testing and Materials are cited at the end of this paper.

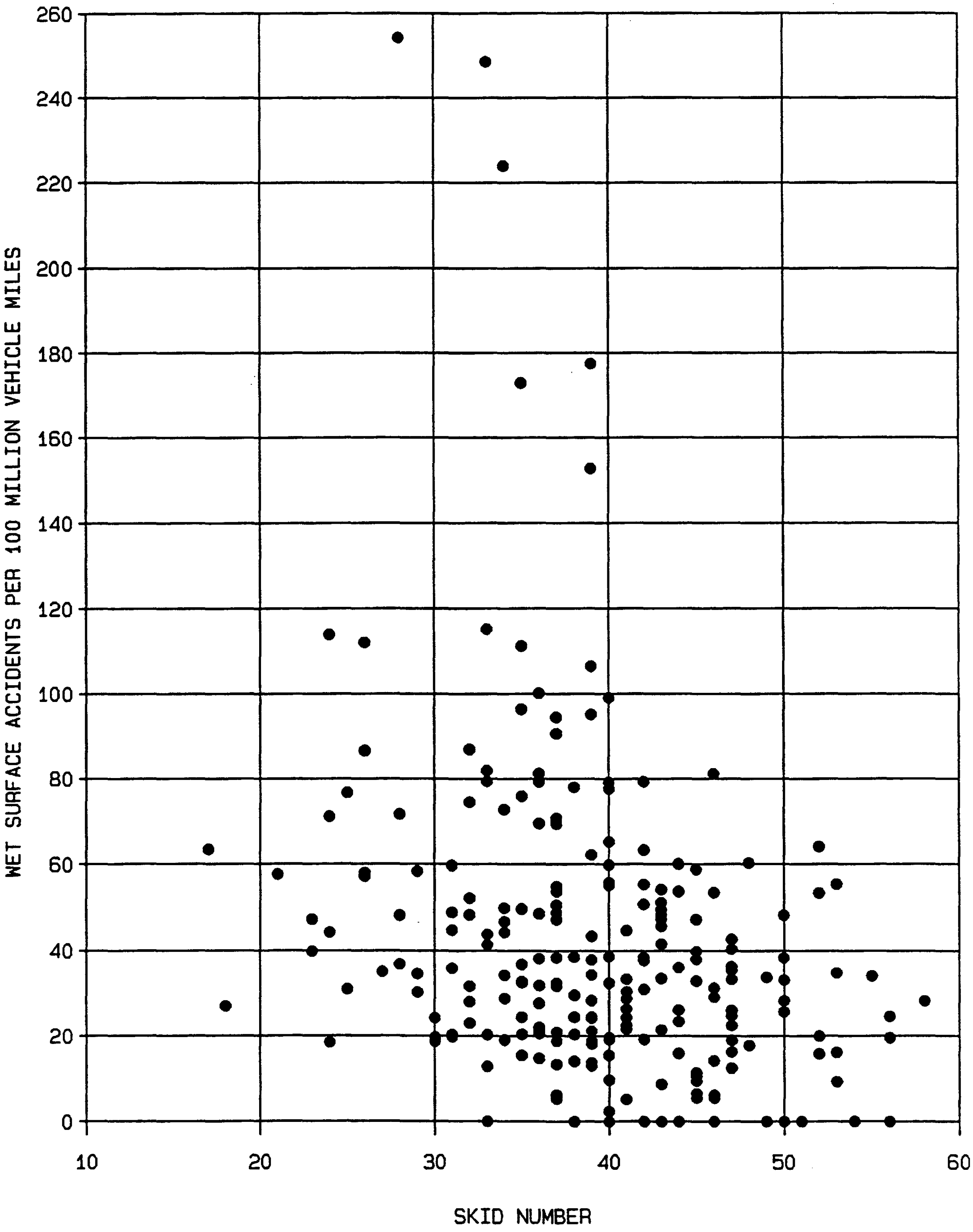

FIGURE 1: DATA FROM RIZENBERGS ET AL. (1976, FIGURE 8, P 8)

1 (and similarly constructed figures) might be explained by use of the ASTM E-501 tire. If, on the other hand, differences in recorded skid numbers between the blank and ribbed tires vary with different pavements, then, indeed, some of the scatter in Figure 1 (and similarly constructed figures) can be explained by use of the ASTM E-501 tire.

In Figure 2 some data provided by Henry are reproduced. These data were collected at four sites (A, B, C and D) and depict skid number ($SN_{40}$) as a function of pavement type (grooved and ungrooved Portland Cement Concrete (PCC)) and tire (ASTM E-501 ribbed and ASTM E-524 blank tires). Note that on the ungrooved PCC, the $SN_{40}$ for the blank tire is approximately 20 and for the ribbed tire it is almost 40. On the grooved PCC, both the blank and ribbed tires have $SN_{40}$'s around 40. The point to be made by this figure is not that the skid number generated by the blank tire is less than the skid number generated by the ribbed tire, but that the solid lines connecting the ribbed tire data are <u>not parallel</u> to the corresponding dashed lines connecting the blank tire data. This lack of parallelism in the data is referred to as an interaction between tire and pavement.

Henry has conclusively shown that for grooved and ungrooved PCC, pavement does interact with tire (i.e., ribbed or blank tire) in the recording of skid numbers. If the data in Figure 1 had been collected on grooved and ungrooved PCC (which they were not), it is clear that some of the scatter in the plot might have resulted from this tire by pavement interaction.

To determine if the tire by pavement interaction reported by Henry on grooved and ungrooved PCC could be observed with "typical" flexible pavements, an experiment was conducted at the Central and Western Field Test and Evaluation Center at the Texas Transportation Institute. The procedures employed in this experiment are documented in the next section.

## PROCEDURE

The experiment reported in this paper utilized three different tires and three different reference surfaces. All tests were conducted with a full-scale, locked-wheel skid measurement system as prescribed in ASTM E-274. The three tires employed were the: ASTM E-501 ribbed tire, E-524 blank tire, and E-1136 radial

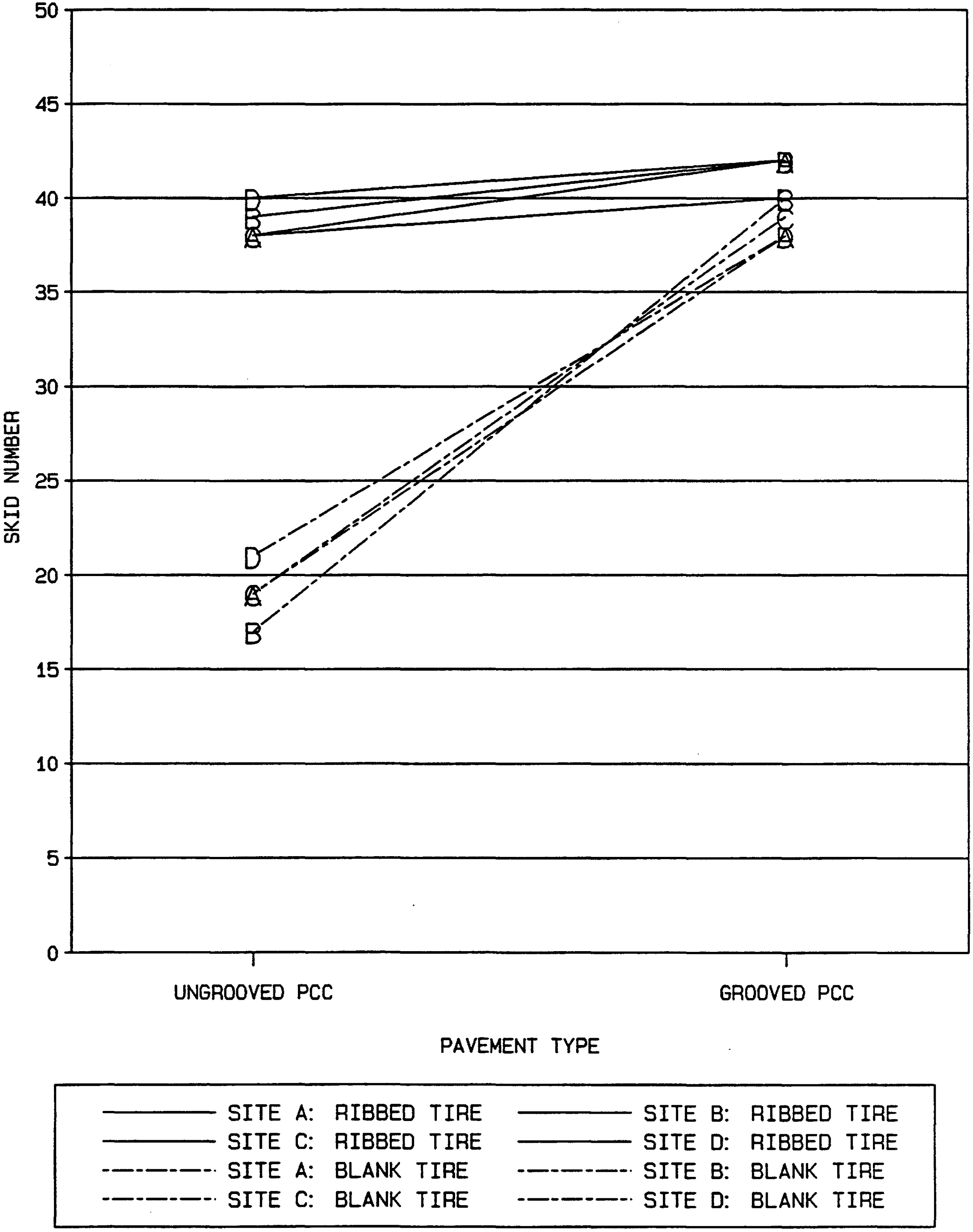

FIGURE 2: DATA FROM HENRY (1980, FIGURE 5, P 3)

tire. The three reference surfaces were:

(1) Jennite Seal Coat (Secondary Reference Surface 2) - A coal tar seal coat with no additives such as sand. Characterized by low macrotexture and low microtexture.

(2) Jennite Seal Coat with Sand (Primary Reference Surface 4) - Same as previous surface with the addition of sand to increase friction. Characterized by moderate macrotexture and moderate microtexture.

(3) Rounded Gravel Hot Mix (Secondary Reference Surface 5) - Asphalt surface with smooth aggregate. Characterized by high macrotexture and low microtexture.

Pavement textures for the three reference surfaces (as measured by ASTM E-965) were 0.610, 0.980 and 1.500 mm, respectively.

## DATA COLLECTION

Skid numbers were recorded under four treatment conditions with each of three different tires in the following order:

| Treatment | Tire | Test Date |
|---|---|---|
| (1) | Ribbed (ASTM E-501) | 7-5-89 |
| (2) | Blank (ASTM E-524) | 7-6-89 |
| (3) | Radial (ASTM E-1136) | 7-7-89 (morning) |
| (4) | Ribbed (ASTM E-501) | 7-7-89 (afternoon) |

Within each of the four treatment conditions, six test runs were made for each of three pavement types [(1) Jennite Seal Coat, (2) Jennite Seal Coat with Sand, and (3) Rounded Gravel Hot Mix] and four speeds [20, 30, 40 and 50 miles per hour]. The order of testing by pavement type and speed was randomized within treatment conditions. Altogether, 288 skid numbers were recorded.[3]

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[3] The raw data for this experiment, the 288 data records, are available from the research agency.

The data were analyzed using multiple regression procedures, with skid number (Y) serving as the dependent variable. Three independent variables (T, T2 and T3) were defined to represent the four treatment conditions. Two independent variables (P1 and P2) were used to represent pavement type, and one independent variable (S) was used to represent speed. The variables were defined as shown in the box that follows.

Y = skid number (Dependent Variable)

Main
<u>Effects</u>

Treatment
T = i-1 for treatments 1 thru 4 (i.e., i = 1 through 4)
T2 = 1 if a blank tire, 0 otherwise
T3 = 1 if a radial tire, 0 otherwise

Pavement
P1 = 1 if Jennite Flush Seal, 0 otherwise
P2 = 1 if Jennite Flush Seal with Sand, 0 otherwise

Speed S = 20, 30, 40, or 50

The "dummy" coding used to represent the four treatment conditions is somewhat unusual, but purposely chosen so that one variable (T) not only served (with T2 and T3) to uniquely define the four different levels of treatment, but also served to define the <u>temporal order</u> of the four treatment conditions. If T is shown to be a significant variable in the multiple regression analyses that follow, then there is evidence that recorded skid numbers were changing during the course of the experiment (e.g., the pavements may have become slicker due to polishing with successive treatments). But, by setting T equal to zero, any temporal (e.g., polishing) effect in the data can be factored out of the analyses. And, when temporal order is factored out of the analyses, the effects of the three tires -- ribbed, blank and radial -- can be assessed, independent of the temporal order in which they were tested.

## SELECTING A REGRESSION MODEL[4]

The first multiple regression model developed contained all three main effects (Treatment, Pavement, Speed), and all possible first and second order interactions of those main effects, as shown in Table 1.[5] This model fits the data quite well ($R^2 = 0.9656$).

To test whether or not there is a significant temporal effect in the data, T (and all interactions with T) will be removed from the previous, full model (Model 1). The new, reduced model (Model 2) is shown in Table 2. If the predictive power (i.e., the $R^2$'s) of Models 1 and 2 differ by no more than chance, then T is not significant; conversely, if Model 1 provides a significantly higher $R^2$ than Model 2, then T is a significant variable.

The significance of the difference between the two models, and therefore the significance of variable T, can be assessed with a standard F test:

$$F = \frac{[SSE(R) - SSE(F)]/[df(R) - df(F)]}{SSE(F)/df(F)} \tag{1}$$

In Eq 1 the sums of squared error for the full and reduced models are represented as SSE(F) and SSE(R), with df(F) and df(R) degrees of freedom, respectively. The test statistic, F, has df(F) - df(R) and df(F) degrees of freedom.

Comparing Models 1 and 2, $F_{(6;\,264)} = 5.49$, which is significant at $\alpha = 0.01$, indicating that there is a temporal effect in the data and that T should not be deleted, i.e., Model 2 is not acceptable.

In an attempt to simplify Model 1, another model (Model 3) was developed by excluding all second order interactions from Model 1 (see Table 3). Taking Model 1 as the full model, Model 3 as the reduced model, and reapplying Eq 1,

---

[4] The statistical significance of five regression models will be assessed in this section. Each model will be assessed at $\alpha = 0.01$. The model finally chosen based upon the 288 skid numbers in the data set is, therefore, significant at approximately $\alpha = 0.05$.

[5] The interaction of T2 by P1 is represented as T2XP1. Other interactions are represented in similar fashion.

Table 1

```
Model: MODEL1
Dependent Variable: Y
                         Analysis of Variance

                            Sum of           Mean
 Source            DF      Squares         Square       F Value       Prob>F

 Model             23  22987.55953      999.45911       322.271       0.0001

 Error            264    818.74367        3.10130
 C Total          287  23806.30319

            Root MSE       1.76105      R-square        0.9656
            Dep Mean      29.84236      Adj R-sq        0.9626
            C.V.           5.90118

                         Parameter Estimates

                    Parameter      Standard     T for H0:
  Variable  DF       Estimate         Error   Parameter=0    Prob > |T|

  INTERCEP   1      48.620000    1.18134914        41.156        0.0001
  T          1      -1.364444    0.55689333        -2.450        0.0149
  T2         1      -0.262222    1.47340125        -0.178        0.8589
  T3         1       0.178889    1.47340125         0.121        0.9035
  P1         1     -13.788333    1.67067998        -8.253        0.0001
  P2         1      -4.825000    1.67067998        -2.888        0.0042
  S          1      -0.165333    0.03215225        -5.142        0.0001

  TXP1       1       0.573333    0.78756609         0.728        0.4673
  TXP2       1       0.738333    0.78756609         0.937        0.3494
  T2XP1      1      -6.968333    2.08370403        -3.344        0.0009
  T2XP2      1      -7.403333    2.08370403        -3.553        0.0005
  T3XP1      1       0.646667    2.08370403         0.310        0.7565
  T3XP2      1      -2.765000    2.08370403        -1.327        0.1857
  TXS        1       0.014222    0.01515672         0.938        0.3489
  T2XS       1      -0.139056    0.04010090        -3.468        0.0006
  T3XS       1      -0.043444    0.04010090        -1.083        0.2796
  P1XS       1      -0.187833    0.04547015        -4.131        0.0001
  P2XS       1      -0.187500    0.04547015        -4.124        0.0001

  TXP1XS     1       0.003500    0.02143483         0.163        0.8704
  TXP2XS     1      -0.004944    0.02143483        -0.231        0.8177
  T2XP1XS    1       0.142667    0.05671124         2.516        0.0125
  T2XP2XS    1       0.146444    0.05671124         2.582        0.0104
  T3XP1XS    1       0.067833    0.05671124         1.196        0.2327
  T3XP2XS    1       0.072889    0.05671124         1.285        0.1998
```

Table 2

```
Model: MODEL2
Dependent Variable: Y

                           Analysis of Variance

                            Sum of          Mean
 Source           DF       Squares        Square       F Value        Prob>F

  Model           17   22885.34469    1346.19675       394.668        0.0001
  Error          270     920.95850       3.41096
  C Total        287   23806.30319

           Root MSE        1.84688      R-square         0.9613
            Dep Mean      29.84236       Adj R-sq         0.9589
            C.V.           6.18878


                           Parameter Estimates

                      Parameter       Standard     T for H0:
  Variable  DF         Estimate          Error   Parameter=0     Prob > |T|

  INTERCEP  1       46.573333     0.87605104         53.163         0.0001
  T2        1        0.420000     1.51736490          0.277         0.7821
  T3        1       -0.503333     1.51736490         -0.332         0.7404
  P1        1      -12.928333     1.23892326        -10.435         0.0001
  P2        1       -3.717500     1.23892326         -3.001         0.0029
  S         1       -0.144000     0.02384309         -6.039         0.0001

  T2XP1     1       -7.255000     2.14587803         -3.381         0.0008
  T2XP2     1       -7.772500     2.14587803         -3.622         0.0003
  T3XP1     1        0.933333     2.14587803          0.435         0.6640
  T3XP2     1       -2.395833     2.14587803         -1.116         0.2652
  T2XS      1       -0.146167     0.04129744         -3.539         0.0005
  T3XS      1       -0.036333     0.04129744         -0.880         0.3798
  P1XS      1       -0.182583     0.03371922         -5.415         0.0001
  P2XS      1       -0.194917     0.03371922         -5.781         0.0001

  T2XP1XS   1        0.140917     0.05840340          2.413         0.0165
  T2XP2XS   1        0.148917     0.05840340          2.550         0.0113
  T3XP1XS   1        0.069583     0.05840340          1.191         0.2345
  T3XP2XS   1        0.070417     0.05840340          1.206         0.2290
```

```
Table 3

Model: MODEL3
Dependent Variable: Y

                         Analysis of Variance

                          Sum of        Mean
  Source          DF     Squares       Square        F Value      Prob>F

 Model            17  22958.29862   1350.48815       429.988      0.0001
  Error          270    848.00457      3.14076
  C Total        287  23806.30319

            Root MSE       1.77222     R-square        0.9644
            Dep Mean      29.84236     Adj R-sq        0.9621
            C.V.           5.93860


                          Parameter Estimates

                     Parameter       Standard     T for H0:
   Variable  DF       Estimate          Error    Parameter=0     Prob > |T|

   INTERCEP   1      49.848403     0.87869387         56.730         0.0001
   T          1      -1.347593     0.35224894         -3.826         0.0002
   T2         1      -3.635185     0.93196309         -3.901         0.0001
   T3         1      -1.462870     0.93196309         -1.570         0.1177
   P1         1     -15.813958     0.95024619        -16.642         0.0001
   P2         1      -6.484583     0.95024619         -6.824         0.0001
   S          1      -0.200431     0.02287924         -8.760         0.0001

   TXP1       1       0.695833     0.24116836          2.885         0.0042
   TXP2       1       0.565278     0.24116836          2.344         0.0198
   T2XP1      1      -1.975000     0.63807151         -3.095         0.0022
   T2XP2      1      -2.277778     0.63807151         -3.570         0.0004
   T3XP1      1       3.020833     0.63807151          4.734         0.0001
   T3XP2      1      -0.213889     0.63807151         -0.335         0.7377
   TXS        1       0.013741     0.00880622          1.560         0.1198
   T2XS       1      -0.042685     0.02329908         -1.832         0.0680
   T3XS       1       0.003463     0.02329908          0.149         0.8820
   P1XS       1      -0.129958     0.02287924         -5.680         0.0001
   P2XS       1      -0.140083     0.02287924         -6.123         0.0001
```

an $F_{(6;\ 264)}$ = 1.57 is calculated. This F is not significant at $\alpha = 0.01$. The second order interactions, therefore, can be deleted with no significant loss of information.

Model 3 now becomes the base model (i.e., the full model) upon which further simplifications or reductions will be performed. Model 4 was defined by removing the first-order, Treatment by Speed interactions (TXS, T2XS, T3XS) from Model 3 (see Table 4). The effect of deleting these interactions is tested by reapplying Eq 1 with Model 3 serving as the full model and Model 4 the reduced model. Since the calculated $F_{(3;\ 270)}$ equals 2.89, which is not significant at $\alpha = 0.01$, these interactions may be safely deleted.

Model 4 replaces Model 3 as the base model (i.e., the full model) from which to work. Model 5 was defined by removing the first-order interactions between Treatment and Pavement (TXP1, TXP2, T2XP1, T2XP2, T3XP1, T3XP2) from Model 4 (see Table 5). Using Model 4 as the full model, and Model 5 as the reduced model, an $F_{(6;\ 273)}$ of 13.72 is calculated (Eq 1). This F is significant at $\alpha = 0.01$, i.e., the Device by Pavement interactions are statistically significant and, therefore, should not be deleted.

Model 4 remains the base model (i.e., the full model) from which to consider further reductions or simplifications. Model 6 evaluates the deletion of the first-order, Pavement by Speed interactions (P1XS, P2XS) from Model 4 (see Table 6). Applying Eq 1 a fifth and last time, an $F_{(2;\ 273)}$ equal to 22.84 is calculated. This F is significant at $\alpha = 0.01$, which means that these Pavement by Speed interactions should not be deleted.

Model 4 is therefore retained as the best model to represent the 288 skid numbers in the data set. The $R^2$ for Model 4 is 0.9632, a value very close to the $R^2$ of Model 1 (0.9656). Note, however, that there are only 14 variables in Model 4, but 23 variables in Model 1.

## RESULTS

Before looking at the results of the multiple regression analysis, four summary figures will be presented that depict mean skid number (based upon six skid runs) as a function of treatment condition [ribbed tire (initial runs), blank tire, radial tire and ribbed tire (final runs)] and pavement [Jennite Seal

Table 4

```
Model: MODEL4
Dependent Variable: Y

                          Analysis of Variance

                            Sum of         Mean
  Source          DF       Squares       Square      F Value       Prob>F

  Model           14   22931.05049   1637.93218      510.887       0.0001
  Error          273     875.25271      3.20605
  C Total        287   23806.30319

             Root MSE       1.79055     R-square       0.9632
             Dep Mean      29.84236     Adj R-sq       0.9613
             C.V.           6.00001


                          Parameter Estimates

                    Parameter      Standard    T for H0:
   Variable  DF      Estimate         Error   Parameter=0    Prob > |T|

   INTERCEP   1     49.470208    0.67887425        72.871        0.0001
   T          1     -0.866667    0.17229534        -5.030        0.0001
   T2         1     -5.129167    0.45585062       -11.252        0.0001
   T3         1     -1.341667    0.45585062        -2.943        0.0035
   P1         1    -15.813958    0.96007317       -16.472        0.0001
   P2         1     -6.484583    0.96007317        -6.754        0.0001
   S          1     -0.189625    0.01634537       -11.601        0.0001

   TXP1       1      0.695833    0.24366241         2.856        0.0046
   TXP2       1      0.565278    0.24366241         2.320        0.0211
   T2XP1      1     -1.975000    0.64467013        -3.064        0.0024
   T2XP2      1     -2.277778    0.64467013        -3.533        0.0005
   T3XP1      1      3.020833    0.64467013         4.686        0.0001
   T3XP2      1     -0.213889    0.64467013        -0.332        0.7403
   P1XS       1     -0.129958    0.02311585        -5.622        0.0001
   P2XS       1     -0.140083    0.02311585        -6.060        0.0001
```

```
Table 5

Model: MODEL5
Dependent Variable: Y

                          Analysis of Variance

                            Sum of          Mean
 Source           DF       Squares        Square      F Value       Prob>F

 Model             8   22667.12472    2833.39059      693.935       0.0001
 Error           279    1139.17847       4.08308
 C Total         287   23806.30319

          Root MSE         2.02066     R-square         0.9521
          Dep Mean        29.84236     Adj R-sq         0.9508
          C.V.             6.77112


                          Parameter Estimates

                   Parameter        Standard     T for H0:
  Variable  DF      Estimate           Error   Parameter=0     Prob > |T|

  INTERCEP   1     48.960139      0.70843363        69.110         0.0001
  T          1     -0.446296      0.11225903        -3.976         0.0001
  T2         1     -6.546759      0.29700947       -22.042         0.0001
  T3         1     -0.406019      0.29700947        -1.367         0.1727
  P1         1    -14.508750      0.95848439       -15.137         0.0001
  P2         1     -6.259583      0.95848439        -6.531         0.0001
  S          1     -0.189625      0.01844604       -10.280         0.0001

  P1XS       1     -0.129958      0.02608664        -4.982         0.0001
  P2XS       1     -0.140083      0.02608664        -5.370         0.0001
```

Table 6

```
Model: MODEL6
Dependent Variable: Y

                         Analysis of Variance

                            Sum of           Mean
 Source            DF      Squares         Square      F Value       Prob>F

 Model             12  22784.59039     1898.71587      511.051       0.0001
 Error            275   1021.71281        3.71532
 C Total          287  23806.30319

          Root MSE         1.92752      R-square        0.9571
          Dep Mean        29.84236      Adj R-sq        0.9552
          C.V.             6.45899


                         Parameter Estimates

                    Parameter        Standard    T for H0:
 Variable  DF        Estimate           Error   Parameter=0    Prob > |T|

 INTERCEP   1       52.620694      0.53031031        99.226        0.0001
 T          1       -0.866667      0.18547535        -4.673        0.0001
 T2         1       -5.129167      0.49072164       -10.452        0.0001
 T3         1       -1.341667      0.49072164        -2.734        0.0067
 P1         1      -20.362500      0.55642604       -36.595        0.0001
 P2         1      -11.387500      0.55642604       -20.465        0.0001
 S          1       -0.279639      0.01015890       -27.526        0.0001

 TXP1       1        0.695833      0.26230175         2.653        0.0084
 TXP2       1        0.565278      0.26230175         2.155        0.0320
 T2XP1      1       -1.975000      0.69398520        -2.846        0.0048
 T2XP2      1       -2.277778      0.69398520        -3.282        0.0012
 T3XP1      1        3.020833      0.69398520         4.353        0.0001
 T3XP2      1       -0.213889      0.69398520        -0.308        0.7582
```

Coat, Jennite Seal Coat with Sand, and Rounded Gravel Hot Mix]. Figures 3 through 6 represent speeds of 20, 30, 40 and 50 miles per hour, respectively. The general impression to be gained from these figures is that although some tire by pavement interaction is evident in the data, that interaction appears, as a practical matter, to be fairly minor. The lines in Figures 3 through 6 are roughly parallel.

Returning to the selected regression model (Model 4) and setting T equal to zero to remove the temporal effects from the predicted skid numbers, the following equation is produced:

$$\begin{aligned} Y = {} & 49.47 - 5.13\,T2 - 1.34\,T3 - 15.81\,P1 - 6.48\,P2 - 0.19\,S \\ & - 1.98\,T2XP1 - 2.28\,T2XP2 + 3.02\,T3XP1 - 0.21\,T3XP2 \\ & - 0.13\,P1XS - 0.14\,P2XS \end{aligned} \tag{2}$$

Breaking Eq 2 down by pavement type produces the following equations:

Jennite Seal Coat $\quad Y = 33.66 - 7.11\,T2 + 1.68\,T3 - 0.32\,S \quad (3)$

Jennite Seal Coat with Sand $\quad Y = 42.99 - 7.41\,T2 - 1.55\,T3 - 0.33\,S \quad (4)$

Rounded Gravel Hot Mix $\quad Y = 49.47 - 5.13\,T2 - 1.34\,T3 - 0.19\,S \quad (5)$

The data for Figures 7 through 10 are derived from Eqs 3, 4 and 5. All four figures (7 through 10) are of exactly of the same form, differing only in terms of height above the horizontal axis. The small deviations from the parallel shown in these figures are statistically significant, though arguably of little practical importance.

From Eqs 3, 4 and 5 the following observations are offered:

(1) The speed coefficient for the Round Gravel Hot Mix (- 0.19) differs considerably from the speed coefficients for the Jennite Seal Coat and Jennite Seal Coat with Sand pavements (- 0.32 and - 0.33), but there appears to be no significant difference between the latter two coefficients. In other words, for any given tire (ribbed, blank or radial), a plot of skid number on speed will yield nearly parallel lines for Jennite Seal Coat and Jennite Seal Coat with Sand, but not for Rounded Gravel Hot Mix.

(2) On all three pavements, the blank tire ($T2 = 1$ and $T3 = 0$) produces significantly lower skid numbers than the other two tires.

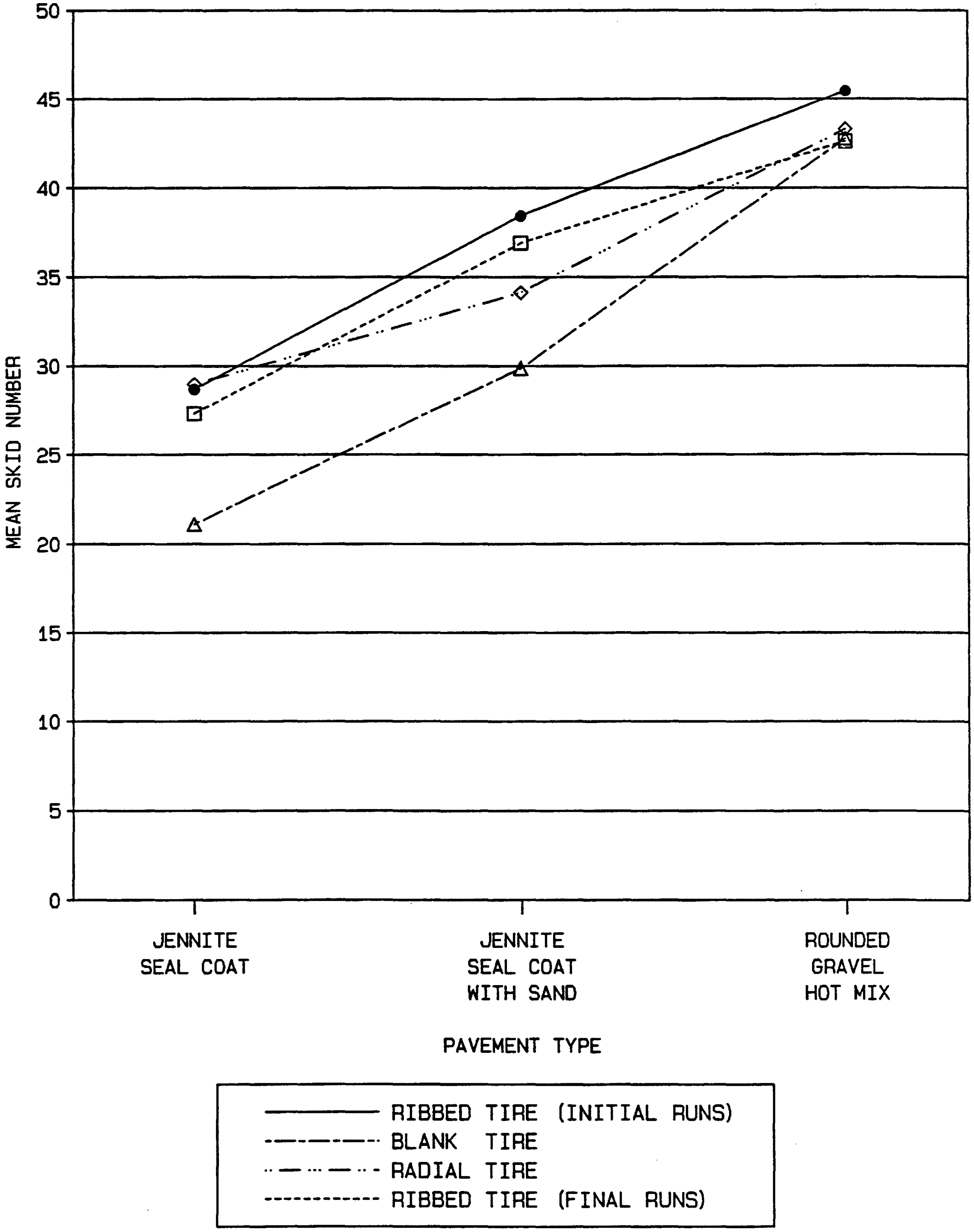

FIGURE 3: MEAN SKID NUMBER BY PAVEMENT TYPE (20 MILES PER HOUR)

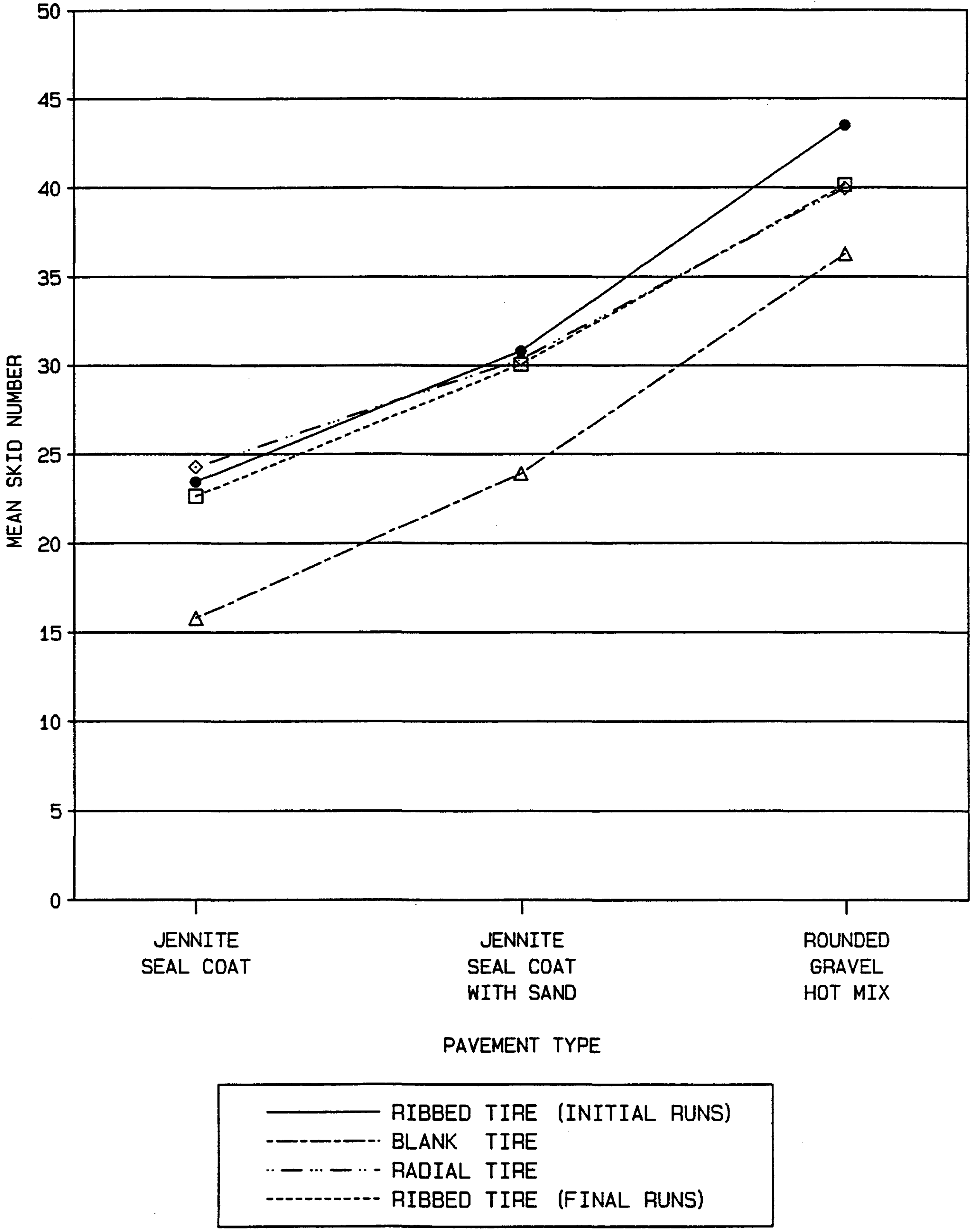

FIGURE 4: MEAN SKID NUMBER BY PAVEMENT TYPE (30 MILES PER HOUR)

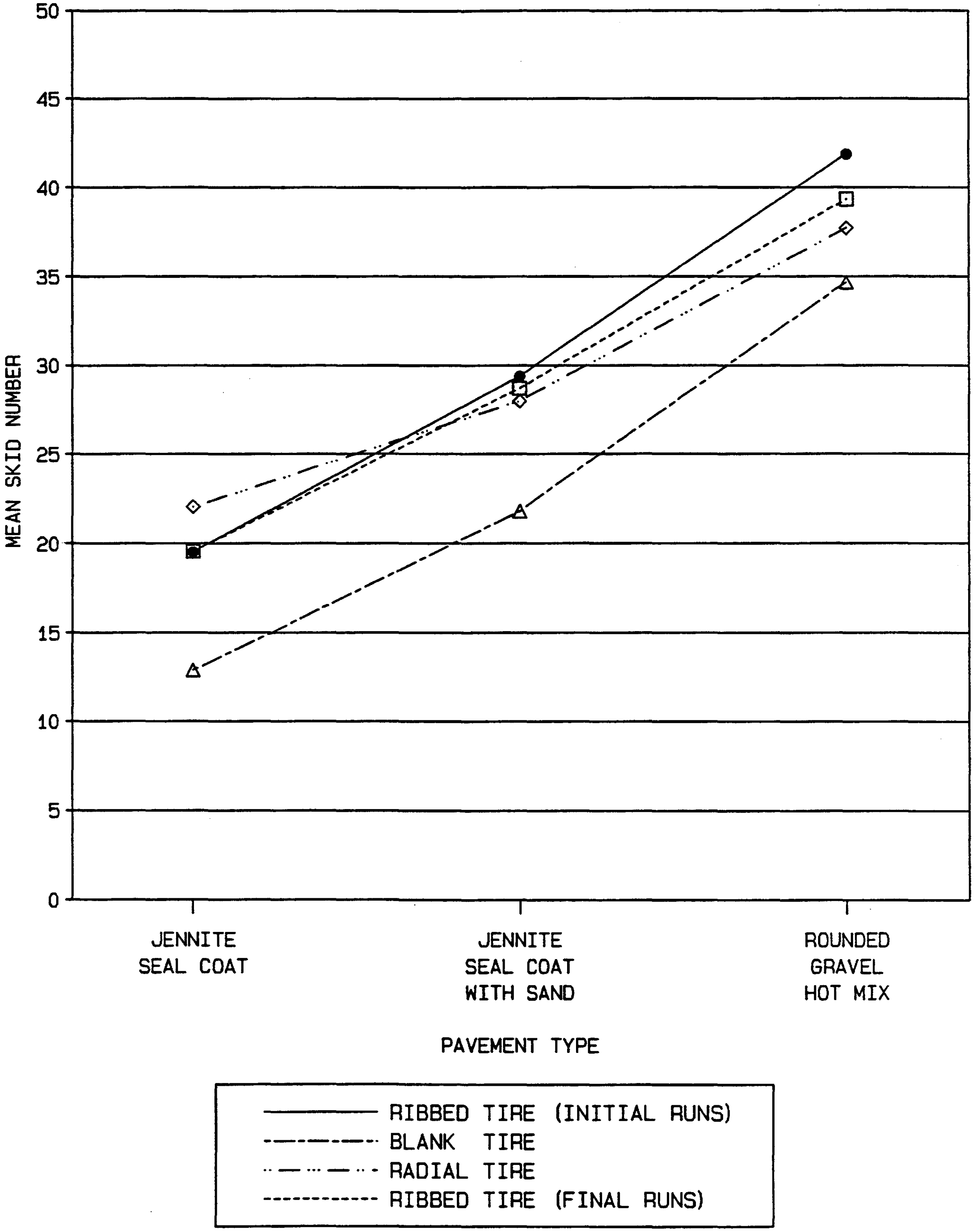

FIGURE 5: MEAN SKID NUMBER BY PAVEMENT TYPE (40 MILES PER HOUR)

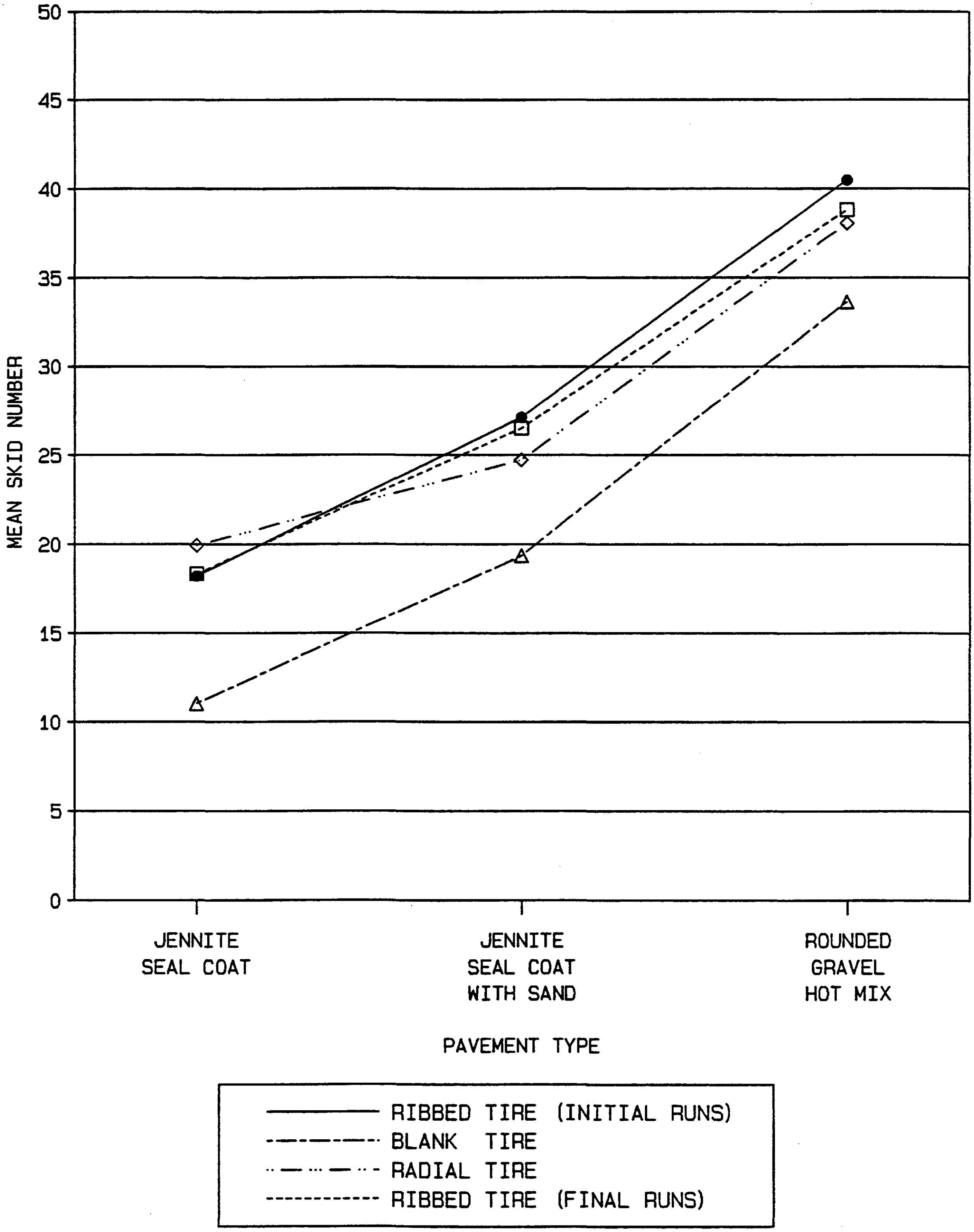

FIGURE 6: MEAN SKID NUMBER BY PAVEMENT TYPE (50 MILES PER HOUR)

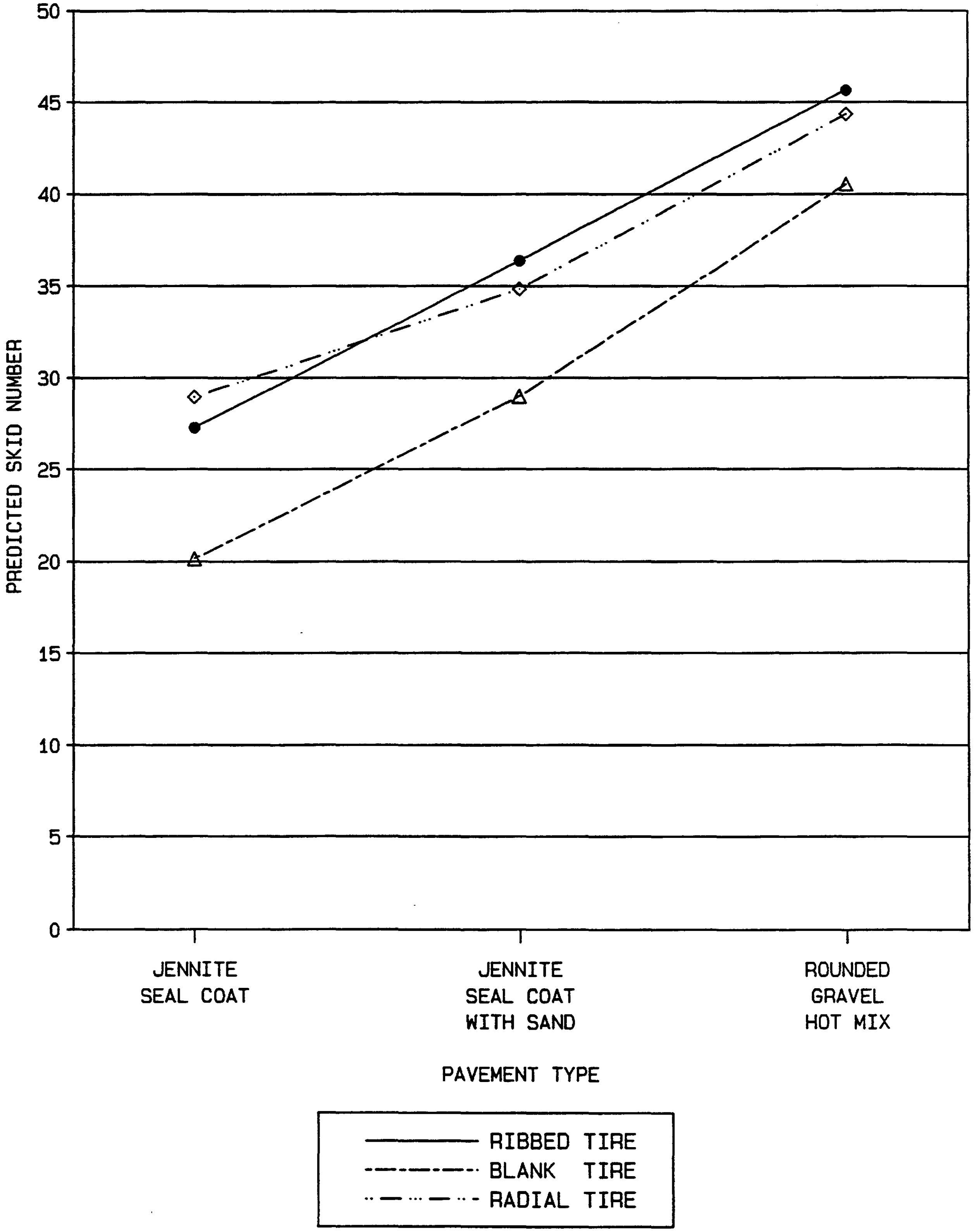

FIGURE 7: FITTED DATA FROM MODEL FOUR (20 MILES PER HOUR)

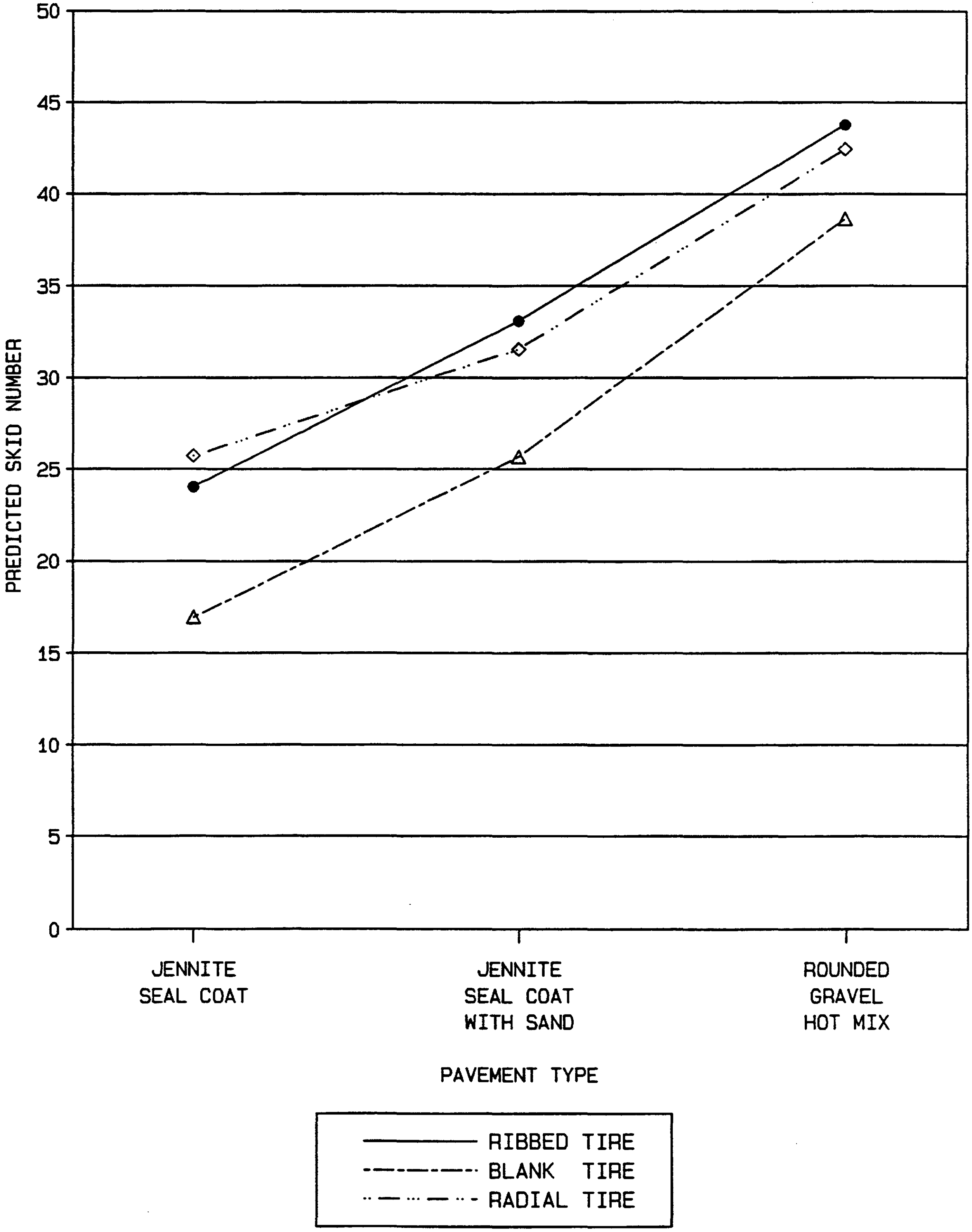

FIGURE 8: FITTED DATA FROM MODEL FOUR (30 MILES PER HOUR)

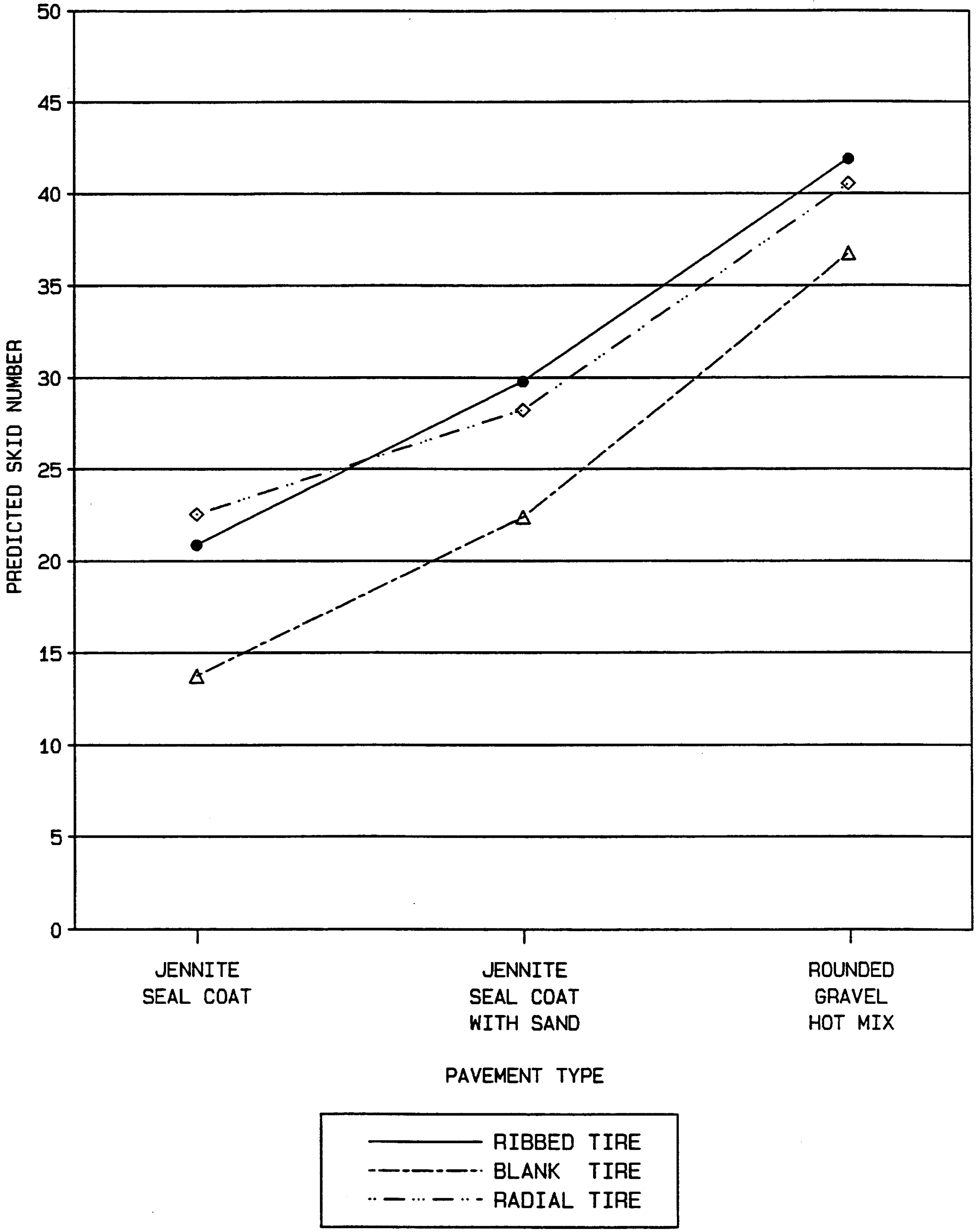

FIGURE 9: FITTED DATA FROM MODEL FOUR (40 MILES PER HOUR)

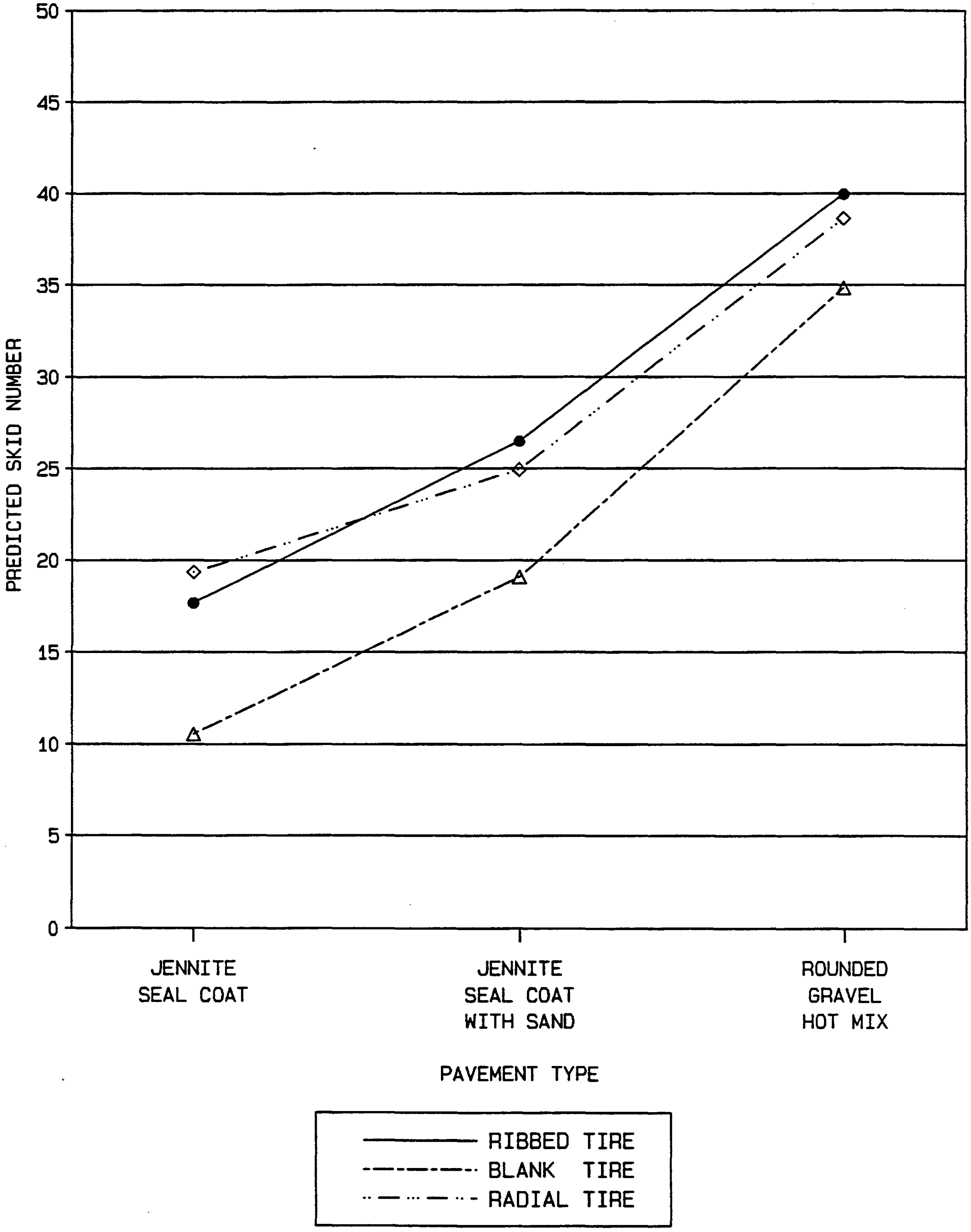

FIGURE 10: FITTED DATA FROM MODEL FOUR (50 MILES PER HOUR)

(3) The radial tire (T2 = 0 and T3 = 1) produces higher skid numbers than the ribbed tire (T2 = 0 and T3 = 0) on the Jennite Seal Coat pavement. The reverse is true on the other two pavements, Jennite Seal Coat with Sand and the Rounded Gravel Hot Mix.

## CONCLUSION

If wet surface accident probability or wet surface accident rate could be shown to be a function of skid number (or skid number acting in concert with other identifiable variables), the possibility of identifying potentially hazardous segments of highways before those segments recorded any significant number of wet surface accidents might be realized. To date, however, various attempts to regress wet surface accident rate on skid number (and assorted other predictor variables) have yielded equations of very low predictive validity.

Henry implies that one factor contributing to this low predictive validity is the ASTM E-501 ribbed tire itself. The surface structure of the E-501 ribbed tire is so unlike the surface structure on passenger car tires involved in wet surface accidents that the skid numbers taken with this tire may be well above the skid numbers that would be recorded with passenger car tires, particularly bald (blank) tires. If the difference in skid number measurements for the E-501 ribbed tire and, say, the E-524 blank tire were constant across all pavement types – regardless of pavement grooving or macrotexture – then both tires would be equally valid for purposes of regression analysis, i.e., the skid numbers generated by the ribbed tire or the blank tire would be equally good for purposes of predicting wet surface accidents. But, such is not the case. Henry has shown that ribbed and blank tires produce very similar skid numbers on grooved PCC, but very different numbers on ungrooved PCC. Thus, if we were to collect skid numbers on, say, 100 grooved and 100 ungrooved PCC segments with a ribbed tire and a blank tire, the blank tire data would be much more variable than the ribbed tire data, and, presumably, much more representative of the wet-pavement surface conditions that would be faced by drivers of passenger cars operated with bald tires.

In the present study, a tire by pavement interaction was found when three tires (the ASTM E-501 ribbed tire, the E-524 blank tire and the E-1136 radial tire) were used on three different flexible pavements with three different levels of macrotexture. The tire by pavement interaction found in this study, however, although statistically significant, was far less prominent than the interaction seen in Henry's data. To the extent that the flexible pavements used in this study are representative of the flexible pavements throughout the highway system – to the extent that the range of pavement macrotextures in the present study is representative of the range of pavement macrotextures in the real world – tire by pavement interaction is not a good explanation for the scatter, the "noise" seen in Figure 1, and similar figures constructed in this format. Simply stated, the inability of a statistician to accurately predict wet surface accident rates on the basis of skid number (and other predictor variables) is little affected by the use of the E-501 ribbed tire (or the E-524 blank tire or the E-1136 radial tire, for that matter), at least for flexible pavements with macrotextures within the range of those used in the present study.

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# APPENDIX B

## Evaluation of the
## Yandall-Mee Friction/Texture Device

# EVALUATION OF THE YANDELL-MEE FRICTION/TEXTURE DEVICE

by

Richard Zimmer

April 1990

Safety Division
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843

# EVALUATION
# of
# THE YANDELL-MEE FRICTION/TEXTURE DEVICE

**by**

**Dick Zimmer**

## INTRODUCTION

The Yandell-Mee Friction Texture Device consists of several units working together to provide static roadway friction and texture measurements. The main unit is an instrument box, which is placed on the pavement. This unit contains a light source, video camera, motion table and control electronics, figure 1. A multiconductor cable connects this unit to a Compaq Portable III computer (PC), monitor and printer, figure 2. Within 30 seconds after placing the instrument box on the pavement, the profile or texture is read into the PC. The pavement friction coefficients are then calculated directly from the profile by algorithms developed by Dr. Yandell at the University of New South Wales. The results of each location are presented on the screen and saved to the hard disk for later printout. The friction meter requires a source of 110 volts, 60 Hz power for the computer. This power is supplied from the vehicle by a 12 VDC to 110 VAC invertor supplied with the system.

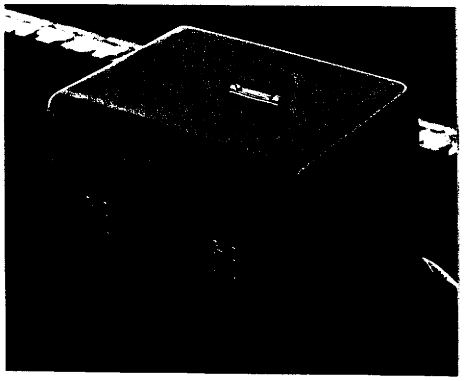

Figure 1.

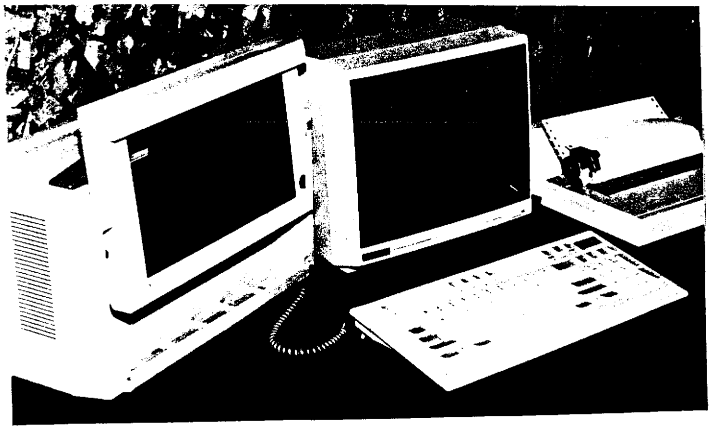

Figure 2.

At each test location the unit will display 'locked' and 'sideways' friction at three speeds. In addition the average and peak texture depths are displayed and recorded.

## EVALUATION TEST PLAN

The Yandell-Mee device was evaluated at the Texas Transportation Institute Proving Grounds by comparing its results with the results obtained by two well established standard procedures used by the Department. The first was ASTM E-274, a skid trailer, which measures the friction between the pavement and a standard tire, in a locked mode, while traveling at 40 MPH. This is the primary method of testing pavement in the U.S. today with each state having one or more units.

The second standard test method the Yandell-Mee device was compared to was the ASTM E-965 method for determining average texture depth using the "sand patch" technique.

In order to compare the unit's operation on various pavement types and textures, five different research surfaces at the TTI Proving Ground were chosen. These were:

Jennite, a coal tar seal coat with no additives such as sand. This surface is also used for a driver training handling pad due to its very low wet friction. (Low macrotexture and microtexture)

Jennite with sand is the same as above but with a sand content to increase friction. (Low microtexture and moderate macrotexture)

Asphalt with round gravel aggregate was used as a test pavement because of the smooth aggregate. (High macrotexture and low microtexture)

Concrete, a common pavement was included. (A moderate macrotexture and microtexture)

Asphalt pavement of the type used by the local SDHPT was available at the TTI Proving Ground and was included. (A moderate macrotexture and microtexture)

The test speeds chosen for the evaluation were 30, 40 and 50 MPH. The rational for this was that 40 MPH is the standard E-274 test speed plus 10 MPH either side would provide three realistic data points.

To provide a statistically sound data base, ten runs were made with the skid trailer on each of the five pavement types at the three speeds. On a given pavement type, the ten runs were repeated over a single path. Prior to the runs with the skid trailer, ten readings were taken along the path at five foot intervals with the Yandell-Mee device. Upon finishing the runs with the skid trailer, ten additional readings were taken with the Yandell-mee device as before, but using a starting point two feet farther down the path, so as to avoid taking readings at the same spots.

## RESULTS

### Friction

The results of these tests are shown in Table 1. Each entry for the E-274 SN is the mean of 10 Skid Number values. The $\sigma$ column is the standard deviation over the ten runs. The two Yandell-Mee LWF (Locked Wheel Friction) values for each pavement/speed combination represent the mean of ten readings taken before and ten readings after the skid trailer tests. Again the $\sigma$ is the standard deviation of the ten readings.

### Texture

The texture results are the mean of two reading each with the sand patch method and the Yandell-Mee device. The sand patch test was made in exactly the same spots on each pavement as the two Y-M tests, reducing the need for multiple tests.

## CONCLUSIONS

The Skid Number and standard deviation values obtained by the E-274 method are consistent with those obtained on these test pavements at other times. As can be seen, the Yandell-Mee values

| PAVEMENT | | FRICTION | | | | TEXTURE | |
|---|---|---|---|---|---|---|---|
| Const. | Speed | E-274 | | Yandell | | E-965 | Y-M |
| Type | MPH | SN | σ | LWF | σ | mm | mm |
| JENNITE | 30 | 24.6 | 1.88 | 8.1 | 2.96 | .610 | .633 |
| | | | | 15.5 | 5.46 | | |
| | 40 | 20.6 | 0.60 | 7.4 | 2.86 | | |
| | | | | 14.6 | 5.50 | | |
| | 50 | 21.0 | 1.46 | 7.0 | 2.80 | | |
| | | | | 14.2 | 5.53 | | |
| JENNITE W/SAND | 30 | 32.6 | 1.43 | 28.0 | 6.80 | .980 | .672 |
| | | | | 28.4 | 7.95 | | |
| | 40 | 30.4 | 0.97 | 27.5 | 7.36 | | |
| | | | | 27.6 | 8.33 | | |
| | 50 | 28.5 | 1.03 | 27.3 | 7.72 | | |
| | | | | 27.3 | 8.63 | | |
| ROUND GRAVEL | 30 | 40.3 | 0.98 | 50.3 | 10.5 | 1.50 | 1.04 |
| | | | | 41.9 | 10.9 | | |
| | 40 | 36.5 | 0.82 | 51.0 | 10.9 | | |
| | | | | 42.3 | 11.3 | | |
| | 50 | 36.2 | 1.64 | 52.2 | 11.4 | | |
| | | | | 43.1 | 11.8 | | |
| ASPHALT | 30 | 68.5 | 2.07 | 21.2 | 4.68 | .648 | .768 |
| | | | | 48.5 | 15.1 | | |
| | 40 | 60.5 | 1.60 | 20.0 | 4.60 | | |
| | | | | 48.8 | 15.8 | | |
| | 50 | 54.3 | 2.36 | 19.6 | 4.63 | | |
| | | | | 49.5 | 16.6 | | |
| CONCRETE | 30 | 51.3 | 0.78 | 16.4 | 5.59 | .610 | .320 |
| | | | | 13.45 | 7.64 | | |
| | 40 | 47.7 | 0.63 | 15.32 | 5.53 | | |
| | | | | 12.5 | 7.58 | | |
| | 50 | 45.7 | 0.66 | 14.8 | 5.56 | | |
| | | | | 12.0 | 7.63 | | |

for locked wheel friction come close to agreeing with the E-274 method on the Jennite with sand surface only. These values are also the most repeatable between the first and second pass with the Y-M. The Round gravel pavement is next in line in nearness of agreement. The other pavements as measured with the Yandell-Mee device appear to be widely separated from the E-274 values.

The standard deviations for the Yandell-Mee device range from 2.8 to 16.6. The higher values of $\sigma$ would require an inordinate number of measurements of a section of pavement to produce a meaningful value.

The texture measurements somewhat closer correlation, especially for the Jennite. Others were diverse such as the concrete.

One reason for the nonagreement with E-274 and different reading from the Y-M on the same pavement could be the manual adjustment of the video aperture. Even though the video aperture was adjusted, as instructed by Dynatest PMS, on each new pavement type there was a level of uncertainty. At best, this is a very subjective adjustment. As the manual states "an incorrect setting will have a drastic affect on the accuracy of the results" and "Judgement on the correct aperture setting should be made on the level of saturation of the image." The system could be vastly improved by removing this requirement from the operator and placing it under computer control.

# APPENDIX C

## Comparison of E-501 Blank & Ribbed Tires Using the Diagonally Braked Vehicle

Another friction measurement device evaluated as part of this study was the Diagonal Braking Vehicle (DBV). This device has been the subject of considerable development and evaluation since 1982 when the Texas Transportation Institute report, "Development of a Skid Resistance Measurement Method for Cities and Counties" was issued.

It was expected that differences between ribbed and blank tires using this device would follow the same trends as produced by the skid trailer. This was not the case. As shown in figures 1 through 6 the results produced by the blank tire as a function of speed are quite different from the indications of the ribbed tire. When these values were first measured the first reaction was to suspect a problem in the DBV instrumentation, braking or water distribution systems. Investigation indicated this was not true. All systems were functioning properly. This anomoly is especially obvious in comparing curves 5 and 6. The strange gyrations of the observations on the Rounded Gravel Hot Mix are simply unexplained. The wide variation of the blank tire at 50 mph and the fact that the average value is some twelve friction numbers above the ribbed tire dictates that the DBV cannot be recommended for use by the Texas DOT at this time.

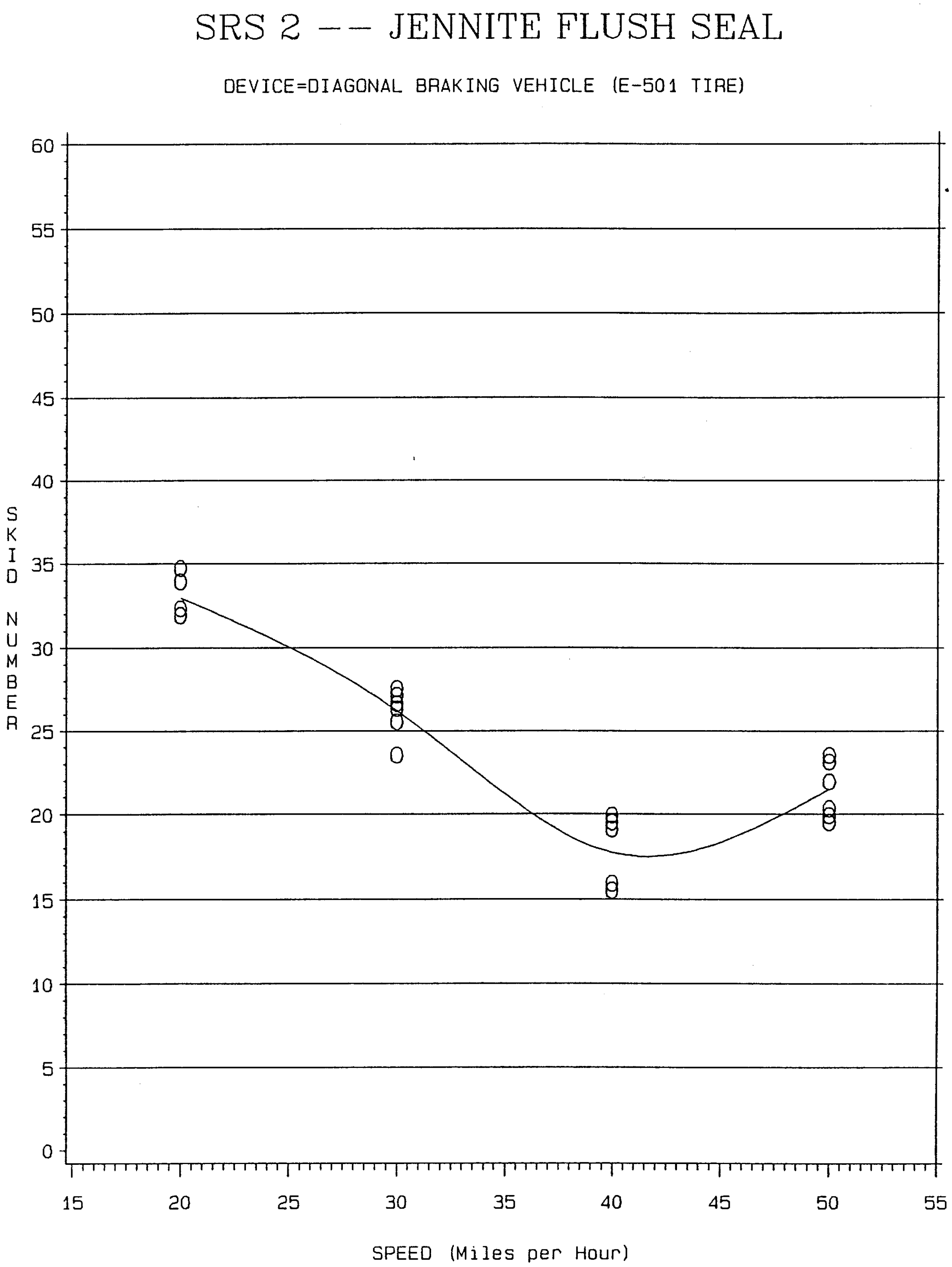

**Figure 1 E-501 Blank Tire**

## SRS 2 -- JENNITE FLUSH SEAL

DEVICE=ASTM E-501 RIBBED TIRE (INITIAL RUNS)

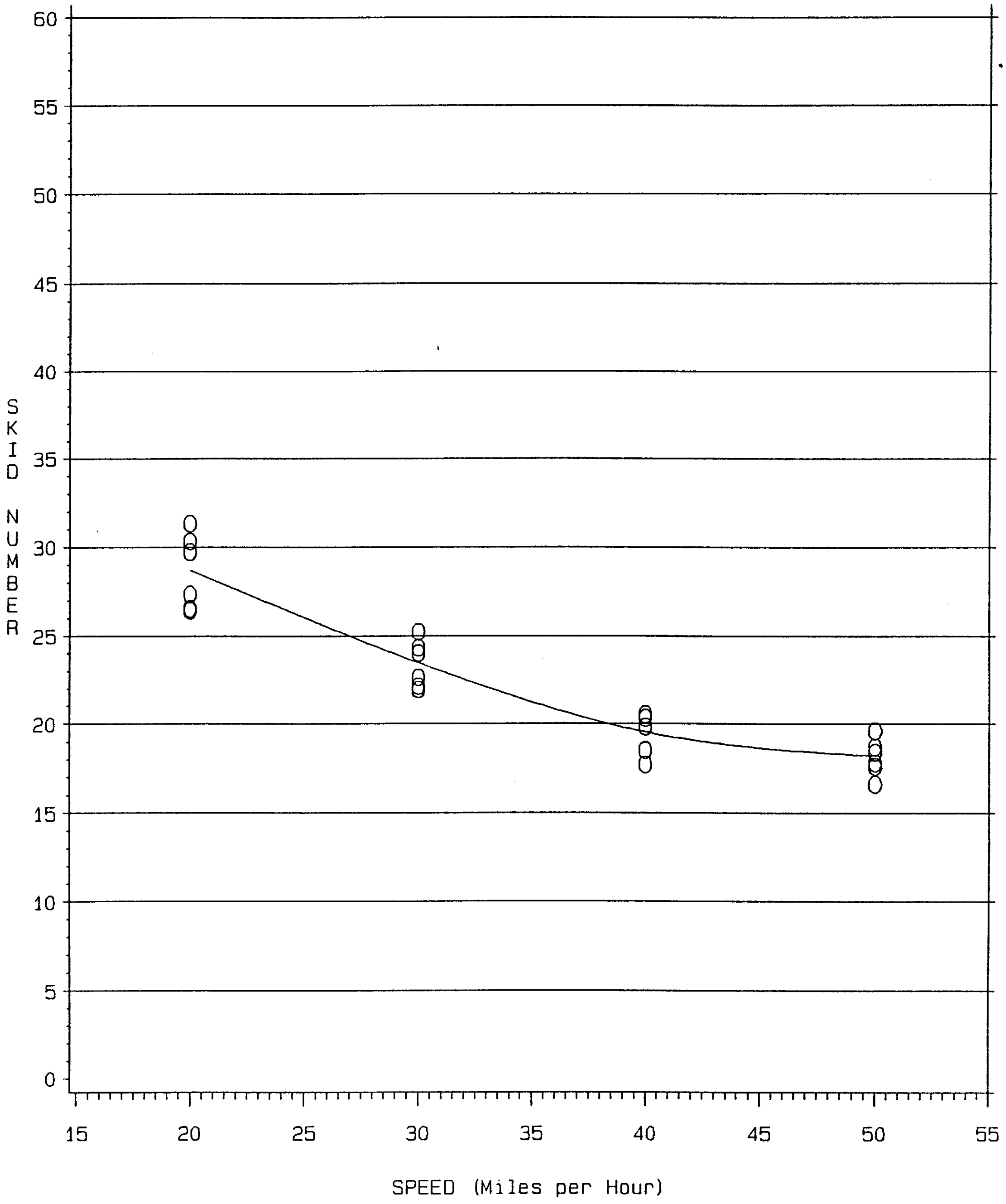

**Figure 2** **E-501 Ribbed Tire**

# SRS 4 -- JENNITE FLUSH SEAL WITH SAND

DEVICE=DIAGONAL BRAKING VEHICLE (E-501 TIRE)

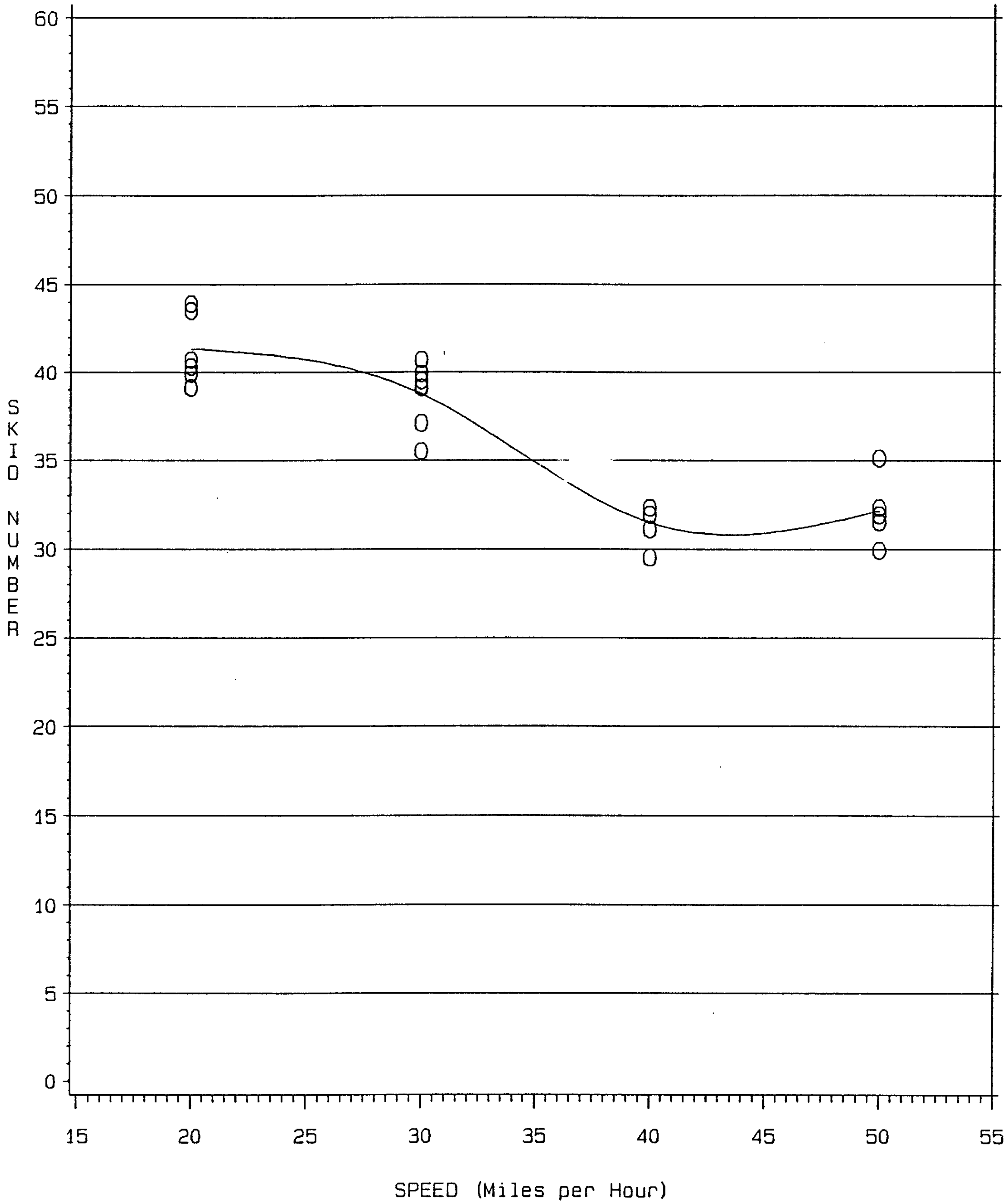

**Figure 3 E-501 Blank Tire**

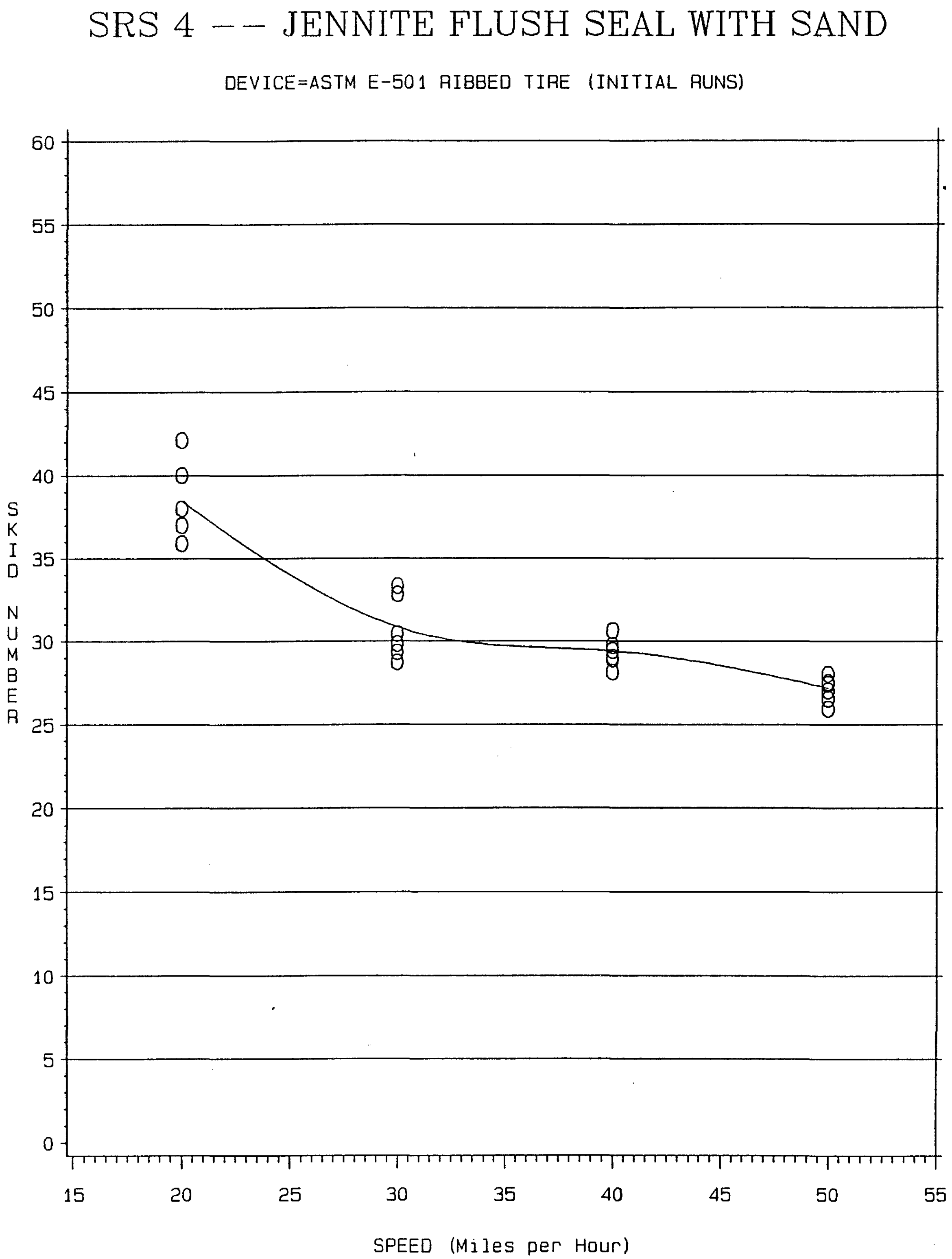

**Figure 4** **E-501 Ribbed Tire**

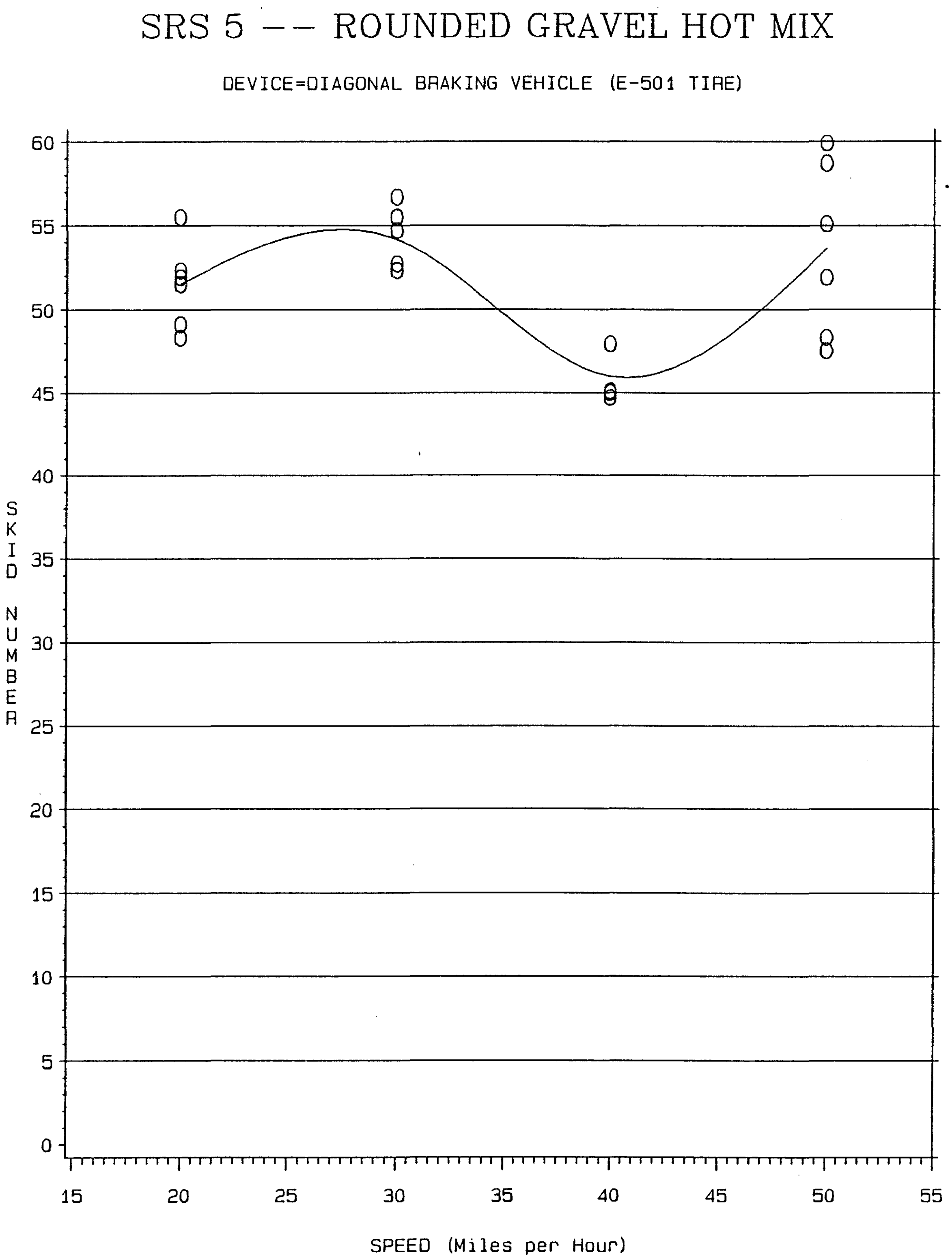

**Figure 5 E-501 Blank Tire**

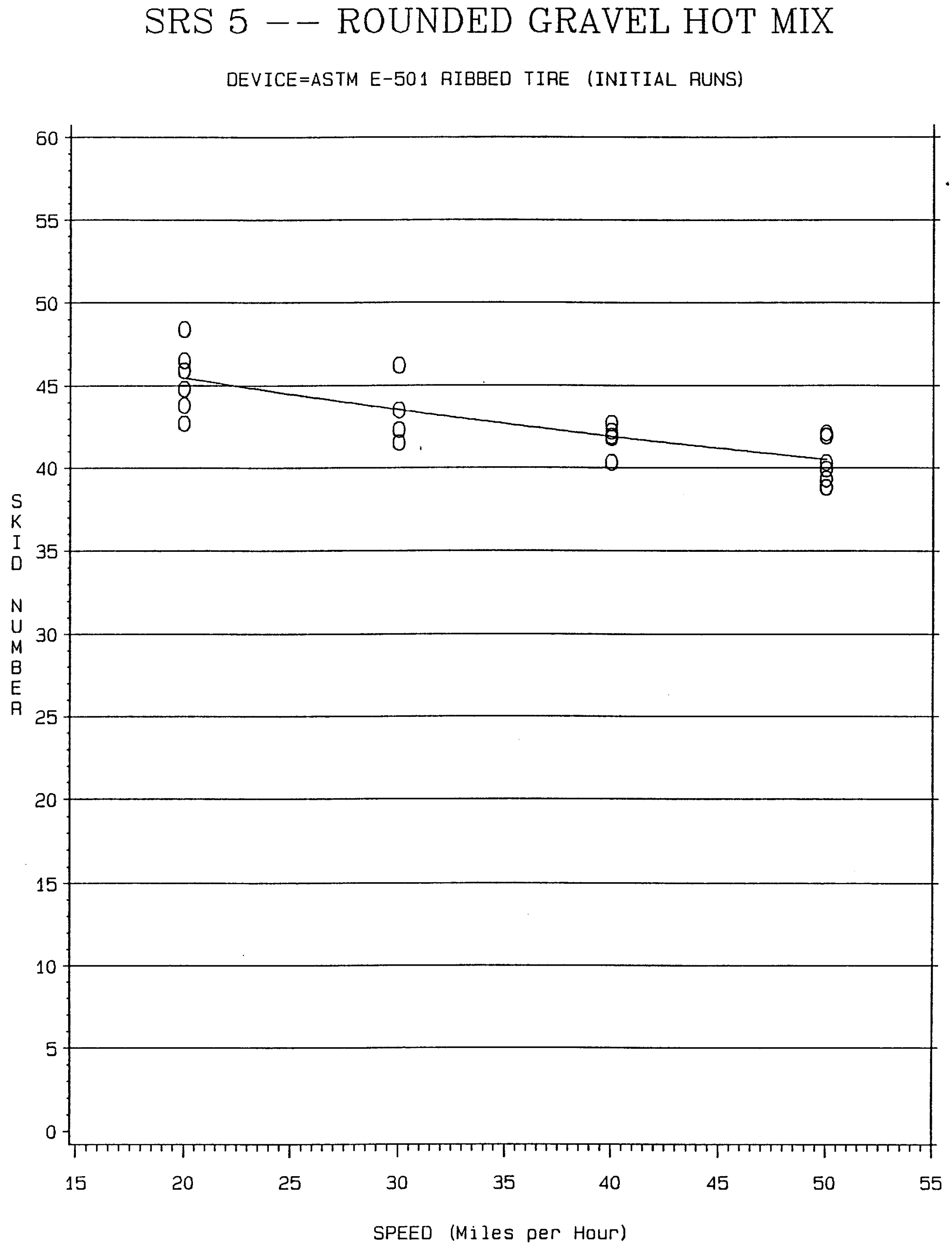

**Figure 6 E-501 Ribbed Tire**

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